ESO - TP - 54

Progress in High Resolution Astronomical Imaging Including Active and Adaptive Optics[1]

Jacques M. Beckers

European Southern Observatory
D-85748 Garching bei München, Germany

ABSTRACT

In this paper I review shortly the status of high angular resolution imaging with astronomical telescopes and arrays of telescopes. Emphasis is given on the topics to be discussed in the Satellite Meeting to this conference on "Active and Adaptive Optics" in Garching, Germany.

1. INTRODUCTION

As implied by their name, astronomical telescopes are devices which collect as much radiation from astronomical (stellar) objects and put it in as sharp (small) an image as possible. Both collecting area and angular resolution play a role. The relative merit of these two functions has changed over the years in optical astronomy, with the angular resolution initially dominating and then, as the atmospheric seeing limit was reached, the collecting area and detection efficiency becoming the most important factor. Therefore it is the habit these days to express the quality of a telescope by its (collecting) diameter rather than by its angular resolution. With the introduction of techniques which overcome the limits set by atmospheric seeing, the emphasis is changing back to angular resolution. This time, however, it is set by the diffraction limit of the telescope so that both angular resolution and collecting power of a telescope will be determined by its diameter. Both telescope functions will therefore go hand-in-hand.

The 240 cm diameter Hubble Space Telescope has overcome the seeing limit by locating it above the earth atmosphere. It is a radical way of solving the atmospheric seeing problems. It is expensive and is almost certainly not affordable for modern 8 - 10 meter diameter telescopes. Its access for instrument modifications and changes is also restricted. Except for wavelengths inaccessible from the ground, astronomers and military programs have therefore been developing techniques which makes diffraction limited imaging possible with earth-based telescopes. One of these, speckle image reconstruction, has been very successful in giving diffraction limited images. The most powerful and promising technique for all astronomical applications is, however, the one using adaptive optics. That is because, for an unresolved image, it puts most of the collected photons in as small an image as possible which benefits both in discriminating against the sky background, in doing high spectral and spatial resolution spectroscopy and in doing interferometric imaging with telescope arrays. For resolved objects adaptive optics allows imaging without the complications of image reconstruction techniques applied to short exposure, noisy speckled images. It therefore extends diffraction limited imaging to much fainter and more complex objects.

In this progress report I will summarize the present status of the high angular resolution imaging with ground based optical telescopes, with an emphasis on astronomical adaptive optics developments. The optical spectrum domain extends from 0.3 μm through 25 μm, interrupted only by a number of wavelengths bands in the infrared in which atmospheric absorption prevents radiation from reaching the earth surface.

2. LIMITATIONS IMPOSED BY ATMOSPHERIC SEEING

Refractive index variations in the earth atmosphere due to temperature/density variations cause astronomical images to become unsharp ("seeing"). Even with the availability of adaptive optics it is important to locate telescopes on sites where seeing effects are minimal since "good seeing" reduces the complexity, and hence the cost, of adaptive optics in addition to extending the sky coverage, and the wavelength and magnitude range. Whereas seeing of 1 arcsec (= full width at half maximum, or FWHM, of the point-spread-function) was

[1] Invited lecture at the 16th meeting of the International Commission for Optics, August 9 - 13, 1993, Budapest.

until recently considered to be exceptionally good, astronomers are now finding that by proper choice of site and by careful management of site, dome and enclosure seeing, 0.5 arcsec seeing is not unusual, with better images being available occasionally.

The shape of the atmospheric wavefront disturbance is an important quantity in wavefront reconstruction techniques in astronomy. For telescopes it is generally taken to be that resulting from a Kolmogorov turbulence spectrum. It gives a "Wavefront Structure Function" (= wavefront variance as function of distance) which depends only on one parameter, the so-called Fried parameter r_o. For telescopes with a diameter $D < r_o$ images are diffraction limited, for $D > r_o$ not. For 0.5 arcsec images and 0.5 μm wavelength r_o equals 20 cm. It decreases linearly with image quality and increases with wavelength proportionally to $\lambda^{1.2}$.

