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Vladimir P. Lukin
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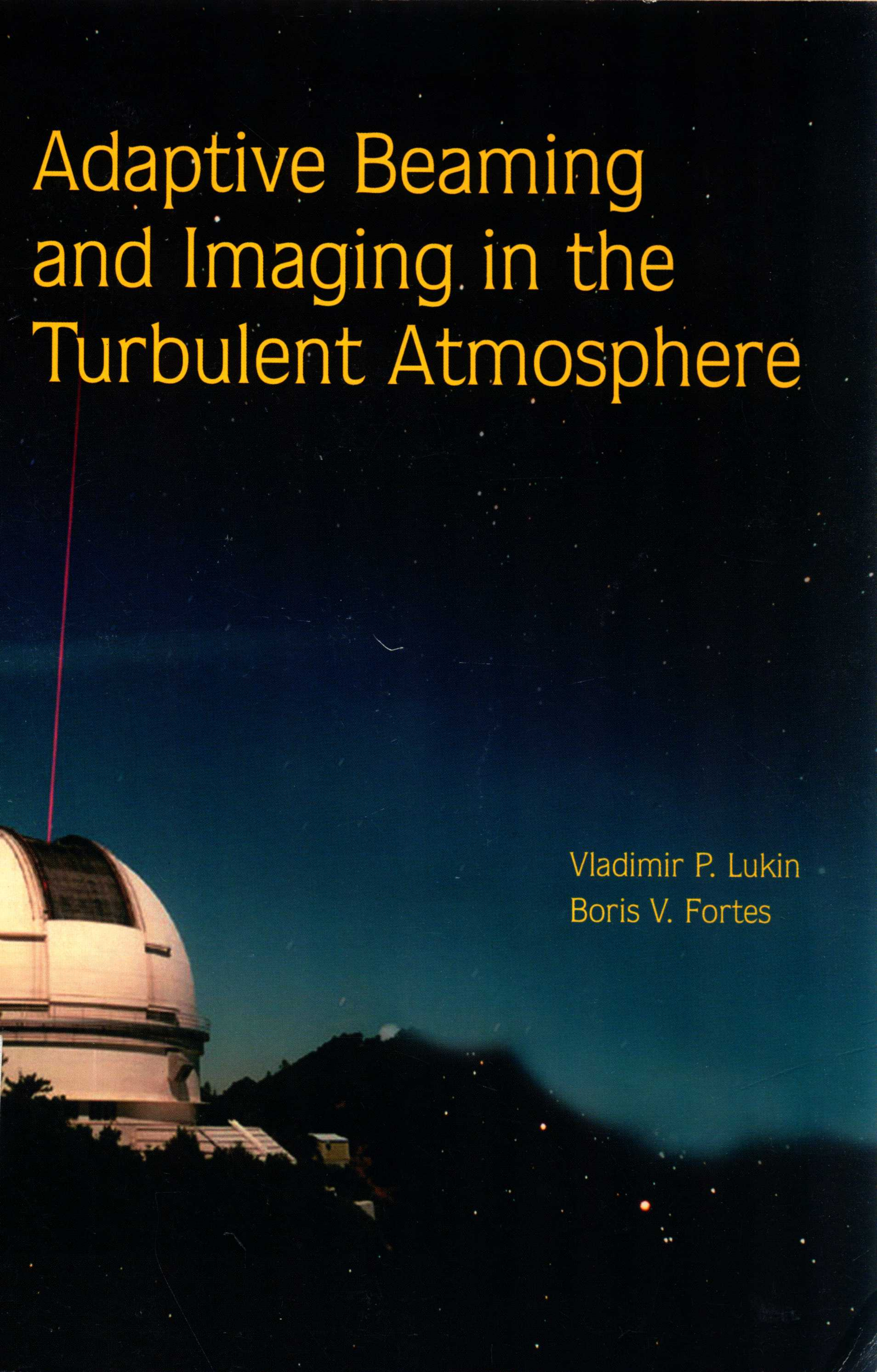

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PREFACE TO THE ENGLISH EDITION

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. Agrovskii 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.

