

ADAPTIVE OPTICS IN ASTRONOMY

The first significant astronomical images are beginning to be produced by adaptive optics systems, which are being developed at many major observatories around the world.

Laird A. Thompson

Optical observations by ground-based astronomers have long been limited by the distorting effects of the Earth's atmosphere. Primary mirrors have been polished to exquisite accuracy for telescopes with apertures as large as 10 meters, but at optical wavelengths these can deliver an angular resolution typically no better than that of a 25-cm telescope, as atmospheric turbulence deforms the image on a millisecond time scale. One (highly expensive) approach to overcome this problem has been to loft instruments such as the Hubble Space Telescope above the atmosphere. Another approach, pursued by instrument builders in the astronomy community and their counterparts in the military, has been to design electro-optical systems that measure and undo the effects of clear-air turbulence in real time. (See figure 1.) A number of such adaptive optic devices have already been built and operated on large ground-based telescopes, delivering near-diffraction-limited performance at infrared and visible wavelengths. With the first significant astronomical images beginning to appear from these adaptive optics systems (see the cover of this issue), the level of interest in this work is rising very rapidly in the astronomy community.

Adaptive optics systems work in a conceptually simple manner. Light arriving from a distant star is essentially a plane wave until atmospheric turbulence deforms the wavefront's shape or, equivalently, induces local phase delays across the wavefront. These deformations or phase delays in the wavefront can be monitored in real time. For a dim or nonpointlike astronomical object, one monitors light from a guide star located in nearly the same direction as the target object. The guide star can be either a moderately bright natural star or a laser-generated "star" placed high enough in the atmosphere to be above the main sources of atmospheric turbulence. By re-imaging a pupil plane of the telescope (usually its primary mirror) onto a deformable mirror and by constantly adjusting the mirror's shape through computer control, the wavefront phase delays can be corrected over the telescope pupil. Incoming light from an astronomical source reflected off the deformed mirror leaves the mirror's surface in its original pristine state, as if it had never encountered any atmospheric distortion. Typically, there is also a tip-tilt

mirror, which corrects wavefront "tilt," the portion of the deformation whose effect is equivalent to telescope tracking errors.

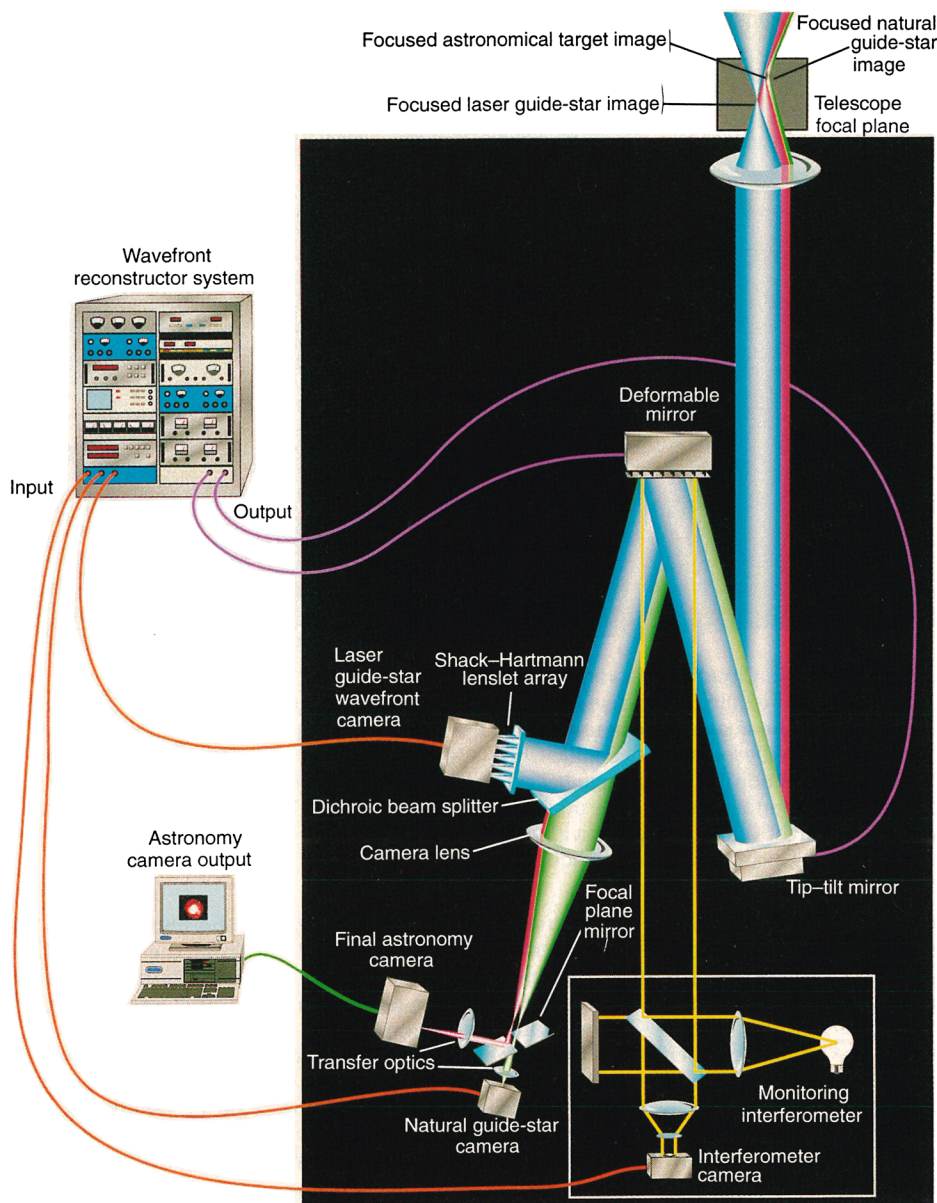
Figure 1 shows a prototypical adaptive optics system that uses both a laser guide star and a natural guide star. A simpler adaptive optics system using only a natural guide star would omit the laser guide star section and would analyze the natural guide star with a so-called Shack-Hartmann array. The basic design allows the astronomical light to pass through the telescope's main focal plane, after which it is collimated and operated upon with a tip-tilt mirror and a deformable mirror. Both of the wavefront sensors (one for the natural star and the other for the laser guide star) are placed downstream from the tip-tilt mirror and the deformable mirror so that the adaptive optics can operate as a closed-loop feedback system.