3. LIMITATIONS IMPOSED BY TELESCOPES

With inherent atmospheric image qualities as good as 0.5 arcsec and better, very high demands are placed on the optical and mechanical qualities of astronomical telescopes to maintain this inherent site quality. Modern telescopes like the two 10 meter Keck telescopes and the four ESO 8 meter VLT telescopes are therefore designed to give image qualities by themselves of $\approx$ 0.2 arcsec FWHM. A number of telescope imperfections contribute to this, like : (i) tracking errors, (ii) mechanical flexure of the telescope structure supporting the optical components resulting in misalignment and aberrations of the optics, (iii) deviations from the perfect optical figure resulting from polishing errors, mirror support and thermal inhomogeneities in the mirror blanks, and (iv) seeing generated by the telescope itself by eg a primary mirror temperature being higher than that of the ambient air surrounding it.

The ESO New Technology Telescope (NTT) incorporates a technique called "Active Optics" which removed a number of these imperfections by controlling the shape of the rather thin primary mirror of the telescope[1]. A number of actuators in the mirror support adjusts its shape until the mirror figure, as measured by a Hartmann-Shack wavefront sensor using a stellar image in the telescope field-of-view, was optimum. This correction is done with a time constant of a few minutes, so that only slow tracking errors, mechanical flexure effects, mirror support and large scale (> actuator spacing) optical figure errors are removed. This has resulted in a very good telescope image quality, in which only fast tracking errors, small scale optical figure errors and mirror seeing remain to limit the telescope image quality. Active mirror supports are now being incorporated in all 8 to 10 meter telescopes. It is an essential ingredient in the achievement of the 0.2 arcsec FWHM image quality.

4. ADAPTIVE OPTICS

Adaptive optics is very similar to active optics instead that it works much faster, in the millisecond range, so that not only the slowly changing telescope wavefront disturbances are removed, but also the rapidly changing atmospheric variations. The concept to use adaptive optics for compensating atmospheric seeing originates with Horace W. Babcock in 1953[2]. Although that paper deals with its application to astronomical imaging at visible wavelengths, it was the first description of a much broader discipline which was to find its application to military, laser power, medical (ophthalmology), and probably other applications. The Babcock paper is quite remarkable in its completeness. In addition to describing the concept (Figure 1), it suggests a way of measuring the atmospheric wavefront distortions, proposes a concept for the adaptive mirror, it describes the small isoplanatic patch size (with a diameter $2\theta_o$ of "a few seconds of arc") over which the image will be corrected, the need for high temporal resolution (τ_o) and the consequent limitation to stars brighter than $m_{Vlimit} = 6.3$ for wave-front sensing. In a recent review paper I describe the present state of astronomical adaptive optics[3].

Atmospheric wavefront distortions, when expressed in linear units, are almost invariant with wavelength. Most astronomical adaptive optics systems therefore are "polychromatic" : the wavefront distortions, or their tilt or curvature, are measured in one wavelength optimized for wavefront assessment (generally in visible), the corrected image is observed at other (generally longer, infrared) wavelengths. The parameters of adaptive optics system ($r_o \approx$ the required spatial resolution, τ_o, m_{Vlimit}, and θ_o) vary rapidly with wavelength (see Table 1).

Table 1 Typical variation of adaptive optics parameters with wavelength and the resulting sky coverage[3]

Spectral Band	λ (μm)	r_o (cm)	τ_o (sec)	m_{Vlim}	θ_o (arcsec)	Sky Coverage (%)
U	0.365	9.0	.009	7.4	1.2	1.8 E-5
B	0.44	11.4	.011	8.2	1.5	6.1 E-5
V	0.55	14.9	.015	9.0	1.9	2.6 E-4
R	0.70	20.0	.020	10.0	2.6	0.0013
I	0.90	27.0	.027	11.0	3.5	0.006
J	1.25	40	.040	12.2	5.1	0.046
H	1.62	55	.055	13.3	7.0	0.22
K	2.2	79	.079	14.4	10.1	1.32
L	3.4	133	.133	16.2	17.0	14.5
M	5.0	210	.21	17.7	27.0	71
N	10	500	.50	20.4	64	100

