Active and adaptive optics for the new generation of large telescopes

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Active and adaptive optics are techniques for improving the image quality of large astronomical telescopes. Active optics is concerned with correcting aberrations produced within the telescope and adaptive optics aims to correct distortions introduced by the Earth's atmosphere. In this paper we describe the principles behind these complimentary techniques in the context of the new generation of large optical telescopes. We discuss the relevant work in this field which is being pursued in India.

THE problems of building a very large telescope by conventional techniques are summarized by the following two points. Firstly the cost of a telescope is approximately proportional to its $(\text{size})^3$, and so financial constraints are very severe. Secondly there is no improvement in telescope resolution by increasing its size because of the distorting effects of the Earth's atmosphere (known as *seeing*, and visually observable as *twinkling*). Within the last decade new designs of telescopes have been developed and these new technologies are currently maturing. The new approaches to building large mirrors have involved ribbed honeycombed structures, thin flexible (meniscus) mirrors, and the use of multiple mirrors. A review of these is given by Angel[1]. Building larger mirrors will obviously enable the telescope to collect more light; however if the quality of the image is not good, be it through telescope aberrations or atmospheric seeing, then the full potential will not even be approached. Active and adaptive optics are real-time techniques for improving image quality by ensuring the precise shape of the primary mirror and the optical alignment, and by correcting for the effects of seeing.

It is important here to distinguish between two sorts of image sharpening techniques, namely *real-time* sharpening and *post-exposure* sharpening. The latter involves collecting all the data (photons) and then analysing them later using computer algorithms to produce high resolution images. Active and adaptive optics is, however, concerned with correcting the light using optical methods before it is recorded. This is an imperative requirement for non-imaging techniques such as spectroscopy. The main advantage of using real-time techniques over post-exposure sharpening is an improvement of signal to noise. If the resolution is improved, the photons collected by the telescope are imaged onto a smaller area and therefore the intensity increases. This is very important for astronomy where one is generally trying to observe very faint objects.

The basic approach to correct the various aberrations is the principle of phase conjugation, as shown in Figure 1. Introduction of distortion in the mirror at the correct place and by the correct amount can bring the suitable correction of the wavefront. It is important to note that one should be able to apply the correct amount of phase conjugate at the right place and if the situation is dynamic then also at the right time. Such a system has three basic components: a wavefront correction device, generally some kind of controllable mirror, a wavefront sensing device to determine the errors, and a control system to connect the two in a servo loop. This is shown schematically in Figure 2.

The review article by Hardy[2] gives an excellent account of the history of active and adaptive optics, describing the state of the art as it existed in 1970. Developments over the last two decades in adaptive optics are described in detail in a book by Tyson[3] and also reviewed by Babcock[4] and Beckers[5]. Recent developments in active optics are described by Wilson[6].

In this paper we explain the principles behind active and adaptive optics, and describe some currently operational devices. We conclude by discussing the latest trends and also the work which is being done in India

