tra. On the other hand, slowly relaxing processes (several nanoseconds) are easily observed in the time-domain experiments, whereas the corresponding bandwidths in the optical spectra are well below the accessible frequency resolution. The picture of molecular liquids, for instance, that emerges from the investigation by means of time-resolved techniques is in many cases more complex than expected. In this respect, the OKE and related time-domain experimental methods are of special interest to the study of critical phenomena, often characterized by very different time scales. The use of the time-resolved OKE technique will lead to substantial gains in the understanding of certain aspects of liquids and solids, such as the structure and dynamics of liquids, mostly in the proximity of phase transitions, where a high degree of molecular organization is likely to appear; the processes involved in the formation of glasses; and the intra- and intermolecular dynamics of liquid crystals.

One of the main problems encountered in this kind of investigation is the generally weak intensity of the nuclear signal (the one containing the dynamical information) with respect to the electronic contribution. The new solid-state laser systems that are now becoming available, providing short, intense pulses at a high repetition rate (typically 100 fs, 500 μJ per pulse at a repetition rate of several kilohertz), are expected to enlarge substantially the field of application of the technique.

REFERENCES

1. S. Kielich, *Acta Phys. Pol.* **30**, 683 (1966).
2. R. W. Hellwarth, *Prog. Quantum Electron.* **5**, 1 (1977).
3. D. McMorrow, W. T. Lottshaw, G. A. Kenney-Wallace, *IEEE J. Quantum Electron* **24**, 443 (1988).
4. Y. Yan and K. A. Nelson, *J. Chem. Phys.* **87**, 6240 (1987); S. Ruhman, A. G. Joly, B. Kohler, L. R. Williams, K. A. Nelson, *Rev. Phys. Appl.* **22**, 1987 (1717).
5. D. McMorrow and W. T. Lottshaw, *Chem. Phys. Lett.* **178**, 69 (1991).
6. M. Cho, M. Du, N. F. Scherer, G. R. Fleming, S. Mukamel, *J. Chem. Phys.* **99**, 2410 (1993).
7. G. L. Eesley, M. D. Levenson, W. M. Tolles, *IEEE J. Quantum Electron* **14**, 45 (1978).
8. D. McMorrow and W. T. Lottshaw, *J. Phys. Chem.* **95**, 10395 (1991).
9. I. Santa, P. Foggi, R. Righini, J. Williams, in preparation.
10. M. Ricci, P. Foggi, R. Righini, R. Torre, *J. Chem. Phys.* **98**, 4892 (1993).
11. P. Foggi, R. Righini, R. Torre, V. F. Kamalov, *Chem. Phys. Lett.* **193**, 23 (1992).
12. P. Foggi, R. Righini, R. Torre, L. Angeloni, S. Califano, *J. Chem. Phys.* **96**, 110 (1992).
13. J. Etchepare, G. Grillon, J. P. Chambaret, G. Hamoniaux, A. Orzag, *Opt. Commun.* **63**, 329 (1987).
14. F. D. Deeg, J. J. Stankus, S. R. Greenfield, V. J. Newell, M. D. Fayer, *J. Chem. Phys.* **90**, 6893 (1989).
15. R. Torre, I. Santa, R. Righini, *Chem. Phys. Lett.* **212**, 90 (1993).
16. P. G. de Gennes, *The Physics of Liquid Crystals, Fundamentals* (Springer, Berlin, 1988).

Active Optics, Adaptive Optics, and Laser Guide Stars

N. Hubin and L. Noethe

Optical astronomy is crucial to our understanding of the universe, but the capabilities of ground-based telescopes are severely limited by the effects of telescope errors and of the atmosphere on the passage of light. Recently, it has become possible to construct inbuilt corrective devices that can compensate for both types of degradations as observations are conducted. For full use of the newly emerged class of 8-meter telescopes, such active corrective capabilities, known as active and adaptive optics, are essential. Some physical limitations in the adaptive optics field can be overcome by artificially created reference stars, called laser guide stars. These new technologies have lately been applied with success to some medium and very large telescopes.

