Atmospheric Adaptive Optics

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SPIE OPTICAL ENGINEERING PRESS

A Publication of SPIE—The International Society for Optical Engineering
Bellingham, Washington USA

Library of Congress Cataloging-in-Publication Data

Lukin, V. P. (Vladimir Petrovich)
[Atmosfernaia adaptivnaia optika. English]
Atmospheric adaptive optics / Vladimir P. Lukin ; translated by Paul F. Schippnick
p. cm.
Includes index.
ISBN 0-8194-1871-4 (hardcover)
1. Meteorological optics. 2. Optics, Adaptive. 3. Atmospheric turbulence. 4. Atmospheric diffusion. I. Title.
QC975.2.L8513 1995
551.5′65--dc20 95-12082
CIP

(An update of the Russian *Atmosfernaia adaptivnaia optika,* published by Nauka, Novosibirsk, 1986)

Published by
SPIE—The International Society for Optical Engineering
PO Box 10
Bellingham, Washington 98227-0010
Phone: 360/676-3290 Fax: 360/647-1445 Email: spie@spie.org

Printed in the United States of America.

Second Printing

In memory of my parents

Peter N. Lukin
and
Tatjana T. Lukina

CONTENTS

PREFACE

The progress of science and technology in the area of quantum electronics has, by leading to the creation of lasers and the practically universal use of optical radiation, quickened the pace of development of related fields. First of all, the peculiarities of coherent radiation—its high degree of monochromaticity and spatial resolution, the possibility of obtaining high power levels and the liberation of large amounts of energy in short times under real atmospheric conditions—have necessitated a new approach to the quantitative analysis of the efficiency of optical systems. Recent studies on the propagation of optical, including laser, radiation have shown that the efficiency of atmospheric optical systems is almost always determined by the properties of the atmosphere as a propagation channel. Even such traditional optical devices as ground-based telescopes require a serious reevaluation. Molecular and aerosol attenuation and scattering as well as atmospheric refraction and turbulence result in a marked degradation of the energetic characteristics of optical systems.

In this analysis of atmospheric action on optical radiation leading to fluctuations of the radiation parameters, we will give primary attention to atmospheric turbulence, refraction of optical beams over extended paths, and the effects of thermal blooming of high-power laser beams.

The choice of thermal blooming, atmospheric turbulence, and refraction as our main topics of consideration is anything but random, since these are the main distorting factors in the atmosphere and we have no choice but to assign their effects to the category of fundamentally unavoidable effects. Other atmospheric effects can be minimized by appropriate choice of the optical system parameters: aperture diameter, radiation wavelength, receiver and transmitter positions, etc. Along with this, it is generally acknowledged that the different measures undertaken to minimize the effects of thermal blooming, atmospheric turbulence, and refraction have not met with substantial success.

One of the most radical means available in the struggle against these unwelcome effects is the use of different types of adaptive methods (algorithms, systems) that almost completely eliminate or at least substantially reduce the influence of atmospheric inhomogeneities. These methods dynamically control the initial radiation field by introducing predistortions based on information about the instantaneous distribution of the characteristics of the propagation medium.

It is customary to use the term *adaptation* to describe the process of varying the parameters and structure of the optical system in response to information about variations of the parameters of the initial signals, the external medium, and the device itself, with the goal of optimizing the system characteristics. Toward this end, provision is made in adaptive optical devices for monitoring the parameters of the external medium and the device itself.[5,91]

First we will consider those optoelectronic systems in which monitoring (tracking) of the changes in the external conditions takes place continuously and where control of the parameters of the device itself is also realized continuously, in real time. The parameters subject to monitoring include those of the radiation source, random variations in the sounding signal due to inhomogeneities of the medium in the propagation channel, and interference due to reflection from the object. In distortion correction systems operating under closed-loop conditions, one usually monitors the main parameters of the optical radiation—its amplitude–phase distribution or functionals of this distribution—in the image plane as well as in the object plane.

