SPIE Milestone Series
Volume MS 92

Selected Papers on

Adaptive Optics for Atmospheric Compensation

James E. Pearson
Editor

Brian J. Thompson
General Editor, SPIE Milestone Series

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Cover illustration (softbound edition only): From the paper "Phase compensation for thermal blooming," L.C. Bradley, J. Herrmann, *Applied Optics* Vol. 13(2), pp. 331-334 (February 1974), reproduced on pp. 259-262 herein.

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Introduction to the Series

There is no substitute for reading the original papers on any subject even if that subject is mature enough to be critically written up in a textbook or a monograph. Reading a well-written book only serves as a further stimulus to drive the reader to seek the original publications. The problems are, which papers, and in what order?

As a serious student of a field, do you really have to search through all the material for yourself, and read the good with the not-so-good, the important with the not-so-important, and the milestone papers with the merely pedestrian offerings? The answer to all these questions is usually yes, unless the authors of the textbooks or monographs that you study have been very selective in their choices of references and bibliographic listings. Even in that all-too-rare circumstance, the reader is then faced with finding the original publications, many of which may be in obscure or not widely held journals.

From time to time and in many disparate fields, volumes appear that are collections of reprints that represent the milestone papers in the particular field. Some of theses volumes have been produced for specific topics in optical science, but as yet no systematic set of volumes has been produced that covers connected areas of optical science and engineering.

The editors of each individual volume in the series have been chosen for their deep knowledge of the world literature in their fields; hence, the selection of reprints chosen for each book has been made with authority and care.

On behalf of SPIE, I thank the individual editors for their diligence, and we all hope that you, the reader, will find these volumes invaluable additions to your own working library.

Brian J. Thompson
University of Rochester

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Introduction

Historical Perspective

Almost simultaneously with the construction of large, high quality astronomical telescopes came the realization that atmospheric turbulence effects limited the seeing resolution to no more than that provided by a diffraction-limited roughly 10 cm diameter telescope. This fact is true at all times, even from high altitude mountain sites. The only solutions to this limitation are to get above the atmosphere, using airborne or space-borne platforms, or to find a way to sense and correct for the atmospheric phase distortions seen from ground-based platforms. H.W. Babcock appears to have been the first to publish ideas for real-time sensing and correction (p. 0; see also p. 2 for a historical reprise). His ideas lay dormant until the early 1970s, when then-classified development work on propagation of very high power lasers through the atmosphere created a renewed interest in what has become known as "adaptive optics."

The advent of lasers also renewed interest in understanding and characterizing optical propagation in the turbulent atmosphere. Prior to 1960, the bulk of the theoretical understanding of the statistical properties of atmospheric turbulence was contained in a book by Tatarski.[1] Fried's pioneering papers (pp. 107 and 116) used Tatarski's statistical results to introduce the concept of a "coherence diameter," r_0, now know as the "Fried coherence length." The ratio r_0/D, where D is the telescope receiver or laser transmitter diameter, characterizes the degree to which the atmosphere degrades the optical system. It is also a fundamental design parameter for adaptive optical systems.

The advent of high power lasers brought a new type of distortion into the propagation problem: thermal blooming. This intensity-dependent distortion, studied extensively by Smith (p. 223) and others, has proved to be a fundamental limitation to high power beam propagation. Adaptive optics can remove some, but not all, of this type of phase distortion; the degree of correction depends on the characteristics of the propagation path and laser transmitter parameters.

The first published experimental work on adaptive optics dealt with techniques known as "coherent optical adaptive techniques," or COAT systems, that utilized the coherence properties of lasers. Cathey et al.[2] at Rockwell Autonetics reported the first experimental demonstration of a real-time COAT system. Their system was a linear phased array, each element of which contained an optical heterodyne detector to sense and an acousto-optic phase shifter to correct the piston phase difference between the transmitted element beam and the return from a target glint point. Although this system demonstrated correction feasibility, its cumbersome design and impractical use with high power lasers prevented further development.