Since its invention 300 years ago, the astronomical telescope has evolved from a small, manually pointed device for visual observations to a large and sophisticated computer-controlled instrument by which information is collected electronically. Throughout this development, two parameters have been particularly important: the light-collecting power or diameter of the telescope (allowing the detection of fainter and more distant objects) and the angular resolution (that is, the sharpness of the image). For a perfect telescope used in a vacuum, resolution can be improved by increasing the telescope diameter. A plane wavefront from distant star (effectively at infinity) would be converted by the telescope into a perfectly spherical wavefront, forming the image, and the ultimate angular resolution achievable is called the diffraction limit.

In practice, however, both atmospheric and telescope errors (Fig. 1) distort the spherical wavefront, creating phase errors in the image-forming ray paths. Even if they were optically perfect, ground-based telescopes observing at visible wavelengths could not, because of atmospheric turbulence alone, achieve an angular resolution better than telescopes of 10- to 20-cm diameter. For a 4-m telescope, atmospheric distortion degrades the spatial resolution by more than one order of magnitude compared with the diffraction limit, and the intensity at the center of the star image is degraded by a factor of 100. The causes of this degradation are random spatial and temporal wavefront perturbations induced by turbulence in various layers of the atmosphere; one of the principal reasons for sending the Hubble Space Telescope into space was to avoid these degradations. In addition, the image quality is affected by permanent manufacturing errors and by long time scale–wavefront aberrations introduced by mechanical, thermal, and optical effects in the telescope, such as defocusing, decentering, or mirror deformations generated by support errors.

Until recently, the astronomical telescope has remained a "passive" instrument. Without any inbuilt corrective devices to improve the quality of star images during observation, the only possible adjustments are those performed off-line or during the daytime while the telescope is not in operation.

Although it was thought that atmospheric distortions could not be avoided, mechanical improvements have been made to minimize the negative effects of the telescope errors. Mirror figuring and polishing were improved, and stiffer structures and thicker mirrors are now used to avoid

European Southern Observatory, Karl-Schwarzschild-Strasse 2, 85748 Garching, Federal Republic of Germany.

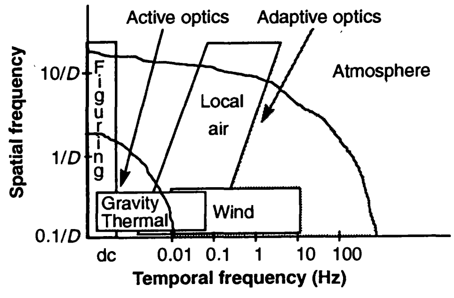

Fig. 1. Frequency domain of wavefront aberrations generated by various sources. The spatial frequency is measured in terms of *D*, the diameter of the telescope.

gravitationally induced deformations. Low-expansion glass was introduced to keep the mirror independent of any environmental temperature variation. To reduce local temperature effects, heat dissipation from motors and electronic equipment was minimized during the night, and the dome, which in addition shielded the telescope from the effects of wind buffeting, was cooled during the day. In properly designed and well-manufactured telescopes of middling size, image quality is limited mainly by atmospheric distortions, although telescope adjustment remains a major problem with conventional telescopes. But as plans were developed to enhance light-collecting power by building telescopes with primary mirrors well above 4 m in diameter, it became clear that conventional methods of maintaining image quality were ruled out by cost and structure weight limitations. As a result, a new technique known as active optics was proposed for telescopes with mirror diameters of about 3 m or more (*1–3*) by which image quality could be optimized automatically by means of constant adjustments by inbuilt corrective optical elements operating at fairly low temporal frequency.

At about the same time, the idea of real-time compensation of star images degraded by the atmosphere came into being. Initially proposed by Babcock in 1953 (*4*), the idea was to use fast active optics operated at higher temporal frequencies to continuously compensate for the wavefront deformations created by the atmosphere. The use of adjustable optical elements to compensate for atmospheric rather than telescope errors became known as adaptive optics, and the technique became a reality 20 years later owing to progress in computer technology coupled with a better understanding of atmospheric behavior (*5–9*). Research in adaptive optics was initially done in the military environment, where most of the information has been kept secret. In the middle of the last decade, adaptive optics started to be applied to astronomy, and nowadays, it is a challenging and vigorous field with exciting prospects for astronomical science (*10–12*).

The elementary definition of adaptive optics is that the technique corrects primarily wavefront aberrations generated by the atmosphere and thereby attempts to restore the image, in real-time, to a quality that is close to the diffraction limit of the telescope. In practice, it is a complex multivariable optimization process linked to atmospheric characteristics during observation, the performance of the adaptive optics system, the observation wavelength, and also the characteristics of the astronomical object observed at a certain angle in the sky.

