Adaptive Beaming and Imaging in the Turbulent Atmosphere
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and Imaging in the
Turbulent Atmosphere

Vladimir P. Lukin
Boris V. Fortes

Translated by A. B. Malikova

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Preface to the English Edition

This monograph is presented by two authors working at the Institute of Atmospheric Optics, Siberia, Russian Academy of Sciences (Tomsk, Russia). It is an overview of our results reported in recent years (up to 1999).

Specialists know that now it is practically impossible to write a book that thoroughly reviews the state of the art in adaptive optics because of the rapid advances in this field. Therefore, in this book we omit such a review and only give the necessary references to original papers (as of 1998, the year this book was written in Russian). We apologize to those authors whose papers were undeservedly ignored and not cited.

This book does not pretend to be a generalization of the most recent results. It is more like a compendium of results and ideas the authors followed when developing this particular area of modern optics. These days, the world community has developed approaches and concepts different from those presented in this book, and they have the right to their own existence and development as well.

With due respect for our readers,

Vladimir P. Lukin
Boris V. Fortes
June 2002
INTRODUCTION

The extensive use of optical technologies for solving problems of information transfer, narrow-directional electromagnetic energy transport, and image formation in an outdoor atmosphere calls for the development of adaptive correction methods and devices of that are an effective means of controlling the decrease in the efficiency of atmospheric optical systems caused by inhomogeneities in large-scale refractive indexes. These inhomogeneities are due to the turbulent mixing of atmospheric air masses and molecular and aerosol absorption in the channel of optical radiation propagation.

Adaptive optical systems (AOS) that operate in real time allow one to

- improve laser radiation focusing on a target, and hence increase the radiation intensity within the focal spot;
- decrease the image blooming of astronomical and other objects in telescopes, increase image sharpness, and decrease the probability of object recognition errors; and
- decrease the noise level and increase the data rate in optical communication systems.

Annual international conferences on adaptive optics held under the auspices of SPIE (The International Society for Optical Engineering), OSA (Optical Society of America), and adaptive optics sessions included in the programs of other conferences on atmospheric optics testify to the urgency of this problem. In 1994, a special issue of the Journal of the Optical Society of America was devoted to problems of adaptive correction of atmospheric distortions. Special annual issues of Atmospheric and Oceanic Optics are published by the Institute of Atmospheric Optics. Recently, AOS has been introduced in astronomical telescopes in many countries, including Russia, where the original Russian project of the AST-10 10-m adaptive telescope is being developed.

Wide practical application of AOS has revealed a number of problems that call for the development of a theory of optical wave propagation under adaptive control conditions. A search for answers to these problems necessitates the development of detailed and adequate mathematical AOS models and the application of research methods such as numerical experiments that solve a system of differential equations describing optical wave propagation in the atmosphere.

This monograph is primarily concerned with the original results of our investigations carried out using numerical experiments (models). The sole exceptions are sections devoted to adaptive image formation. Numerical experiments allow the maximum number of parameters to be considered to
correctly model AOS and to investigate practically any significant radiative characteristic—the effective size of the light spot, the peak radiant intensity, the radiation power incident on the receiving aperture, the statistical characteristics of the radiant intensity and phase—in the context of a universal approach. A numerical experiment with applications to AOS allows one to predict the efficiency of various system configurations. Much time and considerable expense would be required to perform field experiments.

Work on numerical modeling of atmospheric distortions of beams and images and also on the possibility of their adaptive correction goes back to the early 1970s. It was started nearly simultaneously in several large U.S. laboratories (including Lincoln Laboratory at Massachusetts Institute of Technology and the Lawrence Livermore Laboratory at the University of California). Here it is pertinent to mention, in particular, the first reports on the results of numerical modeling of thermal self-action obtained by Gebhardt and Smith, Bradley and Herrmann, and Ulrich et al. The first work devoted to phase compensation for thermal blooming was published in 1974, and the first work devoted to a numerical investigation of the adaptive correction for turbulent image distortions was published in the same year. In 1976, Fleck, Morris, and Feit described in detail a procedure for solving the nonstationary problem of thermal self-action in a turbulent atmosphere. The first special issue of the Journal of the Optical Society of America, which summarized the results of theoretical and experimental investigations into adaptive optics in the United States, was published in 1977.

