05

Correction of large- and small-scale wavefront aberrations in dual-loop adaptive optical system

© V.V. Toporovsky[1,2], I.V. Galaktionov[1,2], A.N. Nikitin[1], V.V. Samarkin[1], A.V. Kudryashov[1]

[1] Sadovsky Institute of geosphere dynamics RAS, Moscow, Russia
[2] Moscow Technical University of Communications and Informatics (MTUCI), Moscow, Russia

e-mail: topor@activeoptics.ru

Received May 04, 2024
Revised May 04, 2024
Accepted October 30, 2024.

An adaptive optical system with the ability to sequentially correct large- and small-scale wavefront aberrations is presented. Artificial turbulence on a laboratory bench was simulated with a fan heater. A 50 mm bimorph deformable mirror with 28 control elements to compensate for low-order phase fluctuations (defocus, astigmatism, coma, spherical aberration) and a stacked-actuator piezoelectric deformable mirror with an aperture of 78 mm and 55 actuators to suppress the influence of high-order phase fluctuations were used as wavefront correctors. Two Shack–Hartmann wavefront sensors were used to analyze the wavefront characteristics and provide closed-loop control.

Keywords: piezoelectric wavefront correctors, bimorph deformable mirror, piezoactuator deformable mirror, Shack–Hartmann wavefront sensor.

DOI: 10.61011/EOS.2024.12.60440.6631-24

Introduction

Impact of atmospheric turbulence effects in laser radiation propagation through an optical path manifests itself in expansion of a dimensional angular structure of a beam, in random change of a center position (drift) and redistribution of energy in its cross section, which is caused by occurrence of local fluctuations in the refractive index [1–3]. Unwanted effect of turbulence may be reduced by using methods and means of adaptive optics [4,5]. The classic adaptive optical system consists of a wavefront corrector, a wavefront sensor and a control unit [6–9]. A wavefront corrector as the main element of the system is often characterized by spatial (resolution of control elements, amplitude of reflecting surface deformation) and time (working frequency range) parameters. However, it is complicated to design a wavefront corrector that would simultaneously meet both the amplitude and working frequency range requirements. Therefore, adaptive optical systems are used with two wavefront correctors [6,8], where devices are used with relatively low spatial resolution of actuators for correction of large-scale aberrations of the wavefront that vary in time with low frequency. To compensate for small-scale phase fluctuations with high frequency of oscillations, correctors are used with high density of control elements, but with the lower amplitude of substrate deformation. The first criterion is quite met by bimorph deformable mirror [10–12], the second one — by piezoelectric deformable mirror of pushing type [13–16].

Besides, a problem arises with the control of the wavefront correctors. Currently there are four main methods of control in similar adaptive optical systems:

— zonal method — control signals are obtained by inversion of a composite interaction matrix [17];

— modal reconstruction — control signals are generated by separation of the modes of low and high frequency components of the spectrum and are calculated separately for both correctors [18];

— Zernike distribution — wavefront aberrations are decomposed into Zernike polynomials, and every deformable mirror corrects the spatially separated wavefront with its own set of polynomials [19];

— two-contour control — the simplest and most reliable control method, which consists in using two separate adaptive optical contours with individual wavefront sensors [20].

Therefore, two-contour control by deformable mirrors was chosen in the developed adaptive optical system.

Two-contour adaptive optical system based on bimorph and piezoactuator deformable mirror

Development of the adaptive optical system to a large extent relies on the selection of wavefront correctors and their main parameters.

As it was mentioned above, a device for compensation of lowest aberrations of the wavefront was a 50 mm bimorph deformable mirror with 28 control elements (fig. 1), where one piezoplate is a common electrode for effective correction of defocus, and the other one is divided into 27 electrodes to compensate for other aberrations of the wavefront. The main advantages of this mirror are the high amplitude of surface bend, and the possibility to correct large-scale fluctuations of the phase using a small number

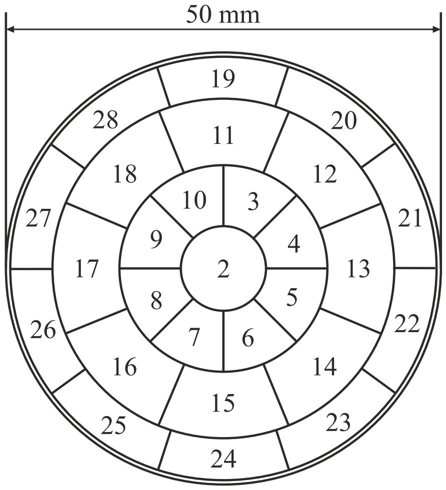

Figure 1. Grid of bimorph deformable mirror electrodes.