Both active and adaptive optics are closed-loop systems, based on the same principle (Fig. 2). Both systems consist of three main elements: a wavefront sensor to measure the distortion of the wavefront coming from a star; a wavefront correction device, which is, in both active and adaptive optics, a mirror, though sizes and types may be very different; and a control computer, which can be relatively slow for active optics but must be extremely fast for adaptive optics.

Active Optics

Active optics deals with wavefront errors of rather low temporal (less than 0.01 Hz) and spatial frequencies (up to about three wavelengths across the surface for a 8-m meniscus mirror with a thickness of 20 cm; a meniscus mirror has about the same thickness everywhere). Measurement of the wavefront is usually performed by means of a so-called Shack-Hartmann wavefront sensor located at an image of the pupil of the telescope, which often coincides with the primary mirror. The sensor splits the wavefront from a suitable, bright guide star into a number of elementary subapertures by means of a lenslet array, the spatial sampling corresponding roughly to the number of adjustable active supports under the primary mirror. Each lenslet creates at its focus a spot on a detector, and analysis of the positions of these spots compared with the positions of the corresponding reference spots recorded beforehand yields the values of the local slopes of the wavefront. Finally, a computation extracts the information that is needed to drive the correcting elements.

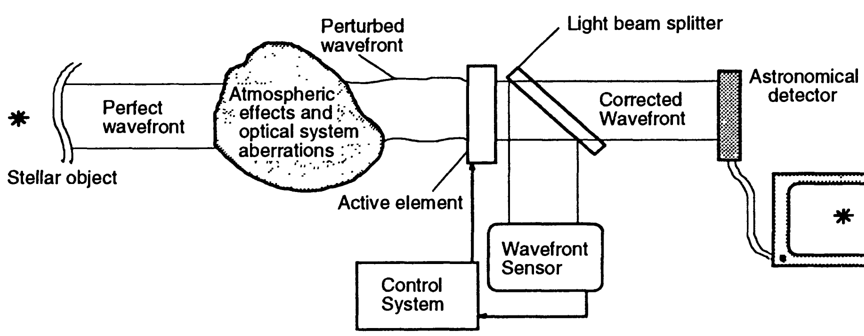

Fig. 2. The principle of active and adaptive optics.

The key to active optics lies in having a large primary mirror that is flexible enough for mechanical devices to provide constant adjustment of its figure in accordance with the wavefront measurement. Focusing and alignment is maintained by means of a rigid but movable secondary mirror. Two types of adjustable primary mirrors are now in use: There are continuous mirrors, which may be either moderately thin menisci or somewhat thicker structured honeycomb mirrors, and there are segmented mirrors, typified by the 36 hexagonal elements that make up the 10-m Keck telescope (*13, 14*). The shapes of the continuous mirrors are controlled by forces applied to them, whereas for segmented mirrors, the positions of the individual segments are adjusted.

For the two mirror types, the formulation of shape adjustment is different. Any continuous mirror can, with a given available range of applied force, be deformed only in specific modes, similar to the free vibrations of this mirror. The best approach for active optics is then a modal one, in which only a limited number of effectively independent deformation modes are corrected (*15, 16*). Knowledge of these modes for any given mirror is essential to the derivation of the force distributions to be applied for the optimization of the active correction, and image analysis must supply the coefficients of the selected modes contained in the distorted wavefront (*17*) (other sets of functions, such as Zernike polynomials, can also be used, but with somewhat lower efficiency over the dynamic range).

For segmented mirrors, on the other hand, a zonal correction method is appropriate. The individual segments are rigid elements that do not deform during the operation of the telescope, and therefore, the shape of the primary mirror is fully defined by the relative positions (in depth and tilt) of the individual segments. The wavefront measurement, in which every subaperture corresponds to one of the segments, along with the constant monitoring of the relative positions of the segments at their interfaces, supplies the appropriate adjustment, in tilt and depth, for all subapertures.

For all large telescopes, the use of active optics is essential if an image quality limited only by the atmosphere is to be achieved. The active optics system must therefore work continuously and independently of the direction of the observation in the sky. A sufficiently bright guide star must then be available within the field of view of the telescope around the astronomical object being observed; the field of view is usually about 30 arc min in diameter. To average out the effects of the atmosphere on the wavefront and to detect only the telescope errors, active optics needs long integration times of at least 30 s. This has two favorable side effects, which ensure that, at least for large telescopes, there is generally no problem in finding a guide star. First, one can use fairly faint stars as guide stars. Second, one can use the telescope's entire field of view because all wavefront errors are constant over the field, except for the ones generated by the atmosphere, which have been averaged out.