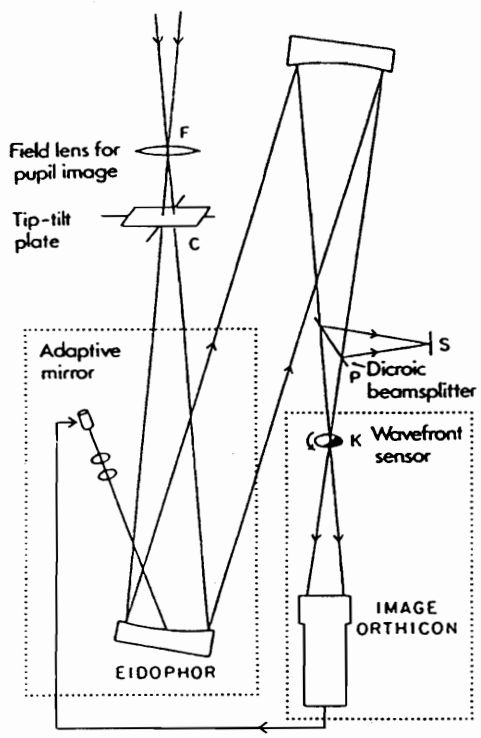

Figure 1 Adaptive optics concept as originally proposed by Babcock. Although the hardware used is different in today's systems, the principle remains unchanged. F images the entrance pupil onto the adaptive mirror (in this case the Eidophor). The shape of the adaptive mirror is servo controlled by a wave-front sensor (in this case a rotating knife edge device K) which follows a beamsplitter P which sends the other part of the light to the astronomer S. The tip-tilt plate C removes the overall image motion (adapted from Babcock[2]).

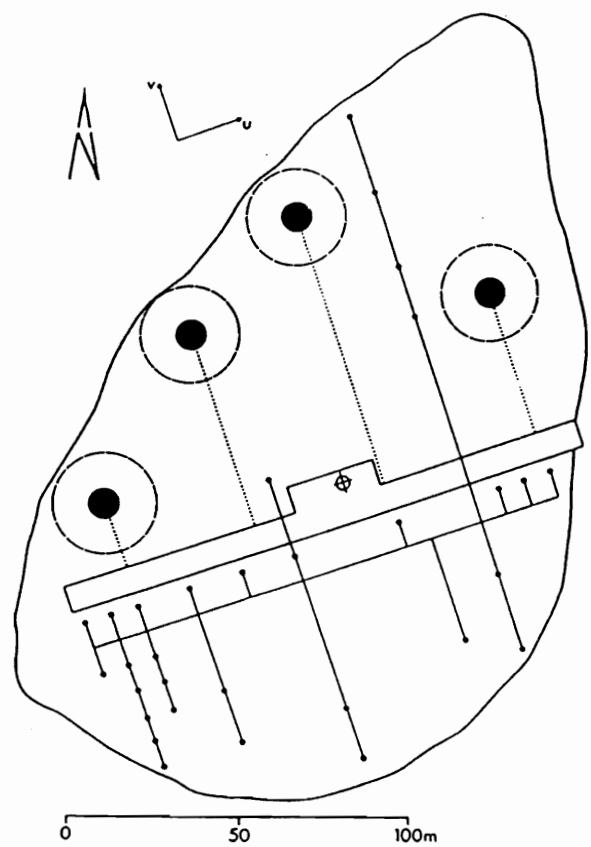

Figure 2 Layout of the VLTI on Cerro Paranal. The large filled circles represent the four fixed 8 meter telescopes, the small circles the 30 stations for the mobile 1.8 meter telescopes. The location of these stations has been chosen to allow optimum imaging either with the 1.8 meter telescopes by themselves or in combination with the 8 meter telescopes.

Table 2 Functioning Astronomical Adaptive Optics Systems (LE = long exposure, SE = short exposure; LGS = laser guide star).