While most adaptive optics systems look like figure 1, there are innovative variations on this standard design. For example, the 6.5-m Smithsonian Institution-University of Arizona Monolithic Mirror Telescope (formerly known as the Multiple Mirror Telescope) located at the Steward Observatory in Arizona will incorporate the deformable mirror function into the Cassegrain secondary mirror surface instead of using the separate tertiary deformable mirror shown in figure 1.

Astronomers have compelling reasons to develop and maintain adaptive optics systems for ground-based telescopes. Not only will adaptive optics provide the means for increasing the angular resolution in direct imaging, they will also provide higher performance for many spectroscopic, interferometric and photometric measurements. For example, if the scientific goal is to make a simple detection of a faint point source such as a star or a quasar in the presence of a bright sky background, the final detected signal-to-noise ratio scales as the ratio D/θ , where D is the diameter of the telescope's primary mirror and θ is the angular resolution attained at the time of detection. Telescope construction, using new technologies, has pushed D to dimensions limited primarily by structural engineering problems, and therefore cost. But decreasing θ is just as important as increasing D . Adaptive optics provides a new opportunity to gain a factor of 4 to 10 in D/θ by decreasing θ .

In this article, I will outline some of the history behind the development of adaptive optics systems for astronomy

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A type II adaptive optics system mounted at the coudé focus of a large ground-based telescope. The telescope (not shown here) delivers a focused image of three objects at the top right corner. The first optical element (usually a mirror, but shown here as a lens) reimages the primary mirror onto the deformable mirror. A dichroic beam splitter diverts the light from the laser guide star (represented by the blue beam) just after it passes the deformable mirror, while light from the natural guide star (green) and the astronomical target object (red) passes on through the system. An array of lenslets divides the laser guide-star light into a set of sub-images, from which the wavefront distortion can be measured. A mirror with a slit or a central hole is used to separate the light of the natural guide star from that of the astronomy target object. An optical interferometer (yellow beams) monitors the shape of the deformable mirror. The focused input beam from the laser is displaced from the focus of the astronomical sources at the initial telescope focal point, because the laser beam originates in the atmosphere and is closer than the astronomical objects. **Figure 1**

and discuss the status of the field. Two particular sub-systems—wavefront detectors and laser guide-star projectors—will be examined in more detail to provide a measure of the current technological challenges.

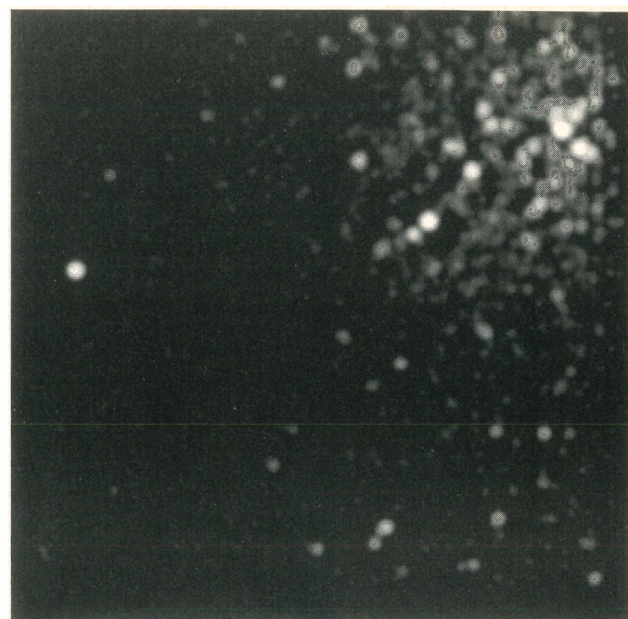
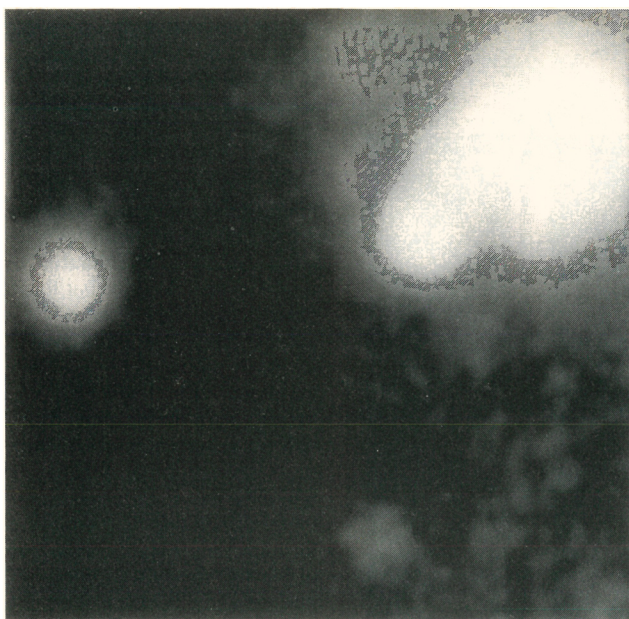
The early history