Within two years of the Rockwell publication, several key enabling technologies were demonstrated: white light wavefront sensors (Wyant, p. 0), continuous surface deformable mirrors (Feinleib et al., p. 419), and multidither control techniques (Bridges et al., p. 0). Although the subsequent years saw substantial improvements and refinements on these technologies, the only fundamental breakthrough until 1985 was the realization that nonlinear optical techniques could be used to remove phase distortions (see Section Five). In 1985, Foy and Labeyrie (p. 355) published the first discussion of the use of laser guidestars to provide a reference for a compensated imaging system. This concept removes a major obstacle to the practical use of adaptive optics in astronomical imaging systems. Experimental confirmation of the guidestar concept was published in 1991 when the Department of Defense declassified work done a few years earlier (Fugate et al., p. 373; Primmerman et al., p. 589).

As the cost of adaptive optical hardware comes down, and thus becomes widely available to the astronomical community, it will revolutionize ground-based astronomy. The resolution achievable will now be limited by the ability to build larger telescopes rather than by atmospheric phase distortions. Ground-based 2 m to 3 m telescopes already in use will surpass NASA's Hubble Space Telescope within the atmospheric transmission window in both their light-gathering and resolution capability. Control and sensing techniques similar to adaptive optic techniques are already being used in the 10 m Keck telescope[3] and will be used to phase large-diameter telescope arrays such as the Very Large Telescope being constructed in Chile by the European Southern Observatory.[4,5]

Organization of the Material

The section topics of this volume represent the primary subjects of adaptive optics: technology overview, atmospheric effects, wavefront sensing and control algorithms and hardware, and system realizations. The collection is intended to represent the basic references useful both to the active researcher or engineer in the field, and to the person new to adaptive optics technology.

The two overview papers contained in Section One provide a good perspective on the state of the art in adaptive optics up to 1980. A recent book by Tyson[6] contains brief descriptions of more recent developments, primarily in hardware design and performance, and an extensive reference list. Other reviews, summaries, and collections of papers are listed in the annotated references at the end of this introduction. Other than guidestar concepts, the primary technical advances during the 1980s were mainly engineering in nature: larger, higher actuator density deformable mirrors, more sophisticated wavefront reconstructors, etc., and system demonstrators. The SPIE Proceedings in the reference list discuss many of these component advances.

Section Two contains the seminal papers on atmospheric turbulence and thermal blooming phase aberrations. The spatial and temporal characteristics of these propagation distortions determine the operating parameters of an adaptive optical system designed to produce a certain level of compensation for a given optical aperture. The other parameter determining the level of correction is the signal-to-noise in the wavefront sensor. The papers by Hudgin (p. 388) and Wallner (p. 413) discuss optimal control models for given noise statistics.

An adaptive optical system consists of three main components or subsystems: a wavefront sensor, a wavefront reconstructor (data processor and control system), and a wavefront corrector (active, movable mirror). In Section Three, the subsection on wavefront sensors contains articles on the two types of sensors that have found primary application: the shearing interferometer and the Hartmann sensor. The third type of "sensor," multidither control (as discussed by O'Meara, pp. 334 and 344), is really a control algorithm since the physical sensor is just a detector, sometimes with a small aperture in front of it. The final two papers in this first subsection are the first open publications of the use of atmospherically backscattered laser light to provide a reference for a wavefront sensor. This concept, which is an enabling technology for high resolution ground-based astronomy, has recently been demonstrated in several systems (pp. 541, 564, 589, 592, and 595).

The next subsection in Section Three contains papers describing how the optical phase correction is determined from received wavefront slope measurements in the presence of sensor noise.

The papers in the final subsection of Section Three deal with the subject of continuous-surface deformable mirrors. Piezoelectrically actuated continuous-surface mirrors have been the most practical implementation to date, although segmented mirrors[7] and electrostatically actuated membrane mirrors (Ref. 8 and Yellin, p. 443) have been demonstrated.

The papers in Section Four describe experimental realizations of complete adaptive phase compensation systems. Some papers present laboratory results; others are field demonstrations with real (rather than simulated) atmospheric effects. Several of the papers in the middle subsection are from recently declassified work using laser-generated "guidestars." The last two papers in the subsection on Energy-Projection Systems describe applications of adaptive optics to laser resonators. These papers are included as an example of adaptive phase control for other than atmospheric propagation.