At present, there are only two functioning active telescopes: the European Southern Observatory (ESO) 3.5-m New Technology Telescope (NTT) at La Silla in the Chilean Andes, which went into operation in 1989 (*18*), and the 10-m Keck telescope, which went into operation when its primary mirror was completed in 1992 (*19*), on Mauna Kea, Hawaii. The NTT has 75 active supports under its monolithic primary mirror, and the axial and lateral position of the secondary mirror is controlled. The Keck telescope has a primary consisting of 36 1.8-m segments. Currently, two telescopes are being converted into active telescopes: the 2.5-m Nordic Optical Telescope on La Palma in the Canary Islands and, despite the limitations imposed by its conventionally thick and therefore rigid primary mirror, the 4-m telescope at Cerro Tololo Inter-American Observatory in the Chilean Andes. Other proposed projects with monolithic active primaries are the 3.5-m "Galileo" telescope, an Italian project on La Palma; the four 8-m units of the ESO Very Large Telescope (VLT), destined for Paranal, Chile (150 active supports); the 8.3-m Japanese National Large Telescope "Subaru", to be built on Mauna Kea, Hawaii; and the two 8-m "Gemini" telescopes—the product of a collaboration of the United States, Canada, the United Kingdom, Argentina, Brazil, and Chile—one of which will be located on Mauna Kea and the other on Cerro Pachon, Chile.

The impact of active optics on the design of telescopes is demonstrated by the fact that, for mirrors of the 4-m class, the weight of the primary mirror can be reduced from typically 12 tons to 6 tons or less. Furthermore, the optical manufacturer does not need to worry about the complete removal of the correctable errors of low spatial frequency and can concentrate on the removal of the uncorrectable errors of high spatial frequency, which leads to an enormous reduction in the cost of polishing.

Active optics, at least for the basic correction rate of 0.03 Hz, is well understood. The major problem is to meet the very stringent requirements for the control of the forces or positions when this technique is applied to mirrors of the 8- to 10-m class. Further development needs to be done to investigate whether the bandpass can be extended to the order of 1 Hz, which would permit, at least in the range of low spatial frequencies, the correction of some of the effects of wind buffeting and temperature inhomogeneities.

Adaptive Optics

To appreciate the formidable task faced by designers of adaptive optics systems, one should understand that an initially plane wavefront traveling 20 km through the turbulent atmosphere accumulates, across the diameter of a large telescope, phase errors of a few micrometers. These have to be sensed with a minimum number of photons and corrected to about 1/50 of a micrometer every millisecond or so. Adaptive optics therefore deals with rapidly varying atmospheric wavefront distortions (up to 1000 Hz) (*20*). Another complication is that, for short integration times, the field of view over which the atmospheric wavefront distortions and hence the images are correlated, the isoplanatic angle, is quite small (only a few arc seconds for visible wavelengths) (*21, 22*).

Because of the high bandwidth and the small field to which corrections can generally be applied, adaptive optics uses a small deformable mirror with a diameter of 10 to 20 cm located within the optical train of the telescope or in a separate box behind the focus of the telescope at an image of the pupil. In some current projects, the possibility of using a large deformable secondary mirror is being studied. The small mirror is either a continuous thin-plate mirror, a few millimeters thick, or is formed by small, individually driven segments. In both cases, the positions are controlled by discrete piezoelectric actuators. The choice of the number of actuators is a complex compromise that depends on the general scientific goals pursued and on the available budget. For instance, a perfect correction for an observation done in visible light (0.6-μm wavelength) with an 8-m telescope would need 6400 actuators, whereas a perfect correction in the near infrared (2-μm wavelength) would require 250 actuators.

A larger number of actuators necessitates a larger number of subapertures in the wavefront sensor, which means that for correction in the visible, the reference star must be at least 25 times brighter than that for correction in the infrared. The current astronomical choice seems to be that the system should provide diffraction-limited images in the near infrared (1- to 2-μm wavelength) with the capability for partial correction in the visible (*23, 24*). However, military systems for satellite observations in the United States have been built to provide corrections in the visible on telescopes in the 1-m class (*25, 26*).