Vladimir P. Lukin
Boris V. Fortes

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CONTENTS

CHAPTER 1

Mathematical Simulation of Laser Beam Propagation in the Atmosphere

A key aspect of the numerical simulation of turbulent effects is generation of 2D random phase screens that imitate distortion of the wavefront during propagation through the atmosphere. One of the first papers devoted to numerical simulation of turbulent distortions of optical waves was by Buckley, who used a Fourier transform (method of spectral samples) to model 1D random phase screens [1]. In papers by Fleck, Morris, and Feit [2], Kandidov and Ledenev [3], and Konyaev [4], the method of spectral samples was used to generate 2D random phase screens in the problem of propagation of a coherent beam through a randomly inhomogeneous medium and, in particular, for estimating the efficiency of phase correction of atmospheric distortions. In a paper by Martin and Flatte [5], a similar method was used to study the probability density of intensity fluctuations.

The Fourier transform method was originally used for numerical simulation in radio engineering [6]. However, a prominent feature of the turbulent atmosphere as a randomly inhomogeneous medium is the wide range of spatial scales of refractive index inhomogeneities. To correctly simulate all of the scales (from inner to outer) of turbulent fluctuations, a computational grid should have at least a thousand nodes along every coordinate, which leads to huge computational time and expense.

To overcome the difficulties connected with the wide-band spectrum of atmospheric turbulence, it makes sense to use some "combined" method, which was first proposed in papers by Duncan and Collins [7, 8], as well as in a paper by Tel'pukhovskii and Chesnokov [9]. The main idea consists in the joint use of spectral (harmonic) and polynomial representations, each of which is used to simulate its own region of spatial scales: spectral decomposition is used to simulate small-scale inhomogeneities, and polynomial decomposition is used to represent scales larger than the size of the computational grid. This approach was further developed in Fortes and Lukin [10], where it was generalized to include nonstationary (dynamic) problems. More recent approaches for optical modeling [11] and physical modeling [12], as well as numerical approaches have also been developed [13-15].

In the following sections we apply our method for numerical solution to two tasks: high-power laser beam propagation in homogeneous media with absorption, and optical wave propagation through a random inhomogeneous turbulent atmosphere. As high-power coherent (laser) beams propagate through a nonturbid atmosphere, *thermal blooming* is one of the main factors causing distortion, along with turbulent fluctuations of the refractive index. This nonlinear effect has the lowest energy threshold and arises as a result of absorption of part of the beam energy and the formation of thermal inhomogeneity in the beam channel. The software developed by Konyaev [16] (Institute of Atmospheric Optics SB RAS, Tomsk, Russia) served as a basic model for numerical simulation of thermal blooming of a paraxial wave beam.

We have implemented several numerical schemes for solving differential equations that describe different hydrodynamic conditions of thermal blooming [17, 18]. In this chapter, we present examples that demonstrate the reliability of the results obtained.

1.1 Numerical Solution to Problems of Coherent Radiation Propagation

For both propagation of coherent beams and imaging in a randomly inhomogeneous medium, the wave equation for the electromagnetic field of an optical wave is the basis for a mathematical model. In the problems considered here, polarization effects are negligible, and the ratio of path length to aperture diameter is chosen so that the small-angle approximation (approximation of paraxial beams) is applicable for a scalar field amplitude [19-21].

1.1.1 Wave equation

Let us introduce a slowly varying component $E(\vec{\rho}, z, t)$ of the complex amplitude of an electromagnetic field in the following way:

$$\sqrt{\frac{cn_0}{8\pi}}\vec{E}(\vec{\rho}, z, t) = \vec{e}E(\vec{\rho}, z, t)\exp(ikz - i\omega t), \tag{1.1.1}$$

so the intensity I is related to the component $E(\vec{\rho}, z, t)$ as

$$EE^* = I\ . \tag{1.1.2}$$

Here, c is the speed of light in a vacuum, n_0 is the refractive index of a medium, $\vec{e}$ is the vector of polarization, $k = 2\pi/\lambda$ is wave number, ω is the frequency of electromagnetic oscillations, $\vec{\rho} = (x, y)$ is the vector of coordinates in the beam cross section (the beam is directed along the $0z$ axis), and t is time.