In order to adapt laser systems to atmospheric perturbations it is necessary to select the main atmospheric effects that lead to substantial changes in the structure of optical beams formed through the atmosphere: primarily, turbulent pulsations of the air refractive index and thermal blooming of high-power optical radiation due to changes in the temperature of the medium. Among the manifold effects associated with the distortion of the phase structure of the sounding signal are jitter, twinkling, spreading of optical beams, and blurring of images.

To countervail these effects, adaptive optical systems, as a rule,[5,21,225] nerally include:

- a transmitting optical system (the transmitter), consisting of a radiation source with a system for coding the transmitted information;
- a receiver system consisting of an optoelectronic device and tracking system for processing the signal being fed to the controllable (active) optical element (i.e, the wavefront sensor) and an electronic system for processing the correction signal;
- controllable optical elements (e.g., mirrors with variable profile of the reflecting surface or electrical phase rotators).

All the elements of an adaptive system are entirely conventional except for the controllable (active) optical element. A fairly complete set of reviews on active optical elements can be found in References 5, 21, 225, and 284.

In the simplest active optical systems (zeroth order) the wavefront is shifted along the axis without any variations; movable mirrors in laser resonators are a typical example. First-order systems are used to regularly adjust wavefront slope. In second-order active optical systems the radius of curvature of the wavefront is varied, thereby controlling the effective focal length. All these active systems make use of solid optical surfaces: conventional mirrors and lenses.

Active optics has undergone further recent development in the construction of deformable mirrors. These systems, which have a large number of degrees of freedom (and whose surfaces are consequently described by high-order polynomials), vary the wavefront on the basis of an expansion of the phase in a system of orthogonal polynomials (modal expansion) or on the basis of a local discrete representation. In the first case we are looking at flexible continuous mirrors,[307,214,274,309,215,225] and in the second, at a segmented coherent optical aperture.[302] Coherent systems for varying the wavefront beyond second order have appeared only recently; they are now being intensively developed for controlling the surface profile of the mirrors of large telescopes, correction of the effects of atmospheric turbulence in real time, and compensation for thermal distortions.

Adaptive systems can be classified in different ways:

1. *They may by distinguished by the intended purpose of the optical system: a wave-emitting system, or a wave-receiving system.*

Wave-emitting systems include communication systems, lidars, systems for forming laser beams with prescribed wavefront profile, and target-designating systems. Wave-receiving systems include image-forming systems and systems for determining the parameters (coordinates, speed, etc.) of motion for a self-luminous (or indirectly illuminated) object, i.e., a source.

Wave-emitting systems are distinguished by the property that in the operation of the entire system not only is the signal reception point accessible (the reflected wave), but also the radiation transmission point. Such a system, by forming the initial radiation distribution on the basis of measurements in the scattered wave, introduces predistortions that optimize the radiation characteristics both at the scattering object and in the sounding signal.[165]

Wave-receiving systems can be manipulated only via radiation transmitted through the random inhomogeneous medium. In this case, to provide adaptive correction it is necessary, generally speaking, to have *a priori* information about the object (e.g., does the optical system resolve the object or not?). In addition to this, if image formation is based on optimization of some image quality criterion, it is necessary to have a logical element in the system that compares the corrected image with the ideal.

2. *They may also be distinguished by the form of the information provided to the feedback loop.*

Here we may distinguish

(a) systems responding to distortions of wavefronts from real reference sources;
(b) systems employing wave reflection (in a number of cases they can be thought of as systems working with "virtual" reference sources);
(c) systems that do not employ measurements of a reference wave.

If the random inhomogeneous medium is such that reciprocity holds between the fluctuations during the forward and return passage of an elementary optical wave, it is possible to construct a correction system in which measurements of the wavefront from a reference source (real or "virtual") are used as the predistortions of the initial distribution.

3. *They can also be distinguished by the form of the algorithm used to introduce the correction.*

Here it is worthwhile to distinguish the most important of the methods presently available for wideband compensation of wavefront distortions. These include

(a) adaptive correction systems with phase conjugation (at the receiver and at the transmitter);
(b) multidither systems using a coherent optical adaptive technique (COAT);
(c) systems implementing a wavefront reversal (WFR) algorithm;
(d) systems based on image sharpening algorithms.