Three methods can be used to measure the degraded wavefront in an adaptive optics system, although the Shack-Hartmann method described above is most often used for large telescopes (*27, 28*). The two other methods are known as shearing interferometry (*29*), which measures, as in the Shack-Hartmann device, the slope of the wavefront, and curvature sensing (*30–32*), where the intensities measured in strongly defocused images provided by the telescope are a direct measure of the local curvature of the wavefront. Correction in a curvature sensing system is often accomplished with a bimorph adaptive mirror, which consists of two bonded piezoelectric plates; the opposite curvatures can be directly generated in the bimorph mirror by the application of voltages proportional to the measured curvatures. With all three methods, the wavefront sensing may be done on a reference star or on the observed object itself if it is sufficiently bright. The measurement can be performed in the visible for observations in the infrared or in the infrared itself (1 to 2 μm) if the visible image of the reference star is too faint (*33*).

Fig. 3. Uncorrected and corrected image obtained with the Come-On-Plus system on the European Southern Observatory (ESO) 3.6-m telescope (ESO and France collaboration). These are images of a double star with a separation of 0.59 arc sec taken at a wavelength of 2.2 μm; exposure time, 10 s. The color scale is linear.

The control system is often a specialized computer that calculates from the wavefront-sensor measurements the commands sent to the actuators of the deformable mirror. The calculation must be done quickly (within 0.5 to 1 ms), otherwise the state of the atmosphere may have changed, rendering the wavefront measurement inaccurate. The required computing power needed can exceed several hundred million operations for each set of commands sent to a 250-actuator deformable mirror. As in active optics systems, zonal or modal control methods are used. In zonal control, each zone or segment of the mirror is controlled independently by wavefront signals that are independently measured for the subaperture corresponding to that zone (*34*). In modal control, the wavefront is expressed as the linear combination of modes or functions (Karhuenen-Loeve functions, for instance) that best fit the atmospheric perturbation (*35, 36*).

Some examples of adaptive optics systems currently working for astronomy are the ESO-France Come-On-Plus system at La Silla Observatory, Chile (52 actuators on a 3.6-m telescope) (Fig. 3), which is an improved version of an early prototype called Come-On (19 actuators on the ESO 3.6-m telescope) (*37–40*), the University of Hawaii system at the Canada-France-Hawaii Telescope on Mauna Kea (12 actuators on a 3.6-m telescope) (*41*), a system on Sacramento Peak, New Mexico, built by Lockheed for solar observations (19 tip-tilt piston segments, that is, 38 degrees of freedom, on a 0.7-m telescope) (*42*), and the six-subaperture Martini project on the 4.2-m William Herschel Telescope, La Palma. A number of military systems are being used on astronomical targets such as the U.S. Lincoln Laboratory Short-Wavelength Adaptive Technique (SWAT) system at the Firepond Facility in Westford, Massachusetts (241 actuators on a 1.2-m telescope) (*25*), the 69-actuator Atmospheric Compensation Experiment (ACE) system installed on a 1.52-m telescope at Mount Wilson (*25*), and the U.S. Air Force Phillips Laboratory Starfire Optical Range system at Albuquerque, New Mexico (241 actuators on a 1.5-m telescope) (*26*). Come-On and Come-On-Plus are two prototypes that were developed to prepare the adaptive optics system for the ESO VLT project (250 actuators on the four 8-m telescopes) (*43*).

Because of the short integration times and the task of detecting and correcting atmospheric influences on the wavefront, implementation of adaptive optics is strongly affected by the size of the isoplanatic angle. It is not always possible to find a sufficiently bright reference star around an arbitrary astronomical object. Conditions are much more favorable for infrared than for visible astronomical observations because the atmospheric turbulence (especially its high spatial frequencies) has, for a given image quality, a weaker effect on longer wavelengths. The spatial and temporal sampling of the disturbed wavefront can therefore be reduced, and this in turn permits the use of fainter reference stars if the number of photons in each subaperture of the wavefront measurement is kept constant. Furthermore, the isoplanatic angle increases almost linearly with the wavelength.

Nevertheless, even for observations at 2.2 μm, the sky coverage achievable by this technique (equal to the probability of finding a suitable reference star in the isoplanatic patch around the chosen target) is only of the order of 0.5 to 1%. Although the use of adaptive optics with natural reference stars is therefore not always possible, the enormous gain in image sharpness has already been exploited in various specific astronomical programs.