The concept of adaptive optics is not particularly new, and like many excellent ideas it seems to have been discovered more than once. Around 1950 Horace Babcock,¹ then director of the Mount Wilson and Palomar Observatories, was the first to suggest how one might build an astronomical adaptive optics instrument. Independently, in 1957 Vladimir P. Linnik² described the same concept in the Soviet journal *Optika i Spektroskopiya*. Although Babcock was very specific in his design concepts and had the resources of Mount Wilson and Palomar at his fingertips, his adaptive optics system was not built. It was simply beyond the technological capabilities of the 1950s. More than 20 years passed before the US military research community took the leading role and built the first fully operational adaptive optics system and installed it on a surveillance telescope at Haleakala Observatory on Maui,

Hawaii, where it imaged satellites launched by the Soviet Union. These early military efforts were recently described by John Hardy,³ one of the lead project engineers responsible for the first military adaptive optics program.

Babcock's conceptual design depended on an electrostatically controlled thin layer of oil to produce the necessary corrective phase delays. Modern adaptive optics systems employ deformable mirrors; most commonly these are thin glass mirrors supported on an array of piezoelectric actuators. Actuators push and pull small sections of the thin mirror face-sheet so that it conforms to the wavefront deformation. At a good astronomical site the total stroke needed (that is, the maximum amplitude that each actuator might have to move) to cancel the most extreme atmospheric perturbations is a few microns. Such amplitudes are within easy reach of the best piezoelectric actuators.

A number of astronomers were aware during the early 1980s of both Babcock's original idea and the military's adaptive optics program. Even so, it seemed at the time that adaptive optics might remain an esoteric concept impractical for astronomy research, even if cost were no



a

b

R136 region in the Large Magellanic Cloud's 30 Doradus nebula at $2.2\ \mu\text{m}$, shown with adaptive optics off (a) and on (b). The region contains more than 30 massive Wolf-Rayet, O and B stars and is known to be a location of recent massive star formation. The image was obtained using the COME-ON Plus system on the 3.6-m telescope at the European Southern Observatory's La Silla, Chile, site. The adaptively corrected image reveals more than 200 stars down to magnitude 19. The image has a full-width, half-maximum resolution of 0.15 arcsec after deconvolution, which further enhances its quality. The field of view is 12.8×12.8 arcsec, corresponding to about 10×10 light years. (Image provided by B. Brandl, B. Sams and A. Eckart, Max Planck Institute for Extraterrestrial Physics, Garching bei Munchen, Germany.) **Figure 2**

consideration. The primary limitation for astronomers was the shortage of bright guide stars required to provide the reference wavefront: To operate an adaptive optics system on a telescope at visual wavelengths, a tenth-magnitude (or brighter) reference source must be located within 1 to 2 arcsec of the astronomical target. Given the limited number of stars brighter than tenth magnitude, less than 0.1% of the sky is accessible at visual wavelengths.⁴

To see why a tenth-magnitude star is needed, we must consider the effects of atmospheric turbulence in more detail. The physical nature of the atmospheric distortions is most conveniently described in terms of the parameter r_0 . Imagine measuring the rms deviations of a reference wavefront that enters the aperture of a telescope. In the presence of fully developed atmospheric turbulence (where all small-scale turbulent cells are in equilibrium with their larger counterparts), a smaller aperture exhibits a smaller rms wavefront variance. The parameter r_0 was defined in 1966 by David Fried⁵ to be the largest aperture within which the total rms wavefront irregularity is less than 1 radian (or $\lambda/2\pi$). The dominant perturbation in any r_0 -sized patch is wavefront tilt, and the tilt-removed rms wavefront error within an r_0 aperture is about $\lambda/17$. Therefore, an astronomer who uses a telescope of diameter r_0 to observe a star will see a nearly diffraction-limited image jittering to and fro in the focal plane. The parameter r_0 is wavelength dependent,

$$r_0 \propto \lambda^{1.2}$$

and by convention it is quoted for $\lambda = 500\ \text{nm}$ (in the middle of the visible portion of the spectrum). In an average backyard, r_0 ranges from 5 to 10 cm, while on the best astronomical mountaintops, r_0 ranges from 20 to 30 cm.

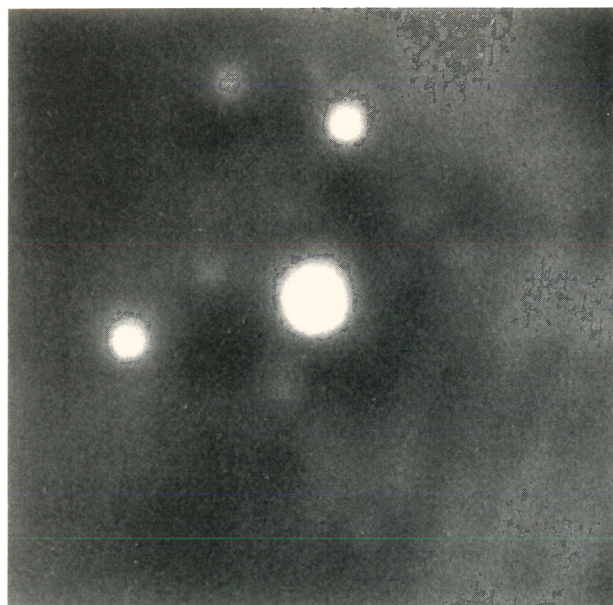
One wants the guide star to be close enough in the sky to the target object so that their light is affected by

the same r_0 patch. Otherwise the coherence between the reference wavefront and the light from the target object will be lost. Because the mean height of the turbulence is about 10 km, the guide star and target must therefore be within about $20\ \text{cm}/10\ \text{km} = 20\ \mu\text{rad} = 4\ \text{arcsec}$.