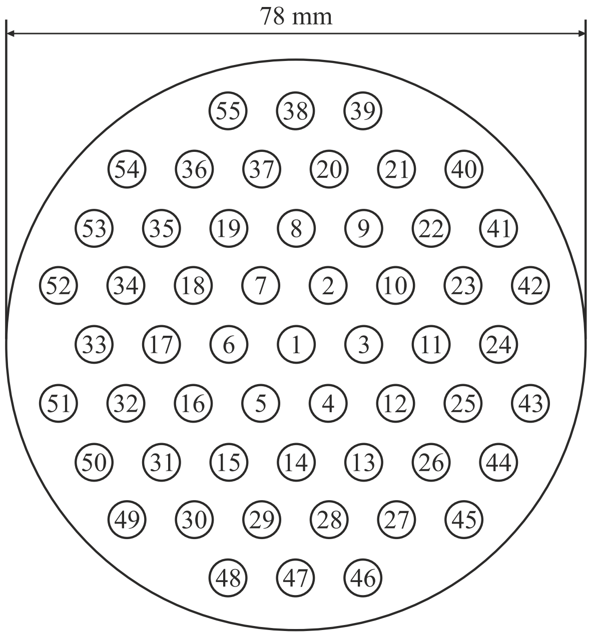

Figure 2. Geometry of location of actuators in deformable mirror of pushing type.

of control electrodes (for example, to compensate for the impact of defocus, astigmatism and coma, 13 electrodes are enough). At the same time they have some disadvantages: low amplitude of high-order aberration correction (from 8 Zernike polynomials), which is due to the high coefficient of mirror electrode coupling and slow amplitude-frequency response, which limits the possibility of their use in the systems for correction of quick-changing small-scale fluctuations of the phase.

To compensate for high aberrations of the wavefront, a piezoactuator deformable mirror was used (fig. 2), the advantages of which are high value of first resonance frequency (factor that determines the system working frequency range) and high accuracy of correction of small-scale aberrations of the wavefront.

The schematic optical diagram of the two-contour adaptive optical system is shown in fig. 3, *a*. It consists of two wavefront correctors (bimorph and piezoactuator), matching optics to increase beam size from 50 to 75 mm. To assess the efficiency of the system operation, a long-focus lens was used, in the focus of which a far field camera was located. Feedback to control actuators of deformable mirrors is provided by the availability of two Shack–Hartmann wavefront sensors. Artificial turbulence at the optical bench was developed using a fan heater, the developed flow of which corresponds to the atmospheric turbulence of Kolmogorov spectrum [1].

The photograph of the assembled experimental setup is presented in fig. 3, *b*.

Conclusion

This paper considers the two-contour adaptive optical system for compensation of large- and small-scale aberrations of the wavefront. A bimorph wavefront corrector with diameter of 50 mm with 28 electrodes was used to correct large-scale aberrations of laser radiation wavefront, and a piezoactuator flexible mirror with diameter of 78 mm with 55 control elements — for compensation of impact from the small-scale phase fluctuations. Turbulence similar to the one occurring in real atmospheric routes was developed using a fan heater on a laboratory bench.

Funding

The paper was supported by grant № 20-19-00597 from the Russian Science Foundation.

Conflict of interest

The authors declare that they have no conflict of interest.