Laser Guide Stars

The most promising way to overcome the isoplanatic angle limitation is the use of artificial reference stars, also referred to as laser guide stars, laser probes, and laser beacons (*44*) (Fig. 4). These are patches of light created by the back scattering of pulsed laser light by sodium atoms in the high mesosphere (*45*) or by molecules and particles located in the low stratosphere. The laser beam is focused at an altitude of about 90 km in the first case and 10 to 20 km in the second case, and a gated wavefront sensor is used to select only the back-scattered light from altitudes within a few kilometers of the focus. Such an artificial reference star can be created as close to the astronomical target as desired, and a wavefront sensor measuring the scattered laser light can be used to correct the wavefront aberrations of the target object.

Several laboratories in the United States (*26, 46–48*), operating under military contracts, have reported the successful operation of adaptive optics devices at visible wavelengths with a laser guide star on a 60-cm telescope [Defense Advanced Research Projects Agency (DARPA) Maui Optical Station (AMOS) situated on top of Mount Haleakala in Maui, Hawaii] and on a 1.5-m telescope (U.S. Air Force Starfire Optical Range). Both collected images with 0.15-arc sec resolution and proved the feasibility of laser probes. A joint program of the Strategic Defense Initiative Organization (SDIO) and the U.S. Navy reported an improved resolution by almost a factor of 10 on a 1-m telescope in San Diego, California (*49*). Some systems for astronomical applications (*50, 51*) are being tested in Europe at Observatoire de la Côte d'Azur, Nice, France, (*52*) and in the United States at the 10-m Keck telescope (*53, 54*), the 6.9-m Multiple Mirror Telescope (MMT) (*55*), and the Chicago Adaptive Optics System (ChAOS) on the 3.5-m ARC telescope at Apache Point, New Mexico (*56*).

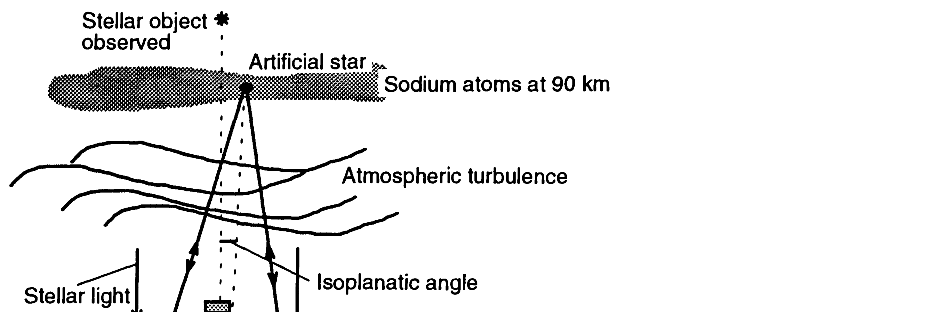

Fig. 4. Adaptive optics with laser guide star.

Nevertheless, there are physical limitations that can only be overcome by the use of more sophisticated and complex laser guide star techniques. A first problem, focus anisoplanatism, also called the cone effect, became evident very early on. Because the artificial star is created at a relatively low altitude, the back-scattered light collected by the telescope forms a conical beam, which does not cross exactly the same turbulence-layer areas as the light coming from a distant astronomical source (*57*). This leads to a phase estimation error, but the problem may be solved by the simultaneous use of several laser guide stars around the observed object (*58*).

More severe is the image motion or tilt determination problem. Because the paths of the light rays are the same on the way up as on the way down, the centroid of the artificial light spot appears to be stationary in the sky, whereas the apparent position of an astronomical source suffers lateral motions. A solution to this problem is to use two adaptive optics systems with two laser beacons, one for the astronomical object and one for a stellar reference star, which should be located as close as possible to the target (*59*). The purpose of the second beacon is to improve the signal-to-noise ratio of a reference star such that it can be used for the correction of the image motion of the target. This improvement is done by the correction, with the help of the laser beacon, of all its aberrations except the uncorrectable tilt. As with the adaptive optics systems with one beacon, the first beacon near the target is then used to correct the other aberrations.