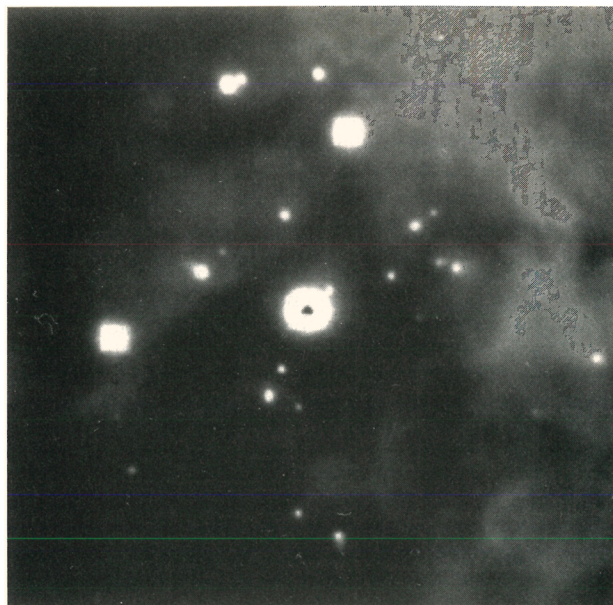
Atmospheric turbulence can be considered to be a relatively frozen phase screen that blows across the telescope's field of view. The time scale for readjusting the electro-optics is therefore about r_0/v , where v is the wind velocity in the turbulent atmosphere. On an average night at an astronomical observatory, r_0/v is of order 30 msec at visual wavelengths. To monitor and then remove the turbulence, an electro-optic control system must operate about ten times faster than the atmospheric changes.

From this analysis it is easy to see why the guide star must be tenth magnitude or brighter. Each subaperture of diameter r_0 in the telescope pupil contains a phase delay that is relatively independent—at least for the higher-order perturbations—of other portions of the pupil. To properly monitor the wavefront, light from the reference star must be parsed into sections, each with a diameter of approximately r_0 . Given reasonable efficiencies for a complete astronomical telescope and its optical system, only stars brighter than tenth magnitude can provide the flux needed to precisely monitor the wavefront over areas of diameter about 20 cm and in periods as short as 3 msec.

While these restrictions discouraged the development of visual-light astronomical adaptive optics systems before 1980, there was a clever solution for the military system designed for satellite surveillance. At the Haleakala Observatory the adaptive optics system was used primarily in twilight hours. During twilight, sky background contamination is relatively low, yet an Earth-orbiting satellite is still illuminated by sunlight. Bright glints of sunlight reflected off the satellite itself provide the reference wavefront.



a



b

Trapezium region in the Orion nebula with adaptive optics off (a) and on (b) at the $H\alpha$ wavelength of $0.6564\ \mu\text{m}$. These images were obtained by the 1.5-m laser-guided adaptive optics telescope at the Starfire Optical Range in New Mexico. The central star, θ^1 Orionis, was used as the tip-tilt reference source. A majority of the faint objects are $H\alpha$ sources associated with the photoevaporating envelopes of low-mass stars. Field of view is 41×41 arcsec, and spatial resolution is 0.4 arcsec. (Image provided by R. Q. Fugate, Phillips Laboratory, and P. McCullough, University of Illinois.) **Figure 3**

Artificial guide stars

In the 1980s several significant events altered astronomers' perception of adaptive optics. First, concurrent with the experimental development of early infrared array detectors, it was realized that the requirements of adaptive correction at infrared wavelengths would be less stringent than those for optical wavelengths.⁶ Because r_0 increases with wavelength, the brightness required of the guide star decreases very rapidly with wavelength. Also, the required corrections become simpler: Fewer actuators are needed and the adjustments needn't be made as rapidly. In this same era, Nick Woolf and Roger Angel⁷ recognized the "polychromatic" nature of adaptive optics: Because the atmosphere is only weakly dispersive, natural stars measured at optical wavelengths can be used to correct wavefront errors at infrared wavelengths. Building upon these two ideas, an ambitious effort was begun in 1984 by the National Optical Astronomy Observatories to build a bona fide adaptive optics system for use on an astronomical telescope.⁸ Unfortunately, the NOAO effort produced more attention than scientific results; other priorities forced the project to end before it was completed.

Last but by no means least important in renewing interest in adaptive optics, two French astronomers, Renaud Foy and Antoine Labeyrie, suggested⁹ in 1985 that the backscattered light from a laser could be used to produce what is now called a laser guide star. Using the Foy-Labeyrie method, astronomers could create an equivalent tenth-magnitude star anywhere on the sky! (Linnik² also suggested the possibility of placing a "beacon" at an 8- to 10-km altitude to provide the reference wavefront. Because he tied this idea to "advances in aviation," Linnik must have imagined not a backscattered beam of light but an airplane or dirigible carrying a portable light source.) As discussed below, US military groups working

in secret independently devised the laser guide-star concept approximately four years before Foy and Labeyrie, but this was not known in the open literature until 1991.

Lasers actually provide only partial freedom, because a natural star still is required for the lowest-order (tip-tilt) correction. The laser light experiences equal and opposite overall tilt upon traveling up into the atmosphere and returning. Nevertheless a much fainter star than tenth magnitude suffices to correct tilt.