References

[1] A. Rukosuev, A. Nikitin, V. Toporovsky, J. Sheldakova, A. Kudryashov. Photonics, **9**, 351 (2022). DOI: 10.3390/photonics9050351
[2] F. Roddier. *Adaptive Optics in Astronomy* (Cambridge University Press, 1999).
[3] D.L. Fried. J. Opt. Soc. Am., **55**, 1427–1435 (1965). DOI: 10.1364/JOSA.55.001427
[4] V. Toporovsky, A. Kudryashov, V. Samarkin, J. Sheldakova, A. Rukosuev. Proc. SPIE, **11266**, 1126619 (2020). DOI: 10.1117/12.2548325
[5] P. Rausch, S. Verpoort, U. Wittrock. Optics Express, **24**, 1528–1542 (2016). DOI: 10.1364/OE.24.001528
[6] I. Galaktionov J. Sheldakova, A. Nikitin, V. Toporovsky, A. Kudryashov. Algorithms, **16**, 337 (2023). DOI: 10.3390/a16070337

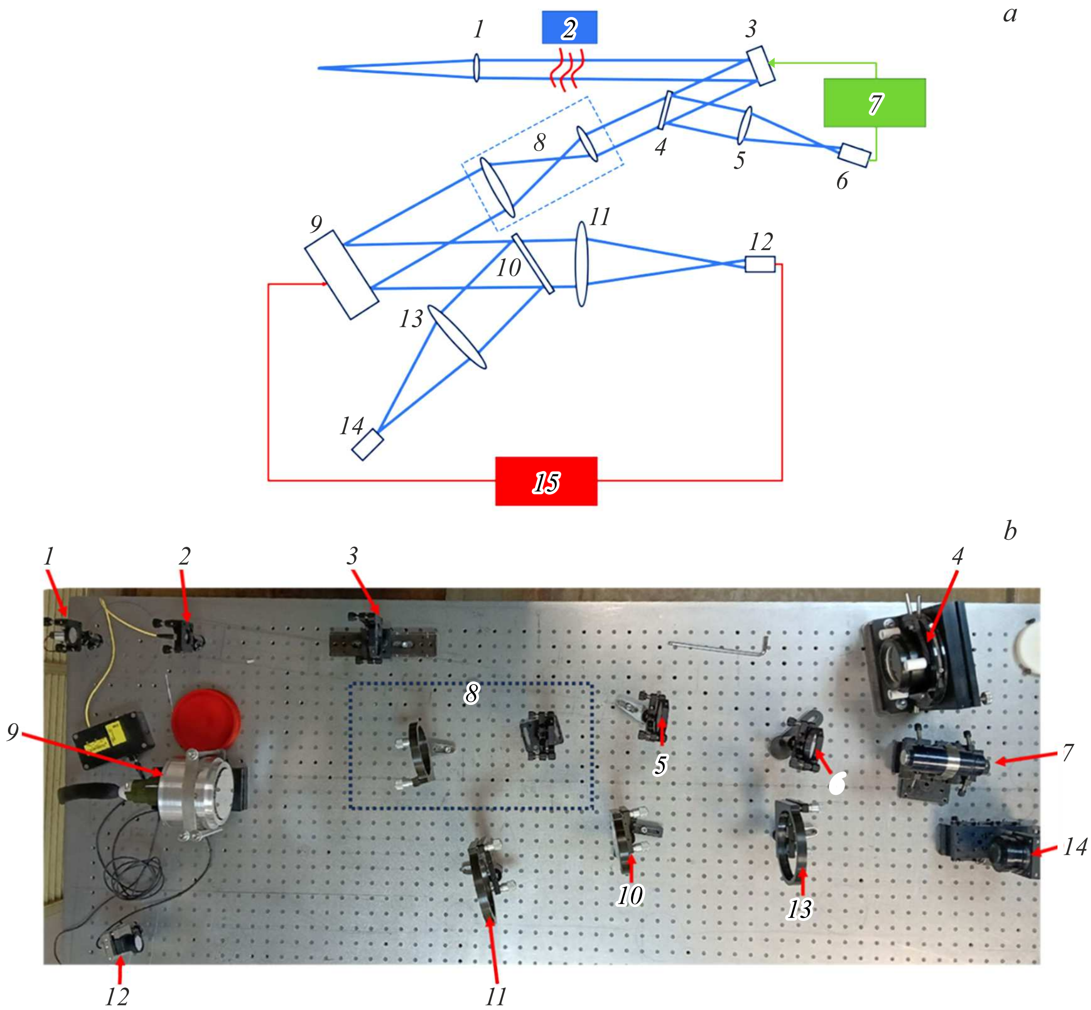

Figure 3. Two-contour adaptive optical system: (*a*) schematic diagram of experimental setup (*1* — collimating lens, *2* — fan heater, *3* — bimorph deformable mirror, *4, 10* — beam-splitting plates, *5, 11* — lenses, *6, 12* — wavefront sensors, *7, 15* — control units, *8* — matching optics, *9* — piezoactuator deformable mirror, *13* — long-focus lens, *14* — far field camera); (*b*) experimental setup photo (*1* — trace laser, *2* — diagnostic laser, *3* — collimating lens, *4* — bimorph deformable mirror, *5, 10* — beam-splitting plates, *6, 13* — lenses, *7, 14* — wavefront sensors, *8* — matching optics, *9* — piezoactuator deformable mirror, *11* — long-focus lens, *12* — far field camera).

[7] J.-F. Lavigne, J.-P. Véran. J. Opt. Soc. Am. A, Optics, Image Science, and Vision, **25**, 2271–2279 (2008). DOI: 10.1364/JOSAA.25.002271
[8] C. Correia, J. Véran. Optics Letters, **37**, 3132–3134 (2012). DOI: 10.1364/OL.37.003132