A complete treatment of the subject of adaptive compensation of atmospheric phase distortions must include nonlinear phase conjugation technologies. Techniques such as four-wave mixing, stimulated Brillouin scattering, and stimulated Raman scattering can produce an output beam that is the phase conjugate of an input beam. Such a conjugate output is exactly what an ideal adaptive optics system should produce. A size limitation prevented a complete treatment of this subject in this Milestone volume. In addition, the demonstrations to date have been mainly at a feasibility level, although phase conjugation cells have found application in certain military laser rangefinders and designators. Section Five contains several of the early papers on the subject. The papers by

O'Meara (pp. 701 and 707) contain several system concept descriptions not widely known. D.M. Pepper has written a nice overview article in *Scientific American.*[9]

The editor would like to thank Brian J. Thompson, series editor, Dixie Cheek, managing editor, and the rest of the SPIE publications staff for their patience as this volume was being assembled. The editor is also grateful to the following people for their suggestions on the selection of papers to be included: Dave Fried, Bob Fugate, John Hardy, Chuck Primmerman, François Roddier, Larry Schmutz, and Bob Tyson.

James E. Pearson
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General Reviews—Books

S.F. Jacobs, M. Sargent III, and M.O. Scully, editors, *Adaptive Optics and Short Wavelength Sources,* Vol. 6 in Physics of Quantum Electronics, Addison-Wesley (1978).

The first four papers are introductory overviews of adaptive optics technology as it had developed by mid-1977. The paper by C.B. Hogge presents information not available in other publications. Each paper has a list of other useful references.

J.E. Pearson, R.H. Freeman, and H.C. Reynolds, Jr., "Adaptive optical techniques for wavefront correction," Chap. 8 in *Applied Optics and Optical Engineering Vol. VII,* R.R. Shannon and J.C. Wyant, editors, Academic Press (1979).

This book chapter covers most of the topics found in this Milestone volume from the point of view of an applications/systems engineer. An extensive set of references is part of the chapter.

Robert K. Tyson, *Principles of Adaptive Optics,* Academic Press (1991).

This is the first book devoted to the subject of adaptive optics. The author treats all the primary subjects, covering some theoretical and design aspects in detail. A list of 408 references is included.

Imaging Through the Atmosphere, J.C. Wyant, editor, Proc. SPIE Vol. 75 (1976).

This collection of 22 papers contains theoretical and experimental papers on atmospheric effects, atmospheric measurements, speckle interferometry, pre-detection compensation (an early term for adaptive optics), and post-detection compensation.

Journal of the Optical Society of America, Special Issue on Adaptive Optics, Vol. 67 (March 1977).

This JOSA issue contains papers from most of the prominent researchers in the field at that time. Several of the papers from this issue are reprinted in this Milestone Series volume.

Adaptive Optical Components, S. Holly and L. James, editors, Proc. SPIE Vol. 141 (1978).

This volume contains 16 papers on early results of component development primarily for high power laser applications.

Adaptive Optical Components II, S. Holly, editor, Proc. SPIE Vol. 179 (1979).

This volume is the proceedings of an SPIE conference held in Washington, D.C., in April 1979. It includes sections on components, systems, and applications. There are several papers on experimental laboratory demonstrations at United Technologies Research Center that present results not reported elsewhere.

Wavefront Distortions in Power Optics, C.A. Klein, editor, Proc. SPIE Vol. 293 (1981).

This conference proceedings contains theoretical and experimental work characterizing the distortions in high power lasers and their beam trains that adaptive optics must correct. Eight papers in Section 4 deal with conventional and phase conjugation correction of such distortions.

Wavefront Sensing, N. Bareket and C. Koliopoulos, editors, Proc. SPIE Vol. 351 (1982).

This collection contains papers devoted to one of the key adaptive optics subsystems.

Adaptive Optics Systems and Technology, R.J. Becherer and B.A Horwitz, editors, Proc. SPIE Vol. 365 (1982).

A variety of component and system topics are addressed, as well as imaging and laser applications.

Adaptive Optics, J.E. Ludman, editor, Proc. SPIE Vol. 551 (1985).

This volume contains 24 papers, with sections on wavefront sensing, propagation models and effects, signal processing, wavefront modulation, and innovative/unconventional adaptive optics.