With this method, fainter natural reference stars can be used to measure the image motion, so the probability of finding such a reference star close to the astronomical object is higher. This concept of dual adaptive optics therefore provides a better sky coverage (up to 90% for a 6-m telescope at 1-μm observation wavelengths). An obvious implication of this system is that the larger the telescope, the greater the sky coverage because the gain in resolution brought about by the increase of the diameter of the optics is fully exploited. On the other hand, it has severe technological implications, as it requires the duplication of all components (deformable mirror, wavefront sensor, and laser guide star).

Adaptive optics with a multicolor laser probe is another concept being investigated to solve the tilt determination problem of laser beacon adaptive optics (*60*, *61*). Only applicable to resonant scattering processes at 90 km, it excites different states of the sodium atoms and makes use of the slight variation in the refraction index of air with wavelength. Its main drawback is the limited returned flux, owing to the saturation of the mesospheric sodium layer and consequently the low brightness of the created artificial star. The multicolor laser guide star may provide corrections without any natural reference star, resulting in a 100% sky coverage, but this idea is in a very early stage of development.

Apart from the physical limitations and the new laser guide star concepts mentioned above, there are still several technological challenges. Among them are the development of fast, low-noise charge-coupled devices (CCDs) for visible wavefront sensors, which would permit the use of fainter reference stars; new high-power sodium lasers; very fast processors that can exceed 10^9 to 10^{10} operations per second; deformable mirrors with bandwidths of several kilohertz and with a few thousand actuators; and secondary adaptive mirrors. The latter will limit the number of additional mirrors usually needed by an adaptive optics system, which is a critical parameter for infrared astronomical observations because it increases the background emission.

In some areas—for example, in infrared observations with telescopes in the 4-m class or visible light observations with telescopes up to 1 m in diameter—adaptive optics has proven its feasibility. But in other areas, such as corrections in the visible for large telescopes or the use of laser guide stars or multiple laser guide stars, much remains to be done. Many recent astronomical discoveries, important to our understanding of the universe, can be directly attributed to new optical observation techniques such as active and adaptive optics. With the construction of large telescopes in the 8- to 10-m class, the implementation of these systems at the early stage of the design phase becomes indispensable. With this equipment, the light-gathering properties of these new, large telescopes along with their remarkable capability to resolve small details of the universe will revolutionize ground-based astronomy in the next decade.