Let us consider these four characteristic adaptive systems for the correction of random wavefront distortions. Here the source of the distortions can be aberrations in the optical system, turbulence and the presence of discrete inhomogeneities along the propagation path, and thermal blooming.

These four main types of adaptive systems (see Fig. P.1) may be given the following brief designations: (a) phase conjugation, (b) multidither, (c) wavefront compensation, and (d) image sharpening.

Systems of types (a) and (b) are radiative systems that serve to maximize the radiative flux density at the target or of the location signal itself.

In a phase conjugation system (a) the light beam, upon reaching the target, is reflected from small segments of it, in the process forming highly localized patches of light, each of which emits a spherical wave. These reflected waves propagate in the

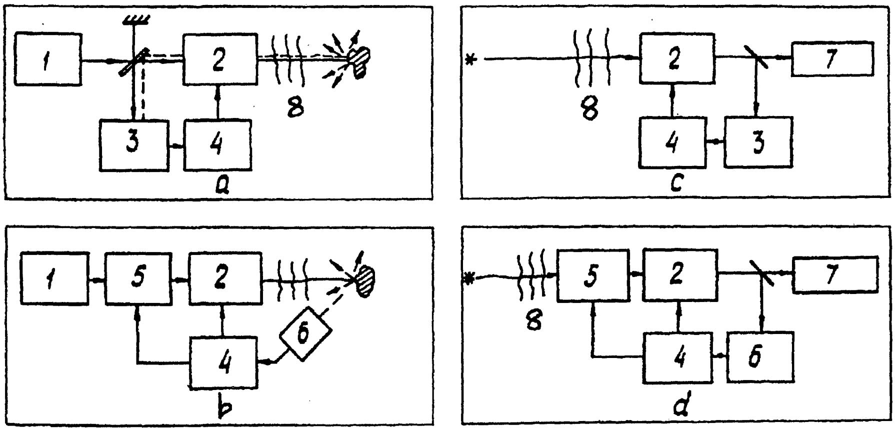

Fig. P1 The most characteristic systems of adaptive optics: (a) phase conjugation, (b) multidithering, (c) wavefront compensation, (d) image sharpening. (1) light source, (2) controllable (active) optical element, (3) wavefront sensor, (4) data processing device, (5) multidither system, (6) optical receiver, (7) imaging receiver, (8) perturbations of the optical path difference due to the atmosphere.

back direction, and consequently, given linear propagation, the inhomogeneities in their paths act identically on their spatial characteristics as on the original beam. In the wavefront sensor the received wave is compared with an etalon or reference wave created in the device, and the data processor calculates the necessary correction, which is phase conjugate to the measured distortion of the wavefront. Upon command the active device then makes the necessary correction in the emitted wavefront, thus the predistortion applied to the radiated wave exactly compensates the distortions incurred along the propagation path. The emitted wavefront arrives at the target with the desired spherical shape, maximizing the light flux density in the speck of light and, consequently, the return signal.

In a multidither system (b), probing perturbations are generated in the emitted wavefront, the power level of the light returned by the target speck is analyzed, and on the basis of this it is determined which perturbations increase the light flux. The iterative process is continued until the flux density is optimized. There are two main methods for creating probing perturbations: multifrequency vibrations and sequential, or multistep, vibrations. In the first method the perturbations consist of an ensemble of sinusoidal oscillations with different frequencies, and in the sequential method the perturbations are produced by successive steps in a definite order.

Both of these algorithms require information about the state of the medium between the source and the target, which the reflected waves carry within themselves. These algorithms are referred to in the literature as *wave reversal algorithms*.

The principle of image sharpening (d) is analogous to that of the multidithering technique. Again, probing perturbations are produced in the received wavefront, and with the help of the receiver located in the image plane their effect is estimated, using the maximum sharpness criterion. For this purpose some quantity associated with image sharpness is used, e.g., the integral of the squared field intensity over the entire area of the image. Image sharpening is an indirect method, since it relies on some other method for distinguishing the individual perturbations in the aperture.