These developments in the 1980s helped to define the range of potential applications of astronomical adaptive optics. At one extreme are adaptive optics systems that aim for observations at infrared wavelengths, where the wavefront corrections are simple and, thanks to the polychromatic properties of adaptive optics, natural guide stars detected at visual wavelengths can provide the wavefront reference. I will call these systems type I. At the other extreme are adaptive optics systems that aim for observations at visual wavelengths, where the wavefront corrections are complex and more expensive electro-optics hardware and laser guide stars are required. These I will call type II adaptive optics systems. The primary advantages of type I systems are simplicity and low cost. However, the simplest adaptive optics systems pay a penalty in that only modest gains in angular resolution are attained. The most dramatic scientific rewards come from type II systems working at the diffraction limit at visual wavelengths. The drawbacks of type II systems are their hefty investments in technology and their complexity.

What astronomers thought in the late 1980s would be an evolutionary drift toward adaptive optics turned into a veritable revolution in the spring of 1991, when US military researchers stepped forward to announce that they too had been investing in both adaptive optics and laser-guide star research.¹⁰ (See PHYSICS TODAY, February 1992, page 17.) An unusual combination of events laid

the foundation for this dramatic declassification.

First, European astronomers had begun to show significant progress with their COME-ON adaptive optics system, a type I instrument designed for infrared observations.¹¹ Second, my collaborators and I from the University of Illinois published experimental results from tests of the Foy-Labeyrie laser guide-star concept¹² and went on to complete a detailed engineering design for a laser-guided adaptive optics telescope.¹³ Third, the cold war ended. So progress with adaptive optics in the astronomy community meant that classified research was being reinvented, while the end of the cold war removed compelling reasons to keep the information hidden.

The astronomers who were working with adaptive optics in 1991 quickly recognized the similarity between their work and the declassified military research programs. During a ten-year effort, several different research groups funded by the Air Force, the Office of Naval Research, and the Strategic Defense Initiative Organization had built type II laser-guided adaptive optics systems. One of these was permanently installed on a 1.5-m telescope at Kirtland Air Force Base, New Mexico, and it was nearly identical in both broad design and detailed components to the adaptive optics telescopes described by astronomers prior to the declassification.^{9,13} The uncanny overlap between the research done by the military and that proposed by the astronomy community meant that astronomers could expect to develop type II systems five to ten years earlier than they had anticipated. Furthermore, the openness fostered by the declassification and the generosity of the military researchers—especially the adaptive optics group led by Robert Fugate at the Kirtland Air Force Base's Phillips Laboratory—provided excellent assistance to those astronomers, both US and European, who were working with adaptive optics.

Current programs

At the present time there are so many new adaptive optics programs in the design and construction phase that it would be impossible in the space of this article to provide a complete and proper description of each. The table on page 29 highlights efforts known to me. None of the military systems are included, with the exception of work being conducted at the Phillips Laboratory; a limited number of astronomers began to use their Starfire Optical Range (type II) adaptive optics system as early as 1991, and more general access to this facility has recently been provided through a special program offered to astronomers by the National Science Foundation. Also omitted from the table are efforts being made in adaptive optics by solar astronomers. Solar astronomy adaptive optics has its own rich history, but for reasons of limited space it is not discussed here. The table includes information from similar reviews published elsewhere.^{4,14} Note that several entries were difficult to define because of the experimental nature of adaptive optics work. One of the better examples is work underway at the Monolithic Mirror Telescope. The group led by Angel and Michael Lloyd-Hart has recently been successful in rudimentary experiments with a sodium laser guide star and a 6-actuator adaptive mirror, but the table mentions only their final system, which will incorporate a 260-actuator adaptive mirror into the Cassegrain secondary mirror.

Scientific results are already beginning to appear from several type I adaptive optics systems and from the type II system at the Air Force's Starfire Optical Range. (See figures 2 and 3.) The cover of this issue shows a composite of adaptively corrected images of the "Frosty Leo" nebula, taken by the Canada-France-Hawaii Telescope on Mauna Kea, Hawaii.¹⁵ Far-infrared emission from this nebula

was first discovered by the Infrared Astronomical Satellite, and the adaptively corrected images reveal that the central source is a double star with an angular separation of about 0.2 arcsec. The stars are seen through a hollow disk of material that absorbs most of the shorter wavelengths. The surrounding nebula is illuminated by light escaping perpendicular to the disk. Visible light from a bright spot in the southern lobe (toward bottom of image) was used as the guide star. The nature of scientific competition, combined with results such as those shown here, make a compelling case for major observatories to consider adaptive optics a necessity rather than a luxury.

To keep a proper perspective on the benefits of adaptive optics systems, it is worth comparing their capabilities with those of space telescopes. First, of course, the opacity of the Earth's atmosphere at uv and ir wavelengths will always hamper ground-based telescopes whether adaptive optics are used or not. Wavelengths shorter than 300 nm are completely blocked, and beyond 1 μm broad bands of emission from the night sky hamper the detection of faint sources, except in select windows such as 1.25 μm . Second, only a relatively small angular field of view can be corrected with adaptive optics systems; space telescopes have no such restriction. For example, at 500 nm near-diffraction-limited performance can be expected from a ground-based adaptive optics system within a field of about 3-arcsec diameter, while at 2.2 μm in the near ir the corrected field grows to approximately 18 arcsec. There is hope that some arrangement of multiple laser guide stars and the use of more than one—most likely two—adaptive mirrors could broaden these angles by a factor of two.¹⁶ Third, there is the need in adaptive optics systems to always have a natural guide star somewhere very near the target of interest. For laser-guided systems, only a faint natural star is needed, and in many situations observational astronomers can select among alternate targets in order to satisfy the guide-star requirements. The Hubble Space Telescope is also, to a lesser extent, limited by its use of natural guide stars for target selection.