Active Telescope Systems, F.J. Roddier, editor, Proc. SPIE Vol. 1114 (1989).

This volume has 57 papers that cover current (at the time) developments in adaptive optics and active control of ground-based and space-based telescopes. Related topics of systems interest include phased arrays, long-baseline optical interferometers, and use of laser guidestars.

Propagation of High-Energy Laser Beams Through the Earth's Atmosphere, P.B. Ulrich and L.E. Wilson, editors, Proc. SPIE Vol. 1221 (1990).

Issues are discussed that arise when delivering large amounts of optical energy to a target through the earth's atmosphere. Adaptive optical solutions to the issues constitute one of the conference's themes.

Adaptive Optics and Optical Structures, R.K. Tyson and J. Schulte in den Bäumen, editors, Proc. SPIE Vol. 1271 (1990).

This volume is the proceedings of the European Congress on Optics held at The Hague, The Netherlands, in March 1990. The 36 papers are from seven sessions on the following topics: adaptive optics systems and controls (8 papers), nonlinear optics applications to adaptive optics (4 papers), adaptive optics components (5 papers), progress in adaptive optics for astronomy (3 papers), progress in adaptive optics for beam propagation (1 paper), large telescopes (8 papers), and optical alignment (6 papers). The first observing results of an adaptive optical system on a 1.52 m telescope in France are reported in a paper by Merkle et al.

Optical Engineering, Special Issue on Adaptive Optical Components, M.A. Ealey, guest editor, Vol. 29(10), (October 1990).

Contains 12 papers on a variety of subjects from deformable mirrors to intracavity correction.

Optical Engineering, Special Issue on Active Optical Components, M.A. Ealey, guest editor, Vol. 29(11), (November 1990).

This companion to the October 1990 issue contains 12 papers dealing primarily with deformable mirrors, active primary telescope mirrors, and tip/tilt fast steering mirrors.

Active and Adaptive Optical Systems, M.A. Ealey, editor, Proc. SPIE Vol. 1542 (1991).

This volume contains 48 papers from a conference in San Diego in July 1991. The papers cover the range of topics in adaptive optics: fundamental limitations, active telescopes, components, and systems application results. A progress review by John Hardy contains 47 references and is a useful "snapshot" of the state of the art at the time of the paper's writing.

Active and Adaptive Optical Components, M.S. Ealey, editor, Proc. SPIE Vol. 1543 (1991).

This companion volume to the preceding one contains 45 papers that treat deformable and fast-steering mirrors and wavefront sensors. A brief overview by Ealey has a useful list of 84 references and outlines some of the major U.S. government sponsored hardware development programs that developed much of the reported technology in the United States.

Lincoln Laboratory Journal, Special Issue on Adaptive Optics, Vol. 5 (Spring 1992).

An overview paper briefly outlines the work of the previous 20 years at Lincoln Laboratory. There are five papers on imaging system experiments, with particular emphasis on guidestar technology. The topic of thermal blooming is treated in two papers, one theoretical describing computer simulation results and one describing laboratory experimental results.

Active and Adaptive Optical Components and Systems II, M.A. Ealey, editor, Proc. SPIE Vol. 1920 (1993).

This volume contains papers on guidestar systems, active mirrors (tip/tilt and deformable), and ground-based imaging system performance using adaptive optics.

Collections of Papers—Nonlinear Optics Technologies

Optical Engineering, Special Issue on Nonlinear Phase Conjugation, D.M. Pepper, guest editor, Vol. 21(2), (March/April 1982).

This volume includes a thorough review by Pepper of the state of the art at the time and an extensive reference list.

Phase Conjugation and Beam Combining and Diagnostics, R.A. Fisher and I. Abramowitz, editors, Proc. SPIE Vol. 739 (1987).

The subject of this collection is mainly nonlinear phase conjugation approaches to removing phase distortions. Papers address a variety of approaches, including stimulated Brillouin scattering, degenerate four-wave mixing, and Raman scattering.

Laser Wavefront Control, Critical Reviews of Optical Science and Technology, J.F. Reintjes, editor, Proc. SPIE Vol. 1000 (1988).

Ten papers review and project the state of the art in nonlinear techniques for wavefront phase correction and control.

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