REFERENCES AND NOTES

1. J. F. Creedon and A. G. Lindgren, *Automatica* **6**, 643 (1970).
2. R. N. Wilson, *ESO Conference on Optical Telescopes of the Future*, F. Pacini, W. Richter, R. N. Wilson, Eds. (European Southern Observatory, Garching, Germany, 1978), p. 99.
3. J. W. Hardy, *Proc. SPIE* **332**, 252 (1982).
4. H. W. Babcock, *Publ. Astron. Soc. Pac.* **65**, 229 (1953).
5. V. I. Tatarskil, *Wave Propagation in a Turbulent Medium*, R. A. Silverman, Transl. (McGraw-Hill, New York, 1961).
6. D. L. Fried, *J. Opt. Soc. Am.* **56**, 1380 (1966).
7. R. J. Noll, *ibid.* **66**, 206 (1976).
8. J. W. Hardy, J. E. Lefevre, C. L. Koliopoulos, *ibid.* **67**, 360 (1977).
9. F. Roddier, *Progress in Optics*, E. Wolf, Ed. (North-Holland, New York, 1981), vol. 19, pp. 281–377.
10. P. Kern *et al.*, *Proc. SPIE* **1114**, 54 (1988).
11. J. M. Beckers, in *Towards Understanding Galaxies at Large Redshift*, R. Kron and A. Renzini, Eds. (Kluwer, Dordrecht, Netherlands, 1988), pp. 319–38.
12. F. Merkle and J. M. Beckers, *Proc. SPIE* **1114**, 36 (1989).
13. J. Nelson, *ibid.* **172**, 31 (1977).
14. ______, T. Mast, G. Chanan, *ibid.* **1114**, 241 (1989).
15. R. N. Wilson, F. Franza, L. Noethe, *J. Mod. Opt.* **34**, 485 (1987).
16. R. N. Wilson, *Contemp. Phys.* **32** (no. 3), 157 (1991).
17. L. Noethe, *J. Mod. Opt.* **38**, 1043 (1991).
18. R. N. Wilson, F. Franza, L. Noethe, G. Andreoni, *ibid.*, p. 219.
19. T. Mast and J. Nelson, in *ESO Conf. Workshop Proc. 42*, M.-H. Ulrich, Ed. (European Southern Observatory, Garching, Germany, 1992), pp. 159–168.
20. D. G. Greenwood, *J. Opt. Soc. Am.* **67**, 390 (1977).
21. D. L. Fried, *ibid.* **72**, 52 (1982).
22. F. Chassat, G. Rousset, G. Primot, *Proc. SPIE* **1130**, 33 (1989).
23. F. Merkle and N. Hubin, *ibid.* **1542**, 283 (1991).
24. J. M. Beckers *Annu. Rev. Astron. Astrophys.*, in press.
25. D. P. Greenwood, *OSA Annual Meeting*, vol. 19 of *Technical Digest* (Optical Society of America, Washington, DC, 1992), pp. 220–222.
26. R. Q. Fugate, in (*19*), pp. 407–410.
27. L. E. Schmutz *et al.*, *Proc. SPIE* **179**, 76 (1979).
28. J. C. Fontanella, *J. Opt.* **16**, 257 (1985).
29. J. W. Hardy and M. Govern, *Proc. SPIE* **816**, 180 (1987).
30. F. Roddier, *Appl. Opt.* **27**, 1223 (1988).
31. N. Roddier, *Proc. SPIE* **1542**, 120 (1991).
32. F. Roddier, J. E. Graves, D. McKenna, M. J. Northcott, *ibid.*, p. 248.
33. F. Rigaut *et al.*, *Astron. Astrophys.* **259**, L57 (1992).
34. C. Boyer, V. Michau, G. Rousset, *Proc. SPIE* **1237**, 63 (1990).
35. J. Y. Wang and J. K. Markey, *J. Opt. Soc. Am.* **68**, 78 (1978).
36. E. Gendron, in *ESO Conf. Workshop Proc. 48*, F. Merkle, Ed. (European Southern Observatory, Garching, Germany, in press).
37. G. Rousset *et al.*, *Astron. Astrophys.* **230**, L29 (1990).
38. F. Rigaut *et al.*, *ibid.* **250**, 280 (1991).
39. N. Hubin *et al.*, *Proc. SPIE* **1780**, 87 (1992).
40. G. Rousset *et al.*, in (*36*).
41. J. E. Graves *et al.*, in (*25*), pp. 173–175.
42. D. S. Acton, *Appl. Opt.* **31**, 3161 (1992).
43. N. Hubin, F. Safa, R. Stopher, in (*36*).
44. R. Foy and A. Labeyrie, *Astron. Astrophys.* **152**, L29 (1985).
45. L. A. Thompson and C. S. Gardner, *Nature* **328**, 229 (1987).
46. C. A. Primmerman *et al.*, *ibid.* **353**, 141 (1991).
47. R. Q. Fugate *et al.*, *ibid.*, p. 144.
48. *Lincoln Lab. J.* **5**, 1 (1992).
49. D. G. Sandler *et al.*, in (*25*), pp. 216–217.
50. E. Kibblewhite, in *Laser Guide Star Adaptive Optics Workshop, Albuquerque, NM*, R. Q. Fugare, Ed. (1992), pp. 24–36.
51. R. Foy, *ibid.*, pp. 487–90.
52. M. Sichaud *et al.*, *ESO Conf. Workshop Proc. 30*, M.-H. Ulrich, Ed. (European Southern Observatory, Garching, Germany, 1988), pp. 705–714.
53. C. E. Max, in (*25*), pp. 204–206.
54. D. T. Gavel *et al.*, *ibid.*, pp. 207–209.
55. R. Angel, in (*36*).
56. E. Kibblewhite, in (*19*), pp. 425–35.
57. R. Foy *et al.*, *Proc. SPIE* **1114**, 174 (1989).
58. D. V. Murphy *et al.*, *Opt. Lett.* **16**, 1797 (1991).
59. F. Rigaut and E. Gendron, *Astron. Astrophys.* **261**, 677 (1992).
60. R. Foy *et al.*, in (*19*), pp. 437–441.
61. R. Foy *et al.*, in preparation.

62. The authors thank S. Milligan, who made corrections and pertinent remarks increasing the overall comprehensibility of this article. We wish to express our gratitude to R. Wilson for fruitful discussions during the preparation of this article.