Finally, the relative cost of the two technologies must be considered. Here adaptive optics has the advantage, being about 400 times cheaper. (The precise cost comparison depends on whether improvements and repairs are part of the estimate.)

To provide a measure of the current technological challenges facing adaptive optics instrument builders, two subsystems will be described here in detail: the natural guide-star wavefront detection system and the laser guide-star projection system. Both incorporate forefront technologies that push one or more physical processes to the limit. Other subsystems could be given the same attention, but the full story would be too lengthy for this forum.

Wavefront sensors

The natural guide-star wavefront sensor (located at the bottom of the adaptive optics system shown in figure 1) aims to squeeze from a minimal number of photons the maximum amount of wavefront information possible. The motivation is clear: If fewer photons can be used, fainter natural guide stars can be used, and this will increase the number of astrophysically interesting targets accessible to the adaptive optics instrument. Type I systems rely entirely on natural stars for wavefront monitoring, and type II systems need as much help from natural stars as possible. The simplest view of type II systems suggests that the natural star need provide only tip-tilt information, since the laser guide star provides the rest. However, type II systems will work better if the natural guide star is used to measure other low-order wavefront terms, such as defocus. Laser guide stars do their best work correcting

Astronomical adaptive optics systems

Instrument and organization	Telescope(s)	Commission date	Type	Actuators in mirror	Status and other notes
SOR Phillips Lab	1.5-m SOR	1989	II	241	In full operation. Rayleigh guide star. Limited astronomical work.
COME-ON France-ESO	3.6-m La Silla	1989-93	I*	19	Was in full operation. Produced ir astronomical images.
COME-ON-Plus France-ESO	3.6-m La Silla	1993	I	52	In full operation. Producing ir astronomical images.
Inst. for Astronomy, Univ. of Hawaii	3.9-m UKIRT 3.6-m CFHT	1993	I	13	Experimental operation. Bimorph mirror; curvature sensor. Producing ir astronomical images.
ACE Mt. Wilson Inst. and MIT-Lincoln Lab	1.5-m MWO	1993	I*	69	In full operation. Military surplus mirror. Limited astronomical work.
WCE Univ. of Chicago	1.0-m Yerkes	1994	I*	69	Just commissioned. Military surplus mirror. Limited astronomical work.
Inst. Optics and Electron., China	2.2-m Beijing Observatory	1994	I*	12	Experimental operation.
WHAT Mt. Wilson Inst.	2.5-m MWO	1994	I-II	241	Under construction.
Lick System LLNL	3.0-m Shane Lick Obs.	1994	I-II	69	Just commissioned at 3 m. Upgrade to type II in 1995 with 10-20-W Na laser.
CFHT-Bonnette CFHT	3.6-m CFHT	1995	I	19	Under construction. Bimorph mirror.
SOR Phillips Lab	3.5-m SOR	1995	II	500	Under construction. Dual Rayleigh-Na guide stars. Upgrades to follow AEOS (below).
ChAOS Univ. of Chicago	3.5-m ARC	1995	I-II	97	Awaiting installation. Na guide star. Adequate for ir only.
UnISIS Univ. of Illinois	2.5-m MWO	1996	II	265	Under construction. Rayleigh guide star. Visible to near-ir.
MMT conversion Univ. of Arizona	6.5-m MMT Mt. Hopkins	1996	I-II	260	Under construction. 5-W Na laser.
MPIA, Heidelberg, and MPE, Garching	3.5-m Calar Alto	1996	I-II	97	Under construction. 3-W Na laser. Planned upgrade to 350-actuator mirror, 20-W laser.
AEOS Phillips Lab	3.67-m AMOS	1997	I	900	Under construction. 0.7 μm to ir operation.
WHT Univ. of Durham	4.2-m WHT La Palma	1997	I	48	Under construction. Optimized for ir.
UKIRT Univ. of Durham	3.8-m UKIRT Mauna Kea	1998	I	48	Under construction. Optimized for ir.
Subaru NAO Japan	8.3-m	1998	I	37	Under construction.
Keck CARA	2 $\times$ 10-m	1998	I-II	—	Design phase. Na guide star. Adequate for ir only.
Gemini NOAO	8.1-m	1998	I-II	>40	Design phase. Possibility of including laser guide star is a design goal.
VLT ESO	4 $\times$ 8.2-m	—	—	—	Design currently on hold.

* Bright (sixth- or seventh-magnitude) natural guide star required.

small-scale (that is, higher order) wavefront irregularities: Focal anisoplanatism impairs the information they provide, especially at the edge of the telescope pupil.

How can a meager number of photons from a natural guide star be used in an optimal way to monitor the wavefront? The first step is to ensure that the detector has the highest quantum efficiency and the lowest system-induced noise. While some researchers considered avalanche photodiodes to be the detector of choice, newer systems rely on custom-designed charge-coupled devices with quantum efficiencies approaching 80-90% (that is, each photon hitting an active part of the CCD has an 80-90% chance of being detected). These CCDs will be configured specifically for use with adaptive optics. For example, the boundaries between pixels on the CCD can be sharpened to improve their use in wavefront sensors as quadrant or edge detectors. For some systems the geometric pattern of the pixels will be configured to

optimize the sampling of the pupil geometry.¹⁷ On-chip CCD amplifiers will be designed in such a way as to match the CCD read-out rates to the time scale of the variations in the wavefront.¹⁸ The CCD fabrication group at MIT Lincoln Lab¹⁹ has designed a special electronic shutter CCD capable of making the CCD insensitive to light when the laser fires to create the laser guide star.