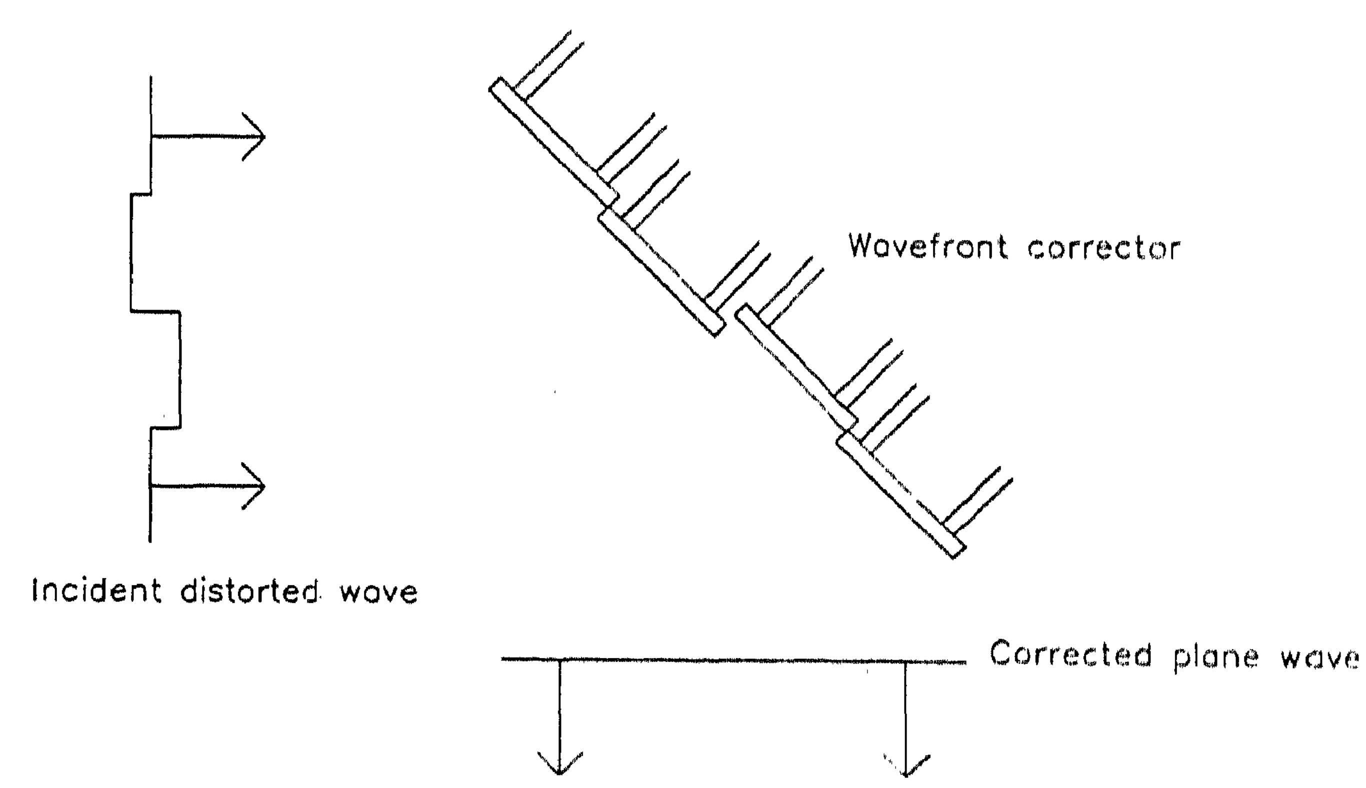

Figure 1. Principle of wavefront correction by controlling optical path length.

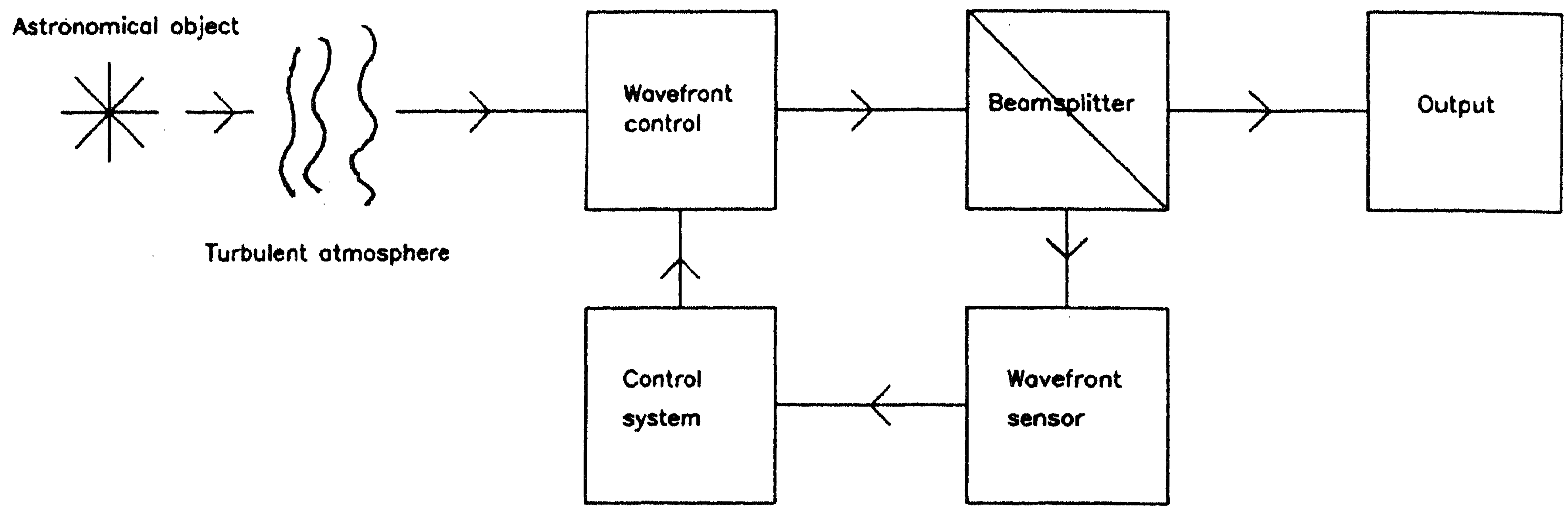

Figure 2. Schematic diagram of a real time wavefront correction system.

in this area. We use here the abbreviation 'AO' to refer to both adaptive and active optics (elsewhere in the literature 'AO' can mean adaptive optics and 'aO' can mean active optics).

Causes of aberration

Whilst observing through a ground-based telescope the light from a distant star is incident at the top of the atmosphere in the form of a plane wavefront. After the passage through the Earth's atmosphere the light is brought to a focus by the telescope optics. The ultimate resolution of the telescope is defined by the diffraction limit governed by the Rayleigh criterion given by equation (1),

$$\theta = 1.22\,(\lambda/D), \quad (1)$$

where λ is the wavelength and D the telescope (aperture) diameter. This performance is a theoretical limit, there are two main factors which degrade the image quality: (a) atmosphere and (b) telescope errors. Errors introduced by the telescope are normally low (temporal) frequency errors and the ones produced by the atmosphere are high frequency.

Atmospheric seeing

Small temperature fluctuations within the atmosphere (< 1°) produce fluctuations in the air density which in turn leads to fluctuations in the atmospheric refractive index. Thus light passing through the atmosphere which is initially a plane wave becomes corrugated and distorted, the magnitude of the distortions being of the order of a few visible wavelengths. In practice these distortions degrade the image so that the size of the actual image (known as the seeing disk) is given by

$$\theta_s = 1.22\,(\lambda/r_0), \quad (2)$$

where r_0 is called Fried's coherence parameter. It is the transverse distance across a distorted wavefront over which the rms phase fluctuations vary by 1 radian. Or, in other words, *for a telescope larger than about 10 cm, the resolution is independent of the aperture size and is limited by the seeing.* To complement r_0, the coherence time of seeing, τ_0 is defined as the time during which the rms phase fluctuations are 1 radian.