Systems (c) and (d) are receiver systems, intended for obtaining the best possible image (or maximum energy) of a distant light source or irradiated object when its radiation passes through an inhomogeneous medium. The optical receiver part of a lidar that operates through the entire atmospheric column serves as an obvious example. Illuminated objects, as a rule, emit incoherent light over a wide spectral band.

For laser systems the wavefront compensation method (c) is similar to the phase conjugation method. The observed object can be treated as a set of unresolved point sources, each radiating a spherical wave that is distorted as it passes through the atmosphere. Such a beam, with a distorted wavefront, after being collected by the aperture of the lidar and passing through the active device (which, to start with, is in its zero position), is split into two subbeams. One of these two subbeams is sent to the wavefront sensor, which determines the local deviation and local slope relative to the ideal wave. In this way a complete picture is constructed of the errors of the received wavefront; next, the required correction is calculated in the data processor and control signals corresponding to each segment of the aperture are sent to the active device. The wavefront error at the sensor now drops to zero, thanks to which the image formed in the receiver is essentially diffraction-limited. A device realizing the described approach was first proposed by V. Linnik.[143]

The level of performance of all these systems depends on such factors as the measurement error of the wavefront, the speed of the feedback circuit in comparison with the time constant of the perturbations, and the spatial resolution of the wavefront corrector.

Phase conjugation systems measure and correct the wavefront on the basis of the principle of optical reversibility,[5,200] according to which the phase distortion of a light beam propagating along a given trajectory in one direction is equal to the complex conjugate of the distortion of the beam traveling along that same trajectory in the opposite direction.

In the present monograph primary attention will be given to systems and algorithms of adaptive phase correction based on reciprocity of the fluctuations. Information on the distribution of inhomogeneities in the medium along the propagation path is extracted from measurements of the fluctuations of the field of the reference sources.

The monograph consists of seven chapters and two appendices and contains a large number of tables and figures.

Chapter 1 is devoted to a grounding of the phase conjugation algorithm based on successive application of the reciprocity principle. Primary attention is given to a comparison of the potential applications of the wavefront reversal and phase conjugation algorithms.

Chapter 2 contains an analysis, developed by the author, of the efficiency of adaptive phase conjugation optical systems under turbulent atmospheric conditions. Questions of correction using a reference source are considered, and the requirements on the frequency band of the phase meter are elucidated. The possibilities of predictive and dual-wavelength adaptive systems are considered here for the first time.

Chapter 3 contains a basic treatment of the peculiarities of phase fluctuations and the modal components of the phase arising during the propagation of the optical wave in the turbulent atmosphere. Statistical and other characteristics of the phase for specular reflection of optical waves are considered.

The theoretical prerequisites for an analysis of adaptive optical systems developed in the first three chapters are applied in Chapters 4 and 5 to a study of the possibilities of using adaptive systems to enhance images formed through the atmosphere and also to aim and focus optical beams. The potential applications of phase-conjugation adaptive systems are considered in conjunction with the simplest correction algorithms. Results are presented of field experiments on the correction of angular shifts of optical beams, modal correction of turbulent distortions, programmed correction of atmospheric refraction, and a number of other applications. The possibilities of adaptive correction based on successive application of the reciprocity principle are considered.

Chapters 6 and 7 contain a comprehensive analysis of the application of adaptive optical systems under conditions of thermal blooming. The main features of the propagation of coherent focused continuous high-power laser beams along atmospheric paths are elucidated in Chapter 6. In particular, we consider the peculiarities of distortions due to thermal blooming along vertical paths, and a study is made of thermal blooming of focused beams in a turbulent medium. The various possibilities of optimized transport of high-power laser beams based on the choice of the initial distribution of the wavefront are investigated. Finally, in Chapter 7 the possibilities of the "fast" phase conjugation algorithm are investigated, and the results compared with those of other authors. A study is also made of the possibilities of programmed phase correction of thermal distortions along vertical paths.

