ADAPTIVE OPTICS IN ASTRONOMY

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CAMBRIDGE
UNIVERSITY PRESS

PUBLISHED BY THE PRESS SYNDICATE OF THE UNIVERSITY OF CAMBRIDGE
The Pitt Building, Trumpington Street, Cambridge CB2 1RP, United Kingdom

CAMBRIDGE UNIVERSITY PRESS
The Edinburgh Building, Cambridge CB2 2RU, UK http://www.cup.cam.ac.uk
40 West 20th Street, New York, NY 10011-4211, USA http://www.cup.org
10 Stamford Road, Oakleigh, Melbourne 3166, Australia

First published 1999

Printed in the United Kingdom at the University Press, Cambridge

Typeset in Times 11/14, in 3B2 [KT]

A catalogue record for this book is available from the British Library

ISBN 0 521 55375 X hardback

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Historical context

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Turbulence in the Earth's atmosphere produces inhomogeneities in the air refractive index, which affect the image quality of ground-based telescopes. Adaptive optics (AO) is a means for real time compensation of the image degradation. The technique was first proposed by Babcock (1953) and later independently by Linnick (1957) to improve astronomical images. It consists of using an active optical element such as a deformable mirror to correct the instantaneous wave-front distortions. These are measured by a device called a wave-front sensor which delivers the signals necessary to drive the correcting element. Although both Babcock and Linnick described methods that could be employed to achieve this goal, development cost was too prohibitive at that time to allow the construction of an AO system for astronomy.

The invention of the laser soon triggered both experimental and theoretical work on optical propagation through the turbulent atmosphere. Studies on laser speckle led Labeyrie (1970) to propose speckle interferometry as a means to reconstruct turbulence degraded images. Following Labeyrie, astronomers focused their efforts on developing 'post-detection' image processing techniques to improve the resolution of astronomical images. Meanwhile, defense-oriented research started to use segmented mirrors to compensate the effect of the atmosphere in attempts to concentrate laser beams on remote targets. This was done by trial-and-error (multidither technique). As artificial satellites were sent on orbit, the need came to make images of these objects for surveillance, and attempts were made to use similar techniques for imaging (Buffington *et al.* 1977). The first adaptive optics system able to sharpen two-dimensional images was built at Itek by Hardy and his coworkers (Hardy *et al.* 1977). A larger version was installed in 1982 at the Air-Force Maui Optical Site (AMOS) on Haleakala. By the end of the 1970s AO systems were widely developed by industry for defense applications (Pearson *et al.* 1979). AO systems with more than a thousand degrees-of-freedom have now been built (Cuellar *et al.* 1991).

Owing to this success, astronomers became interested in applying AO to astronomy. Unfortunately, most interesting astronomical sources are much dimmer than artificial satellites. Astronomers are used to expressing the brightness of a star in terms of magnitudes, a logarithmic scale in which an increase of five magnitudes describes a decrease in brightness by a factor 100. On a clear dark night, stars up to magnitude 6 are visible to the naked eye. The AMOS adaptive-optics system goes barely beyond. Astronomers often observe objects as faint as mag 20 or fainter. Therefore, they need more sensitive systems. They soon realized that compensation requirements are less severe for infrared imaging, in which case one can use a fainter 'guide' source to sense the wave front. In the 1980s, great progress was being made in developing InSb and HgCdTe detector arrays for imaging in the near infrared, and infrared astronomy was blooming. Therefore two important astronomical institutions decided to sponsor a development program on AO for infrared astronomy: the European Southern Observatory (ESO) and the US National Optical Astronomy Observatories (NOAO).