Seeing is an intrinsic property of the observing site and much care must be taken in choosing a suitable place. Good observing sites tend to be high peaks protruding from a relatively flat surrounding, for example Mauna Kea, Hawaii, or La Palma, the Canary Islands. Once a good site is selected then the air temperature and flow inside the telescope dome must also be carefully controlled to avoid *dome seeing*.

Sources of telescope aberrations

A large telescope weighs many tonnes and for perfect optical quality the primary mirror surface, the secondary mirror, and the alignment between the two and the focus must be accurate to sub-micron precision. This is obviously difficult, however when one considers that the whole structure must move around under the influence of gravity then it can be seen to be impossible.

Table 1 lists the factors causing degradation of image quality in telescopes and their corresponding bandpass. By correcting many of the errors shown, active optics can also reduce the required tolerances in actually building the telescope and therefore lowers construction costs.

Broadly speaking, 1–7 in Table 1 are low frequency errors (DC – 10^{-2} Hz), are addressed by active optics and high frequency errors (10^{-2}–10^{3} Hz) fall under adaptive correction. In practice there is some overlap. For example wind deformations will be corrected by

Table 1. Sources of image degradation in a telescope

Type of error		Source of error	Bandpass
Static	1.	Design and manufacture of optical components	DC.
Very long term	2.	Mechanical distortions of mirror and telescope structure (warping)	$< 10^{-6}$ Hz (years)
Long term	3.	Maintenance errors of mirror supports and structure	$< 10^{-5}$ Hz (weeks)
	4.	Thermal distortions	
		i. –mirrors	$< 10^{-4}$ Hz
		ii. –structure	$< 10^{-3}$ Hz
	5.	Errors due to flexure of telescope as it tracks	$< 10^{-3}$ Hz
	6.	Focussing errors	$< 10^{-3}$ Hz
Short term	7.	Wind deformation	$< 10^{-3}$–2 Hz
	8.	Tracking errors	5–10^{2} Hz
	9.	Seeing	
		i. –dome	10^{-3}–10^{2} Hz
		ii. –atmospheric	10^{-2}–10^{3} Hz

both active and adaptive optics.

Specifications of an adaptive optics system

The basic parameters describing an adaptive optics system are as follows: wavelength of light to be corrected; number of correction elements; speed of correction (bandwidth); required magnitude of guide star; and sky coverage.

Table 2 shows typical parameters for different wavelengths. r_0 is the spatial coherence (Fried's) parameter. For full wavefront correction, the individual correction elements must be of this scale. The number of required correction elements is then calculated by dividing the telescope area by the area corresponding to r_0. The timescales of correction are calculated by using the 'Taylor hypothesis'. This assumes that on the timescales of seeing the atmospheric refractive index, variations remain static and the changes occur because the air moves across the telescope aperture due to wind. The timescales are then just typical times for the air to move across the distance defined by r_0.

When light from a particular star is corrected, the light from a small area around it is also corrected. This is called the *isoplanatic patch.* Objects of astronomical interest are generally very faint, and so a nearby bright star must be used to provide enough signal for the system to operate. If the light from this *guide star* is sharpened then the light from objects within the isoplanatic patch is also sharpened.

The required brightness of the guide star is another important parameter. The wavefront sensing arm of the system must obviously provide detail about the wavefront shape on the appropriate spatial and temporal scales for correction. Therefore, in the visible range the guide star needs to be very bright. One can calculate the fraction of the whole sky that would be within the isoplanatic patch of a bright enough star. At wavelengths of 10 μm this will be almost 100%, whereas for visible wavelengths it is less than 1%. Fortunately a solution to this problem is under development, by creating an artificial star or beacon (see separate section).

Table 2. Adaptive optics parameters for an 8 m telescope at different wavelengths

Wavelength (λ), (μm)	0.5	2.2	5.0	10
$r_0 \propto \lambda^{5/6}$ (cm)	10	60	160	360
Number of elements for 8 m telescope	6400	180	12	4
Timescale of correction (ms)	6	35	95	220
Isoplanatic patch (arcseconds)	2.5	15	40	90

It can be seen that adaptive optics is considerably easier to implement for longer wavelengths, however there are larger gains to be made at shorter wavelengths because of the smaller diffraction limit.

Components of a wavefront correction system

As mentioned in the introduction, a system is made up of three main elements; sensing, control, and correction, which we will consider in turn.

The sensing and control components are common to both the active and adaptive systems. The sensor must be able to rapidly determine the wavefront shape in order to apply the necessary corrections to the relevant mirrors. Many sensing systems use the Shack–Hartmann technique, because of its simplicity. An array of lenses is placed in the sensing arm, each of which produces an image from part of the full telescope aperture. Local wavefront tilts cause the images to be displaced and so the tilts can be determined, as shown in Figure 3. These are described further in reference 12.

In general optical testing, interferometry is one of the most commonly used techniques and this has also been applied to the measurements of wavefronts in real time.