In the USSR, this field has developed since the late 1970s. The first work devoted to the theory of adaptive correction was published by V. P. Lukin in 1977. B. S. Agrovskekii and V. V. Vorob’ev et al. (Institute of Atmospheric Physics RAS) and P. A. Konyaev (Institute of Atmospheric Optics SB RAS) studied AOS numerically. At the same time, M. A. Vorontsov, S. S. Chesnokov, V. A. Vysloukh, K. D. Egorov, and V. P. Kandidov (Moscow State University) published papers devoted to phase correction for nonlinear distortions. Special issues of the journal Izvestiya Vysshikh Uchebnykh Zavedenii, Fizika and monographs by M. A. Vorontsov and V. I. Shmal’gauzen (Principles of Adaptive Optics); V. P. Lukin (Atmospheric Adaptive Optics); and M. A. Vorontsov, A. V. Koryabin, and V. I. Shmal’gauzen (Controllable Optical Systems) review previous work in this field.

The current state of research on numerical modeling of adaptive optical systems can be characterized as follows. Basic numerical methods of solving the problems of optical wave propagation in randomly inhomogeneous media, including the thermal action of high-power beams, have been developed, and work on the development of numerical models of individual AOS components that takes into account their geometrical parameters and spatiotemporal resolution has been started, along with a search for the most efficient correction algorithms. This monograph summarizes the main results of our work in this field from 1985 to 1997.
The first chapter considers methodological aspects of numerical modeling of propagation of monochromatic coherent radiation in a randomly inhomogeneous, weakly absorbing medium. It describes numerical methods used to solve the inhomogeneous wave equation together with mathematical models of turbulent distortions and thermal inhomogeneities arising during optical radiation propagation through an absorbing medium. Numerical techniques of dynamic modeling of random phase screens are further developed and methods of modeling large-scale portions of the turbulence spectrum are described. In the last section of this chapter, the lens transformation is generalized to the case of an arbitrary optically inhomogeneous medium.

The second chapter describes numerical modeling of a closed AOS system and numerical models of a reference wave, sensors, and wavefront (WF) correctors. Mathematical models and the main points of numerical modeling are described for the following AOS components: an oncoming reference beam; natural and artificial reference stars; an ideal-square law and Hartmann wavefront sensors; and modal, segmented, and flexible adaptive mirrors.

In the third chapter, the problem of minimization and adaptive correction for turbulent distortions is solved. Here, the effect of the outer scale of turbulence on the main parameters of image formation in an atmosphere–telescope system, including the Strehl factor (SF) and the angular resolution (the width of the point spread function, PSF), is studied. The possibility of wavelength optimization is estimated quantitatively in a situation in which the size of the outer scale of turbulence is comparable to the aperture diameter. The angular resolution is further studied for incomplete (partial) correction for turbulent image distortions. In the last section of this chapter, the efficiency of phase correction is analyzed for extended paths and weak intensity fluctuations of the reference and corrected waves.

In the fourth chapter, the efficiency of adaptive correction for thermal activity is investigated. At the beginning of the chapter, the thermal effect of a wide-aperture high-power beam propagating along a vertical path represented by a composite nonlinear phase screen is analyzed. The parameters of beam power optimization and lower-mode correction for phase distortions are calculated for various intensity distributions over the beam cross section with allowance for the altitude dependence of the wind direction. The salient features of the functioning of phase-conjugation (PC) AOS used to correct for nonstationary action on a homogeneous horizontal path are further studied. A correlation between oscillations arising in these systems and phase dislocations in the reference wave is demonstrated. The results of numerical experiments for an AOS with the Hartmann WF sensor are given in the last section together with the modified phase conjugation algorithm and curves of power optimization that prove the efficiency of this modification.

The fifth chapter is devoted to an urgent problem of compensation for turbulent jitter in the image of an astronomical object when a laser guide star (LGS) is used as a reference source. Different configurations (bistatic and monostatic) of the system for measuring the random refraction are considered.
The efficiency of jitter correction is studied as a function of the ratio of the receiving and transmitting apertures. An algorithm of optimal correction for wavefront tilts is suggested and its efficiency is estimated.

The authors are indebted to their colleagues who were both formal and informal co-authors of the scientific results presented here: they include P.A. Konyaev, N.N. Maier, and E.V. Nosov; the staff of the Laboratory of Applied and Adaptive Optics; and many researchers at the Institute of Atmospheric Optics. Communications with them have helped determine the content of our monograph.

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