In the paraxial approximation, propagation of a monochromatic linearly polarized beam in a dielectrically inhomogeneous nonmagnetic medium is described by the parabolic equation for the complex amplitude E:

$$2ik\frac{\partial E}{\partial z} = \left[\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + 2k^2(n^2/n_0^2 - 1)\right]E, \tag{1.1.3}$$

or as

$$2ik\frac{\partial E}{\partial z} = \left(\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + 2k^2\delta n\right)E, \tag{1.1.4}$$

on the assumption that deviations of the refractive index from unity are small; i.e.,

$$n_0 \approx 1, \quad \delta n = (n-1) << 1. \tag{1.1.5}$$

Initially, algorithms based on various finite-difference methods were used to solve the parabolic equation [22]. But, currently, the common method for solution in the domain of spatial frequencies of the complex amplitude E is the splitting algorithm applied together with a discrete Fourier transform (DFT).

The solution to the parabolic equation (1.1.4) corresponding to propagation of a wave from the plane z_l to the plane z_{l+1} can be written in operator form [2]:

$$E(x,y,z_{l+1}) = \exp\left[-\frac{i}{2k}\left(\Delta z\nabla_\perp^2 + 2k^2\int_{z_l}^{z_{l+1}}\delta n dz\right)\right] E(x,y,z_l), \tag{1.1.6}$$

$$\nabla_\perp^2 = \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2}.$$

This equation can be approximated [23, 24] by a symmetrized split operator:

$$E(x,y,z_{l+1}) = \hat{D}\left(\frac{1}{2}\Delta z\right)\hat{R}(z_l, z_{l+1})\hat{D}\left(\frac{1}{2}\Delta z\right)E(z_l) + O(\Delta z^2),$$

$$\hat{D}(\Delta z) = \exp\left(-i\frac{1}{2k}\Delta z\nabla_\perp^2\right), \quad R(z_l,\ z_{l+1}) = \exp\left(-ik\int_{z_l}^{z_{l+1}}\delta n dz\right). \tag{1.1.7}$$

Here, the operator $\hat{R}(z_l,\ z_{l+1})$ describes *refraction* on inhomogeneities of the refractive index, and the operator $\hat{D}(\Delta z)$ corresponds to the solution of the problem of free *diffraction*. The second order of accuracy of this approximation has been proved analytically [2, 23] and confirmed by numerical experiments [24].

For optical waves, the *problem of free diffraction* at an arbitrary distance z can be solved using the representation for the complex amplitude in the form of a finite Fourier series [25]:

$$E(x,y,z)=\sum_{m=-N/2+1}^{N/2}\sum_{n=-N/2+1}^{N/2}E_{mn}(z)\exp\left[\frac{2\pi i}{L}(xm+yn)\right], \qquad (1.1.8)$$

where

$$E_{mn}(z)=\frac{1}{4\pi^2L^2}\int_0^L\int_0^L dxdyE(x,y,z)\exp\left[-i\frac{2\pi}{L}(xm+yn)\right] \qquad (1.1.9)$$

are the expansion coefficients, L is the size of the domain of expansion, and N is the number of terms in the series. It is also assumed that the spectrum of spatial frequencies for the function $E(x, y, z)$ is finite and the function itself is periodic or can be supplemented by a periodic function. In a numerical simulation, a continuous field $E(x, y, z)$ is replaced by a discrete field defined at the nodes of a computational grid. The transition from the domain of the original function to the spectral space and back is performed by DFT.

Substituting the spectral representation into the parabolic equation (1.1.4), we obtain

$$2ik\frac{\partial E_{mn}}{\partial z}=-\frac{4\pi^2}{L^2}(m^2+n^2)E_{mn} \qquad (1.1.10)$$

with the following exact solution

$$E_{mn}(z)=E_{mn}(z=0)\exp\left[-\frac{4\pi^2 z}{2ikL^2}(m^2+n^2)\right]. \qquad (1.1.11)$$

To solve *the problem of refraction* in the layer Δz, we need to obtain the numerical representation for inhomogeneities $\delta n(\vec{\rho}, z)$ of the refractive index. Refraction is described as beam passage through a phase screen:

$$\hat{R}(z_l,z_{l+1})=\exp[i\varphi_l(\vec{\rho})], \qquad \varphi_l(\vec{\rho})=-ik\int_{z_l}^{z_{l+1}}\delta n(\vec{\rho},z)\,dz. \qquad (1.1.12)$$

The mathematical model of refractive index inhomogeneities depends on the process by which they arise. Here we consider two effects: a lowest-threshold nonlinear effect known as random thermal blooming and fluctuations induced by atmospheric turbulence.