CCD is the most popular imaging detector in astronomy because of its high quantum efficiency (~ 85%); however up to now their long read-out time has limited their use in wavefront sensing. Recent technology has achieved kHz speeds by using small arrays and frame transfer techniques. Other new types of technology also include avalanche photodiodes and solid-state photomultipliers.

The main criterion that the control loop must satisfy

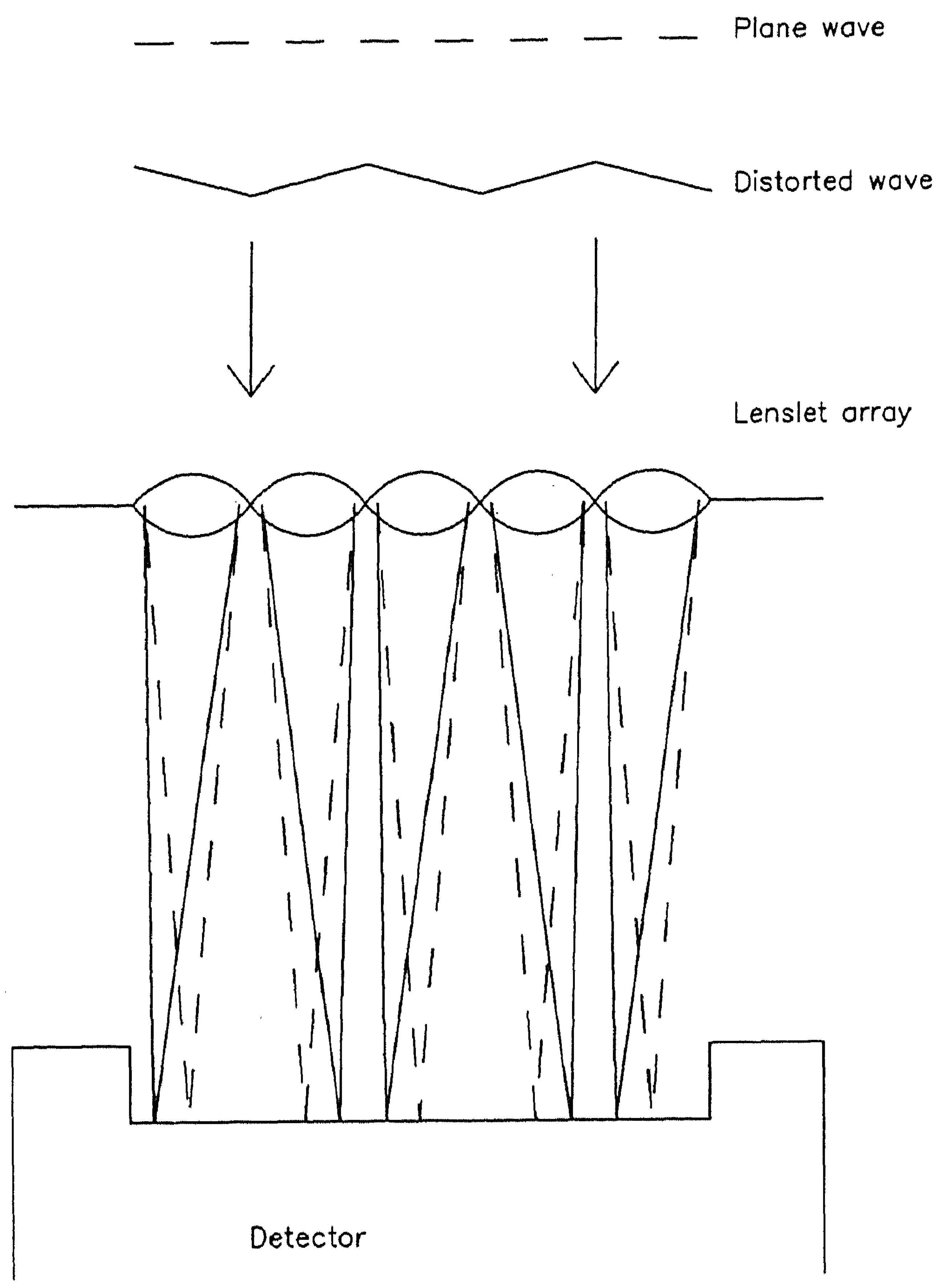

Figure 3. Sensing wavefront tilts using a Shack–Hartmann array of lenslets.

is that it is able to analyse the data from the wavefront sensor and then calculate the necessary corrections required for the adaptive mirrors in timescales much shorter than the atmospheric coherence time. In addition to applying on-line corrections in an active optics system, some corrections can be implemented using prior knowledge of the telescope performance. For example the telescope flexes as it points towards different parts of the sky, so the appropriate first-order corrections can be applied without any wavefront sensing.

The actual correction elements are different for adaptive and active optics. Active optics is concerned with correcting relatively large errors over long timescales. In this case it is the primary and secondary mirrors whose position and shape are controlled. Behind the primary mirror, which must be deformable (a meniscus mirror), is an array of actuators to transfer a driving force, from either a stepper motor, or from hydraulic or pneumatic supports. The secondary mirror is also controlled to eliminate defocus, lateral shifts, and tilts. In contrast, adaptive optics is concerned with the correction of relatively small errors (a few visible wavelengths) at high frequencies and so direct control of the primary mirror is unfeasible. Instead control is achieved by small adaptive mirrors which are placed downstream from the telescope focus. The mirror actuators employ an electro-mechanical effect, generally piezo-electricity to control the mirrors. Further descriptions of wavefront correction devices can be found in references 9 to 11.