[9] W. Zou, S. Burns. Appl. Optics, **51**, 1198–1208 (2012). DOI: 10.1364/AO.51.001198
[10] V. Toporovsky, A. Kudryashov, V. Samarkin, I. Galaktionov, A. Rukosuev. Proc. ITNT-2022, 1–5 (2022). DOI: 10.1109/ITNT55410.2022.9848711
[11] V. Toporovsky, V. Samarkin, A. Kudryashov, I. Galaktionov. Proc. SPIE, **12218**, 1221806 (2022). DOI: 10.1117/12.2632914
[12] S. Kokorowski. J. Opt. Soc. Am., **69**, 181–187 (1979). DOI: 10.1364/JOSA.69.000181
[13] V. Toporovsky, V. Samarkin, A. Kudryashov, I. Galaktionov, A. Panich, A. Malykhin. Micromachines, **14**, 2004 (2023). DOI: 10.3390/mi14112004
[14] V. Toporovsky, A. Kudryashov, V. Samarkin, J. Sheldakova, A. Rukosuev. Proc. SPIE, **10772**, 107720U (2018). DOI: 10.1117/12.2324271
[15] V. Toporovsky, V. Samarkin, A. Kudryashov, A. Panich, A. Sokallo, A. Malykhin, J. Sheldakova. Proc. SPIE, **11987**, 119870M (2022). DOI: 10.1117/12.2614509
[16] V. Toporovskiy, A. Kudryashov, V. Samarkin, J. Sheldakova, A. Rukosuev. Proc. SPIE, **11135**, 111350A (2019). DOI: 10.1117/12.2533984
[17] R. Conan, C. Bradley, P. Hampton, O. Keskin, A. Hilton, C. Blain. Appl. Opt., **46**, 4329–4340 (2007). DOI: 10.1364/AO.46.004329
[18] S. Hu, B. Xu, X. Zhang, J. Hou, J. Wu, W. Jiang. Appl. Opt., **45**, 2638–2642 (2006). DOI: 10.1364/AO.45.002638
[19] S.M. Jones, S. Olivier, D. Chen, S. Joeres, S. Sadda, R.J. Zawadzki, J.S. Werner, D.T. Miller. Proc. SPIE, **6467**, 64670H1 (2007). DOI: 10.1117/12.711189
[20] D.C. Chen, S.M. Jones, D.A. Silva, S.S. Olivier. J. Opt. Soc. Am. A, **24**, 1305–1312 (2007). DOI: 10.1364/JOSAA.24.001305

Translated by M.Verenikina