What type of optical system can best sample the natural-star wavefront? Early military adaptive optics systems used the Shack-Hartmann design, which relies on a lenslet array to create a grid of sub-images, each of which measures the local slope of the wavefront. (In figure 1 the Hartmann-style lenslet array samples the laser guide-star light.) Although the rectangular grid geometry ordinarily used with the Shack-Hartmann sensor is conceptually simple, it is not the most efficient way to detect the lowest-order wavefront perturbations. Newer adaptive optics systems will instead use detectors that have radially symmetric geometry. The largest-amplitude wavefront perturbation, after tip and tilt, is defocus. In the pupil plane this is manifested as either concave or convex curvature. The detection of defocus in photon-starved circumstances is best done with a radially symmetric sensor. One type of radially symmetric wavefront sensor is called a

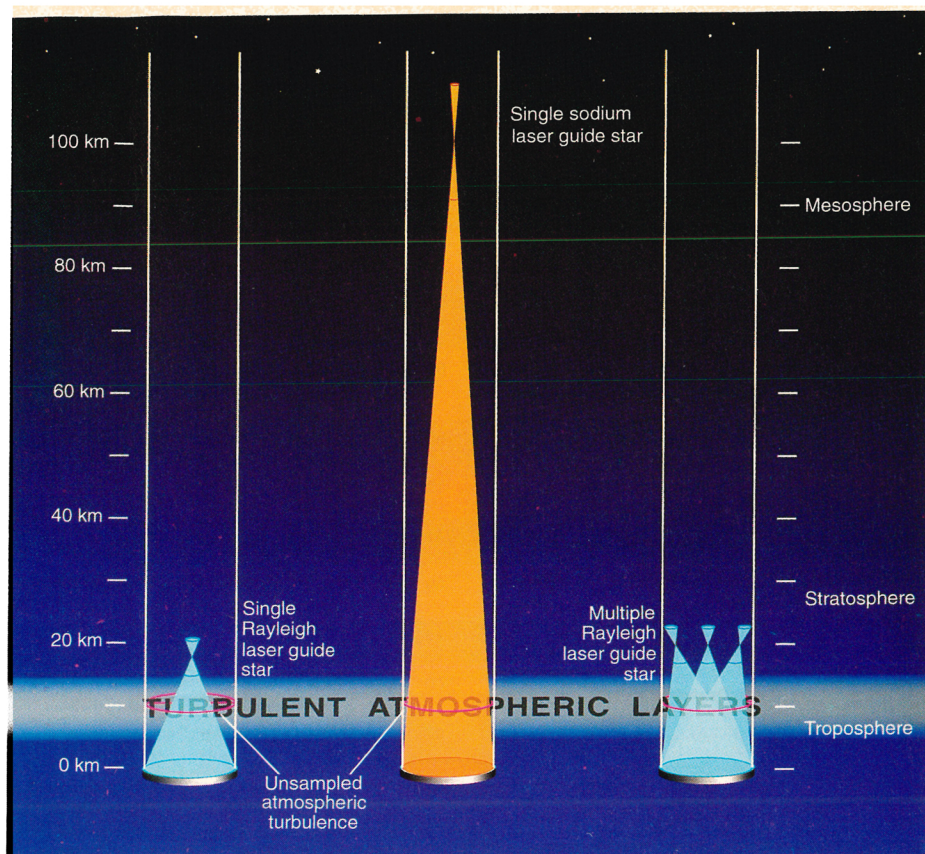
curvature sensor. It compares the signal strength from two equally defocused images, one just inside and the other just outside the focal plane.²⁰ The two-dimensional difference between these signals provides information on low-order wavefront perturbations. Another type of wavefront sensor was recently discussed by David Sandler and coworkers.²¹ It relies on a neural network that is trained to watch two images of the same star. One image is detected very near focus, and the other image is detected slightly out of focus. After the neural network has been trained, it is able to report the amplitudes of the lowest-order wavefront perturbations based on the appearance of the two images. Much work remains to be done in this area of natural-star wavefront sensing.

Laser guide-star projection

A second major technology issue is how to create and project laser guide stars in the atmosphere. The two

Types of laser guide stars—

Rayleigh scattered (a), sodium resonance (b) and multiple Rayleigh (c)—are shown schematically with horizontal dimensions greatly exaggerated. Light entering the telescope aperture from stars “at infinity” forms a cylinder (white outline). Note that the cone of light producing the laser guide star fails to illuminate the outer annulus of this cylinder (pink circle). This lack of sampling in the outer annulus is the major contributor to focal anisoplanatism; the second (minor) contributor is unsampled turbulence at altitudes above the laser guide star. Focal anisoplanatism can be reduced substantially by projecting an array of laser guide stars into the atmosphere, as shown in (c). **Figure 4**



atmospheric scattering processes that can provide the brightest laser guide-star return signal are

- ▷ Rayleigh scattering of photons off molecules in the stratosphere and
- ▷ resonance scattering off sodium atoms in the mesosphere.