A schematic diagram of a telescope system fitted with both adaptive and active optics is shown in Figure 4.

Current systems

In this section we outline three examples of systems currently in operation.

The new technology telescope (NTT), the first fully active telescope

NTT (operated by ESO at La Silla, Chile) was the first, and currently the only, telescope equipped with active optics, although many of the planned large telescopes will incorporate it.

A seeing monitor had previously tested the atmosphere and had frequently reported potential image quality which was better than results being obtained by existing telescopes at the site. In other words the telescopes were not seeing-limited, but aberration-limited. NTT was built in order to take advantage of good seeing conditions by controlling the 3.5 m primary and secondary mirrors actively with actuators, and it saw its first light in March 1989. Under good conditions the image size was measured to be 0.33 arcseconds. The best potential image quality (i.e in the absence of seeing) was calculated to be around 0.2 arcseconds. These impressive results have indicated that active optics is a feasible technology so that more ambitious projects may be undertaken for an 8 m class of telescope.

A complete description of the device is given by Wilson *et al*[13], and summarized in Wilson[6].

MARTINI, an adaptive optics system for use in the visible

MARTINI (*m*ultiple *a*perture *r*eal *t*ime *i*mage *n*ormalisation *i*nstrument) was designed and constructed at Durham University, U.K.[14–16]. This instrument is designed to correct visible wavelengths at the 4.2 m William Hershel Telescope (WHT) in the Canary Islands. WHT has a specially designed optics laboratory mounted at the Nasymth focus where MARTINI is mounted on an optical bench. The instrument utilizes the fact that there exists an optimum aperture size from the point of view of resolution, as described earlier. Downstream from the Nasymth focus an aperture mask produces 6 sub-apertures each of the optimum size (this can be changed depending on seeing conditions). Behind each mask there is an

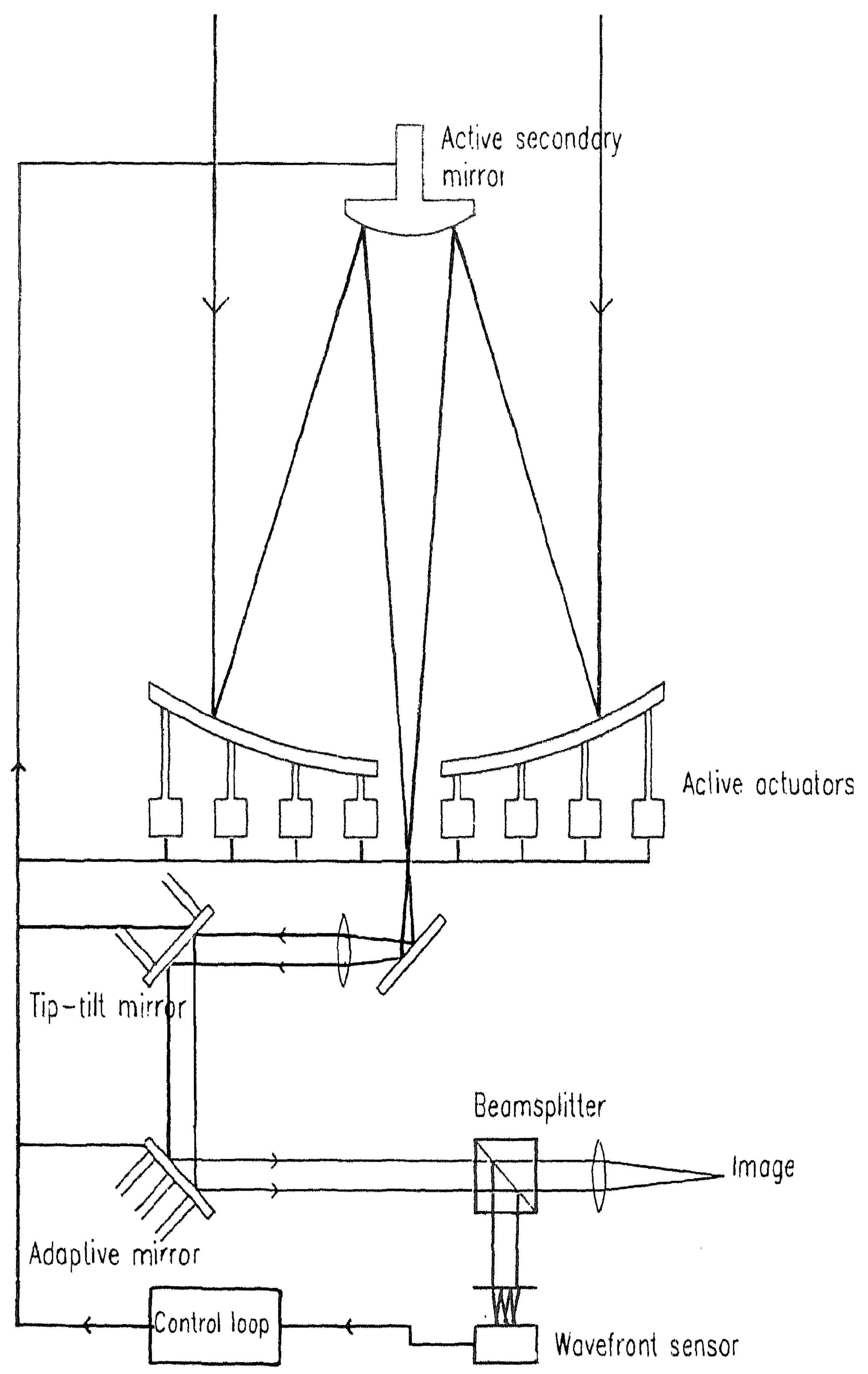

Figure 4. Schematic of a telescope system incorporating active and adaptive optics. Red denotes wavefront correction, blue denotes wavefront sensing, and green denotes the control loop.