Appendices A and B contain some auxiliary calculations. Tables and figures are numbered sequentially from the beginning to the end of the book. A combined list of references is given at the end of the book.

For the most part, the material of the book is based on work by the author at the Institute of Atmospheric Optics, Siberian Branch of the Russian Academy of Sciences.

The book is oriented toward—and, I hope, will turn out to be useful to—not only scientists but also optical engineers involved in the design of adaptive optical systems.

The author expresses his deep appreciation to Academician V.E. Zuev for formulation of the program of study, and for discussion and support, and to Dr. Phys.-Math. Sci. S.D. Tvorogov for discussions and useful advice made in the course of reading the manuscript.

I would also like to express my deep gratitude to all of the members of the Applied and Adaptive Optics Laboratory of the Institute of Atmospheric Optics, in particular, O.N. Emaleev and Dr. P.A. Konyaev.

I am also indebted to Drs. P.A.Bakut, É.A. Vitrichenko, A.S. Gurvich, V.P.Kandidov, and M.I. Charnotskii for their collaboration, advice, and critical remarks, which helped determine the direction of this work.

The monograph was first published in Russian in 1986 by the publishing house "Nauka" in Novosibirsk.

I would like to express my deep appreciation to the staff of SPIE who have made it possible to publish this monograph in English.

I also specially thank the translator, Dr. Paul F. Schippnick, for his cooperation in the process of preparing the manuscript for publication.

INTRODUCTION

As was stated in the Preface, the practical implementation of laser optical systems research has greatly stimulated the development of related fields of science and technology. The use of coherent optical radiation, where not only the intensity but also the phase carries information, has had a revolutionary effect on the development of a previously so traditional field as optics. The possibility has arisen of controlling the phase of optical radiation by optical means. Traditional "fixed" optics has now been superseded by "active," "live," or "adaptive" optics.[5,135,186,188,232,189,252,166,167,221,193,209,137,21,226,143,155] The possibilities imbedded in it of predetector control of optical radiation have laid the foundation for the development of a new field of science and technology—the propagation of optical radiation under conditions of adaptive control.

At present this field is still in its initial stage of development—even the terminology is still formative. For this reason the present monograph does not presume to give a detailed historical survey of the development of the problem. In this context it should be noted that the first efforts in this field were made by H. W. Babcock (1953) and V. P. Linnik (1957). However, they considered only the fundamental possibilities of eliminating the effect of atmospheric turbulence on the quality of images of astronomical objects. In the 1960s investigations into the possibilities of adaptive optical systems began to proliferate. There can be no question that this growth was stimulated by the appearance of Refs. 5, 17, 21, 135, 188, 189, 232, 252, 226, 143, 155, 186, 162, and 218. Earlier, in the Foreword, we considered a classification of adaptive systems into two broad classes: phase-conjugation systems and multidither systems. In Refs. 21, 218, 226, and 252 it is shown that under certain conditions these systems give identical results. Some of the earliest papers[5,17,209] were devoted to the application of adaptive systems to problems connected with the formation of high-power laser beams.

In the field of adaptive optics itself it is possible to distinguish two areas of interest: (1) the creation of a theoretical basis for adaptive technology,[221,186,226,280] including wavefront reversal methods as a means of focusing optical radiation, and (2) studies of adaptive systems themselves.

The aim of the present book is to investigate the various aspects of the use of adaptive optical systems under real atmospheric conditions, i.e., what is called the problem of propagation of optical radiation under conditions of adaptive control. Two fundamentally unavoidable atmospheric factors are considered: atmospheric turbulence, and thermal blooming of continuous radiation due to molecular absorption.

Adaptive phase-conjugation systems, based on the reciprocity principle, are also considered. Feedback to the adaptive system must pass through the atmosphere when using radiation from reference sources.

The results obtained in this work are presented as formulas estimating the correction quality, or as numerically calculated distributions of the corrected field.

Efforts connected with the creation of the technical basis of adaptive optics are not considered in this book, although they are reflected in the references.