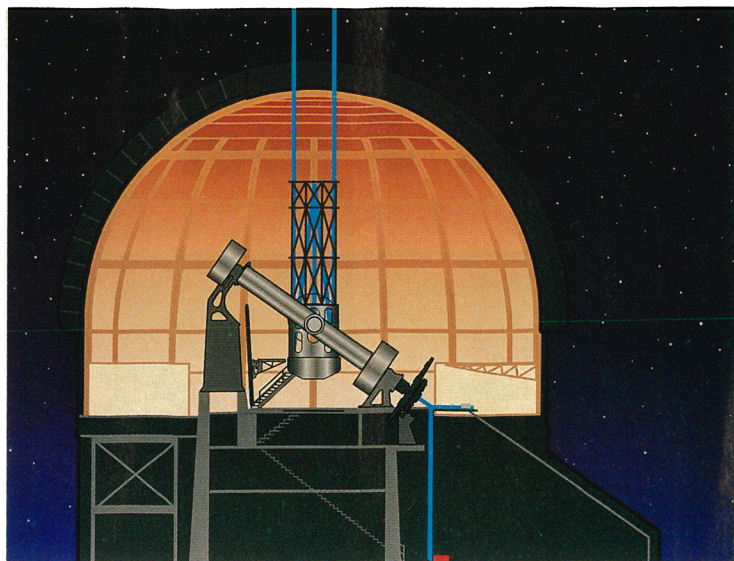
For Rayleigh scattering, there are two laser systems suited to the task: a 530-nm/550-nm copper-vapor laser and a 351-nm excimer laser working with XeF.²² Both systems are available as reliable commercial products capable of delivering, respectively, 200 watts and 50 watts output power, sufficient for each to create a tenth-magnitude star at 10–20-km altitude. The second laser guide-star technique relies on resonance scattering at 589 nm off the neutral sodium atoms present in abundance at an altitude of about 95 km. For this technique, special experimental lasers must be built and tailored to the requirements of the sodium excitation. The copper-vapor and excimer systems operate in the pulsed mode, while sodium-wavelength lasers are either pulsed or continuous wave. Details of the excitation and scattering properties of sodium atoms determine the design parameters of the laser.¹³ In particular, if too much energy is pumped into the sodium layer, saturation occurs and stimulated emission may decrease the backscatter that produces the laser guide star.

Sodium laser guide stars have many advantages, but at present there is no laser—commercial or experimental—capable of producing sufficient output power in a tightly focused image to operate an adaptive optics system at visual wavelengths. Because the deficiency is a tantalizing factor of 5 to 10, a major investment of resources has been made by adaptive optics groups to increase the total power output of sodium-frequency lasers. Forefront

experimental laser groups at MIT Lincoln Laboratory, Phillips Laboratory and Lawrence Livermore National Laboratory are all making contributions to this work.²³ These research efforts include the design and construction of a high-power experimental dye laser capable of being mounted on the side of a large ground-based telescope, and ongoing tests of a laser system in which 589-nm photons are produced in a frequency mixing crystal that is excited by diode-pumped YAG lasers. The latter arrangement circumvents the inefficient dye-laser conversion process.

Laser guide-star systems produce a reference wavefront that emanates from a finite altitude in the Earth's atmosphere, and this leads to complications that have been given the name focal anisoplanatism. The nature of focal anisoplanatism and techniques that can be used to minimize it are shown in figure 4. Sodium laser guide stars have less focal anisoplanatism because they are created 5–10 times higher in the atmosphere than Rayleigh laser guide stars. The role of arrays of multiple laser guide stars was first discussed in the open literature by Foy and Labeyrie⁹ and in classified studies by military researchers, but such arrays have not yet been thoroughly investigated in experiments. Those working on astronomical adaptive optics systems are now continuing this experimental effort.

What is the best way to project the laser light into the upper atmosphere? Figure 5 illustrates one of the options discussed here. If the raw laser beam has poor beam divergence properties, which is generally the case for commercial excimer and the copper-vapor lasers, the telescope's full primary mirror must be used as a primary element in the laser projection system. Figure 5 shows



Laser guide-star projection system (in simplified form) as will be used in the University of Illinois's UNISIS system at the Mount Wilson 2.5-m telescope. The laser beam is sent through the coudé path and projected off the telescope's primary mirror. Alternative systems include projection from behind the Cassegrain secondary mirror and use of an auxiliary projection telescope mounted on the side of the primary mirror cell. **Figure 5**

how laser light will pass through the Mount Wilson 2.5-meter telescope for a type II adaptive optics system currently under construction.²⁴ If the laser emits a near-diffraction-limited output beam, the projection system becomes simpler than that shown in the figure. A side-mounted projection system can be placed on the telescope structure and bore-sighted with the main telescope (this is one of two proposals for the NAO's Gemini 8.5-m telescope). Alternatively, the laser beam can be sent to the top of the telescope structure, where it can be projected along the telescope's optical axis from behind the Cassegrain secondary mirror; this setup has been proposed for the University of Arizona's Monolithic Mirror Telescope. In the MMT design, low-altitude scattered light that would otherwise be a contaminant remains in the shadow of the secondary mirror as viewed from the astronomy detectors. Such an arrangement allows a continuous-wave laser to illuminate the sodium layer without any additional baffling. If a pulsed copper-vapor or excimer laser is sent off the telescope primary mirror, potential contamination of the astronomy detectors becomes an issue. Rotating mechanical shutters that run in synchronization with the pulsed laser and dichroic filters prevent the laser light from reaching the final astronomy focal plane.

The technical issues discussed above are just a sampling of those currently being pursued to clear the path for improving the image quality delivered by ground-based telescopes. Telescopes at nearly all of the largest major observatories in the world—the dual 10-m Keck Observatory telescopes, the 8.3-m Subaru telescope of Japan, the 8-m Gemini telescope and the 6.5-m Monolithic Mirror Telescope—will incorporate adaptive optics into their scientific operation. With the newly merged astronomy and military adaptive optics communities openly working toward similar goals with enthusiastic support from their respective broader communities, hopes remain high that many, if not all, astronomers in the next decade will have access to adaptive optics systems providing near-diffraction-limited performance.

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