adaptive mirror with 3 degrees of freedom to control the wavefront tilts (this is a zonal approach). The wavefront sensor is a segmented lens (a variant of the Shack–Hartmann method) which images onto an IPD (imaging photon detector). First results with MARTINI were obtained in 1989, and improvements in resolution by a factor of ~2 have been achieved. The system is now being refined and is being used for astronomical observations[17,18]. A 76 actuator mirror has been purchased and will be used to ensure coverage of the full telescope aperture.

COME – ON: an infrared adaptive optics system

A collaboration of several European institutions centred at the European Southern Observatory has developed an adaptive optics system for use in the infra-red. It is a two-stage correction system, whereby a single tip-tilt mirror removes the global wavefront tilt, and then a secondary deformable mirror with 19 actuators (modal approach) corrects for the higher order aberrations. The wavefront sensor is a Shack–Hartmann device. This group produced the first diffraction limited images (in the infra-red) using adaptive optics[19] at the 1.52 m telescope Observatoire de Haute-Provence (France). It has now been installed at the ESO 3.6 m telescope at La Silla, Chile. Current work involves up-grading the system to work at the ESO- VLT ('COME–ON PLUS'[20]). This will use an array of effectively 52 piezo actuators. Results of image sharpening with COME–ON are shown in Figure 5.