The ESO effort, involved astronomers, defense research experts, and industry, and led to the construction of a prototype instrument called 'COME-ON' (Rousset *et al.* 1990; Rigaut *et al.* 1991). An upgraded version of COME-ON called 'COME-ON-PLUS' has since been regularly used for astronomical observations at the ESO 3.6-m telescope in Chile (Rousset *et al.* 1993). A new version called ADONIS is now a user instrument facility. These developments are described in Chapter 8. The technology is basically the same as that developed for defense applications (Shack–Hartmann wave front sensor and thin-plate piezo-stacks deformable mirror), but the number of different aberrations that can be corrected (number of degrees-of-freedom) is smaller than that of defense systems. It allows these systems to sense the wave front with fainter 'guide' sources (up to mag 14 on a 3.6-m telescope), but limits their application to the near infrared.

The NOAO effort was discontinued after 4 years, but work soon started at the Institute for Astronomy of the University of Hawaii (UH) on a novel technique that had been conceived at NOAO. It involved the development of a new type of wave front sensor called a 'curvature sensor', and a new type of deformable mirror called 'bimorph' (Roddier 1988; Roddier *et al.* 1991). The technique was believed to be better adapted to astronomical observations. An experimental instrument was built and successfully tested at the coudé focus of the Canada–France–Hawaii telescope (CFHT) on Mauna Kea. The first astronomical observations were made in December 1993 (Roddier *et al.* 1995). A Cassegrain-focus visitor instrument was then built and first used in December 1994 at the CFHT $f/35$ focus. It has since been widely used for astronomical observations. Compared with the European AO systems, the UH system uses an array of high performance detectors called avalanche photo-diodes (APDs), which allows the sensing of the wave front to be performed on fainter guide sources (up to magnitude 17 on a 3.6-m telescope). A consequence is that a larger number of objects is accessible to wave front compensation. A user AO system based on this technique has now been built for the 3.6-m CFHT. Another one is under construction for the Japanese 8-m Subaru Telescope (Takami *et al.* 1996). Several other institutions are also considering the use of this type of system. These developments are described in Chapter 9.

Because the brightness of the source severely limits the sensing of the wave front, Foy and Labeyrie (1985) proposed the use of laser beacons to create artificial sources with light back-scattered by the atmosphere. We now know that the same idea had been independently proposed earlier by US defense researchers, and was already being developed as classified research (McCall and Passner 1978, Benedict *et al.* 1994). In 1991, after the political changes in Russia, the US National Science Foundation (NSF) convinced government authorities of the importance of the technique to astronomy, and obtained its declassification. The current state of US defense technology was presented in an open meeting held in Albuquerque in March 1992 (Fugate 1992). As a result, many US groups joined the effort and pursued the development of artificial laser guide sources for astronomical applications (see the January and February 1994 issues of *J. Opt. Soc. Am.*). Although the technique has not yet matched astronomers' expectations, encouraging results have been obtained. These are presented in Chapters 11 to 13 together with a description of the difficulties encountered.

At the time of writing, a growing number of observatories are becoming equipped with AO systems to be used with or without laser beacons. The purpose of this book is to describe the current state of the art with its potential and limitations. We hope it will be useful to both engineers in charge of designing and building astronomical instrumentation, and to astronomers whose observations will benefit from it. Chapter 2 describes the statistical properties of the turbulence-induced wave front distortions to be compensated, and their deleterious effects on images. Part II (Chapter 3 to 7) gives performance goals that a theoretically ideal AO system would achieve, describes practical means which have been developed to approach these goals, and shows how to estimate their real performance. Concepts discussed in part II are illustrated in part III by a description of the COME-ON/ADONIS systems (Chapter 8), and of the UH/CFHT systems (Chapter 9). It has not been possible to do justice here to all the work done with natural guide sources at other astronomical institutions such as Durham University or Mt Wilson Observatory. However, we have included a section on solar astronomy (Chapter 10). Part IV (Chapters 11–13) introduces laser beacons and their application to astronomy. Part V (Chapters 14–16) discusses the practical aspects of astronomical observations with AO, shows examples taken from among the wealth of successful results that have now been obtained, and discusses the impact of AO on future observations and instrumentation.

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