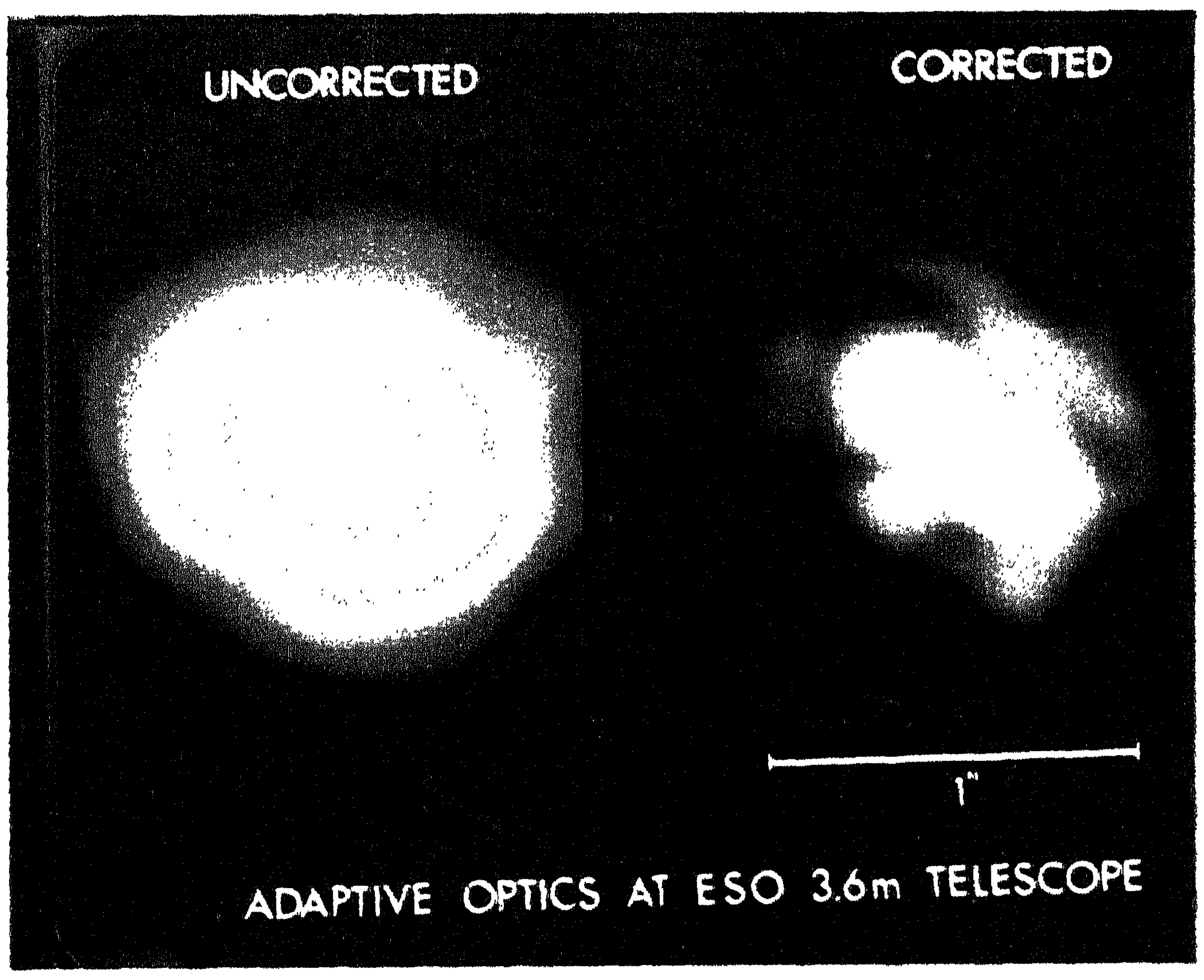

Figure 5. The photo illustrates the dramatic improvement in the image sharpness obtained using adaptive optics at the ESO 3.6 m telescope. The corrected image on the right reveals the double nature of star HR6658 (5.5 magnitude) observed in the infrared L-band (λ = 3.5 μm). The diameter of the uncorrected image is about 0.8 arcsec, corresponding to the seeing disk. The corrected image diameter is only 0.22 arcsec. The angular separation between the components is 0.38 arcsec. (Courtesy of Roy Wilson, European Southern Observatory.)

Future developments

The current period is an exciting one for adaptive optics because within the last 2 years the U.S. military has declassified some of its work in this field. They were interested in surveillance, and in laser beam transmission for communication and directed energy weapons systems. These fields involve the same basic problem of the transmission of electromagnetic fields through a turbulent medium. As mentioned earlier, a bright guide star is needed in order that there is enough signal to operate the AO system, and this is one development to come from the defence research. This is especially a problem in the visible and if natural guide stars are used then this very severely limits the usefulness of an adaptive optics system. A solution to this is to create an artificial guide star by focussing a laser beam in the lower atmosphere (between 4–10 km) to produce a beacon by Rayleigh scattering. Alternatively a guide star of higher altitude (90–100 km) can be produced by using resonant scattering from sodium atoms (see Collins[21] and references therein).

AO in India

Requirements

The following are two quotes from a conference[22] held in August 1989 in which India's astronomers discussed astronomical facilities which would be required in the future. During these meetings a consensus emerged that the Indian astronomical community needs to add a larger size of telescope to its current facilities.

> There is a clear need for setting up a most modern large sized optical telescope in the best possible site in the country...

> While planning for large optical telescopes in the 90's it is important that all options including new technology telescopes, built around thin mirrors, incorporating active and adaptive optics, multi-mirror technologies, etc. are carefully examined....

It was felt that a 4 to 5 m aperture telescope would be a reasonable quantum jump in view of the recent completion of the 2.34 m Vainu Bappu Telescope. The working group has thus recommended the following as the basis of the detailed design concept in its preliminary report.

(a) The weight of the primary mirror must be as low as possible. A thin meniscus glass blank could be used for reducing the weight of the primary mirror.

(b) The availability of a 4.2 m meniscus glass blank from Schott, Germany can, to a certain extent, dictate the size of the telescope to be 4.2 m. The primary mirror focal ratio may be chosen as low as $f/2$, and a Ritchey–Chrétien $f/8$ cassegrain secondary.

(c) It is planned that this telescope will have active and adaptive optics correction systems to achieve high quality, near diffraction limited images. The methods of active and adaptive correction described in earlier sections will have to be incorporated in the detailed design report of the telescope.

(d) Servo drives and electronics with the minimum nossible thermal load and flexible, user-friendly control stems are essential features of the basic design concept.

) Altitude-azimuth mounting, rotating dome and build-g and other concepts of the New Technology Telescope ve to be adopted to keep the costs low whilst offering ›erational conveniences.

It is planned to use the telescope at both visible and near infrared wavelengths. It is therefore imperative that the telescope site should meet the requirements of low water vapour, in addition to a large number of cloud-free nights with good atmospheric seeing. Higher mountain sites in the Himalaya may offer a suitable choice. Site testing has been undertaken[23].

The working group is likely to continue work on the comprehensive feasibility report and associated site survey work.

Thus work in adaptive and active optics is of current importance to ensure optimum results and performance from the large investment involved in building a telescope.

Current work in India

There are many parallel developments taking place in the country with regards to techniques for optical metrology and instrument control which can be utilized for the development of AO systems. As well as specific interest for the large telescope project some others are mentioned below.

A method of wavefront sensing for AO has been developed at the Indian Institute of Astrophysics[24]. It involves the use of two crossed Babinet compensators to produce a simple interferometric device and can be used effectively with broad spectral bandwidths in real time using digital techniques.

Groups at the Raman Research Institute (RRI), Bangalore, and Udaipur Solar Observatory (USO) are currently building simple first-order adaptive optics systems (a 'star tracker') in order to remove the wavefront tilt across an aperture. RRI's interest lies in stellar interferometry and USO's is in removing image motion from solar images. Both these require only small apertures and so first-order correction will provide significant gains.

Work has been in progress to investigate replacing the mechanically-driven mirrors in adaptive optics systems with electrically controllable liquid crystal (LC) cells, at the RRI and Durham University, U.K.[25–27]

Conclusions

The short-term aim of adaptive and active optics is to produce diffraction-limited images with large (4–8 m) telescopes in the near infrared (2.2 μm), and to make these common user instruments. In the future the goal is to produce diffraction-limited visible images. The potential addition to our knowledge of the universe that could be made with such devices means that AO is currently one of the most exciting areas within astronomy.

1. Angel, R., *Q. J. R. Astr. Soc.*, 1990, **31**, 141–152.
2. Hardy, J. W., *Proc. IEEE*, 1978, **66**, 6.

3. Tyson, R. K., *Principles of Adaptive Optics*, Academic Press, New York, 1991.
4. Babcock, H. W., *Science*, 1990, **249**, 253–257.
5. Beckers, J. M., 'Adaptive optics for astronomy: principles, performance and applications'. To be published in *Annu. Rev. Astron. Astrophys.*, vol. **31**, 1993, Also ESO preprint no. 877.
6. Wilson, R. N., *Contemp. Phys.*, 1991, **32**, 157–171.
7. Fried, D. L., *J. Opt. Soc. Am.*, 1965, **55**, 1427.
8. Noll, R. J., *J. Opt. Soc. Am.*, 1976, **66**, 207–211.
9. *Opt. Eng.*, 1990, **29**(10), Special issue on adaptive optical components.
10. *Opt. Eng.*, 1990, **29**(11), Special issue on active optical components.
11. Ealey, M. A. (ed.), *Proceedings SPIE 1543*, San Diago, 1992, vols. 1 and 2.
12. Artzber. G., *Opt. Eng.*, 1992, **31**, 1311–1322, and references therein.
13. Wilson, R. N., Franza, F., Noethe, L., and Andreoni. G., *J. Mod. Opt.*, 1991, **38**, 219, and references therein.
14. Doel, A. P., Dunlop, C. N., Major, J. V., Myers, R. M. and Sharples, R. M., in *Active and Adaptive Optical Components* (ed. Ealey, M. A.), SPIE 1543, 1991, 319–327.
15. Doel, A. P., Dunlop, C. N., Major, J. V., Myers, R. M., Sharples, R. M., in *Active and Adaptive Optical Components* (ed. Ealey, M. A), SPIE 1543, 1991, 1543 pp. 472–478.
16. Doel, A. P., Dunlop, C. N., Major, J. V., Myers, R. M., Sharples, R. M., in *Proc. ESO Conference on Progress in Telescope and Instrumentation Technologies* (ed. Ulrich, M. H.), 1992.
17. Tanvir, N. R., Shanks, T., Major, J. V., Doel, A. P., Dunlop, C. N., Myers, R. M., Redfern, R. M., O'Kane, P. and Devaney, M. N., *Mon. Not. R. Astr. Soc.*, 1991, **253**, 21–24.
18. Shanks, T., Tanvir, N. R., Major, J. V., Doel, A. P., Dunlop, C. N., Myers, R. M., Redfern, R. M., O'Kane, P. and Devaney, M. N., *Mon. Not. R. Astr. Soc.*, 1991, **256**, 29–31.
19. Rousset, G., Fontanella, J. C., Kern, P., Léna, P. and Gigan, P., *Astron. Astrophys.*, 1990, **230**, L290–L232.
20. Rousset, G., Madec, P. Y., Beuzit, J. L., Çuby, J. G. and Gigan, P., in *Proc. ESO Conference on Progress in Telescope and Instrumentation Technologies* (ed. Ulrich, M. H.), 1992.
21. Collins, G. P., *Phys. Today*, 1992 (Feb.), 17–21, and references therein.
22. Parthasarathy, M. (ed.), in *Proc. Natl. Large Telescope Workshop held at the Indian Institute of Astrophysics, Bangalore*, October 1989.
23. Bisht, R. S., Iyenger, K. V. K., and Tandon, S. N., *Pub. Astr. Soc. Pac.*, 1990, **102**, 599–603.
24. Saxena, A. K. and Lancelot, J. P., *Wavefront Sensing using Two crossed Babinet Compensators.*, In SPIE 1121, pp. 42–45, 1989 and references therein.
25. Love, Gordon, D., *Appl. Opt.*, 1993, **32**, 2222–2223.
26. Love, Gordon, Myers, Richard, Purvis, Alan, and Sharples, Ray, in *ICO-16 Conference on Active and Adaptive Optics, Garching*, August 1993, European Southern Observatory, 1993.
27. Purvis, Alan, Bailey, Nick, Love, Gordon, D. and Major, John V., in *Current Developments in Optical Design and Optical Engineering III, Proc. Soc. Photo-Opt. Instrum. Eng.*, 2000, July 1993.

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RESEARCH ARTICLES

Appulses of faint stars by fragments of Comet Shoemaker–Levy 9

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Geocentric circumstances of stellar occultations by coma around the fragments of the split comet Shoemaker-Levy 9 are presented. Estimation of the extinction of starlight during its passage in the vicinity of the fragment (an appulse) will help in studying the density of dust in this region. A method to revise the predictions using corrections to the cometary coordinates is suggested.

COMBES *et al.* first pointed out that observations of stellar occultations by comets can lead to measurement of density of dust in comae without any assumption of their albedo[1]. Larson and A'Hearn[2] and Lechacheux *et al.*[3] have reported results of cometary occultations and indicated that this technique could be exploited as a powerful tool in cometary research. Much interest now centres in studying the nature of the fragments of comet Shoemaker–Levy 9 (S–L 9) and its dusty environment. This object was discovered by Shoemaker *et al.*[4] as a dense linear bar. Subsequent observations by other groups revealed several fragments[4,5]. Jewitt *et al.* identified and numbered 21 fragments[6]. Recent computations by Marsden[7] indicate that the original comet was disrupted into these fragments during its last close encounter with Jupiter on July 7.8, 1992. Observations by the Hubble Space Telescope (HST) of S–L 9 during July 1993 indicated that each nucleus is surrounded by a roughly spherical