Location	Telescope	Nr. Elements or Actuators	λ (μm)	Strehl Ratio (bright star)	FWHM (arcsec)	Faintest Star Used for Wavefront Sensing
ESO/France						
(COME-ON)	3.6^m (La Silla)	19	3.9 (L)	85 %	0.21	
			2.2 (K)	65 %	0.13	$11.5(m_V);1.6(m_K)$
			1.7 (H)	45 %	0.11	
			1.2 (J)	10 %	0.13	
(COME-ON+)	3.6^m (La Silla)	52	1.2 (J)	TBD	0.106	
U. Hawaii	3.6^m (CFHT)	12	.85 (I)	10 %	0.08	Arcturus
Lincoln L. (SWAT)	0.6^m (AMOS)	241	.5 (B)	37 % (SE)	0.2	LGS, Arcturus
Lockheed/NSO	0.63^m (SPVT)	19	.48 (B)	?	?	Sun
Mt. Wilson/ACE	1.52^m	69	.7 (R)	?	0.125	βDEL
USAF/SOR	1.5^m	241	.88 (I)	25 % (LE)	0.18	Arcturus
				64 % (SE)	0.13	Arcturus
				48 % (SE)	0.13	LGS
Univ. Arizona	6.8^m (MMT)	6	2.2 (K)	? (LE)	0.08	γDRA

Because of the decreased demands placed on adaptive optics systems (fewer adaptive elements, longer time constant, brighter sensing stars) and the much larger sky coverage, present astronomical adaptive optics systems emphasize longer wavelengths. Only in the past few years have a number of astronomical systems become operational. Table 2 summarizes those for which there are published results. It is likely to be out of date by the time this paper is published because of the rapidly changing status of the subject. In terms of performance of the systems, the most important characteristics are the Strehl ratio and the faintest object which can be used for wavefront sensing. The FWHM is of less significance as a performance parameter since the point-spread-function of a partial adaptive optics system consists of a combination of a narrow Airy disk profile and a broad profile with a width comparable to the original seeing disk. The fraction of energy in the Airy profile is close to the Strehl ratio, but, since it is much narrower than the broad profile, the FWHM is determined by the Airy profile making it almost independent of the Strehl ratio, even for very small values[3].

Table 3 Published Properties of Lasers used for Laser Guide Star Generation on the Mesospheric Sodium Layer.

Authors	Pulse Length (μsec)	Rate (Hz)	Duty Cycle (%)	Energy per Pulse (J)	Average Power (W)	Power in Pulse (W)	Predicted Stellar Magnitude[a] (V)
Thompson et al.	2.0	7.5	.0015	.020	0.15	10 000	14
Jeys et al.	0.1	1000	.01	.0003	0.3	3 000	12
Humphreys et al.	4.0	20	.008	.12	2.4	30 000	12
Max et al., Gavel et al.	0.8	26000	2	.07	$\geq$100	$\geq$5000	$\approx$6
Ultimate Limit (CW laser, Na layer saturation)			100		5 000+	5 000+	2

[a] Assumes 2×10^9 Na atoms/cm^2 in sodium layer and laser guide star image diameter of 50 cm.

Table 2 lists in column 7 two systems in which laser guide stars (or "laser beacons") have been used for wavefront sensing. Laser guide stars (LGSs) are used to overcome the severe sky coverage limitation resulting from the use of natural stars (see Table 1). They are created by Rayleigh scattering of laser radiation off molecules and aerosols in the high (10 - 15 km) atmosphere or by resonance scattering off the 90 km height layer of neutral sodium atoms. The LGSs used so far rely on Rayleigh scattering. It is anticipated that Na-LGSs will be in use shortly. They are superior to Rayleigh LGSs because of their greater distance from the telescope so that the differences in light path between the LGS and the astronomical object is minimized. Table 3 summarizes the properties of Na-LGSs so far achieved.

Laser guide stars are likely to play a major role in astronomical adaptive optics. There are a number of problems to be solved with their use, specifically the so-called "cone or focus anisoplanatism" effect caused by the LGS's finite distance, the "tilt determination problem" caused by the motion of the LGS due to the bending of the light in the up-going beam, and the "perspective elongation effect" due to the thickness of the sodium layer when the laser is placed at some distance away from the telescope. Details on the use of LGSs in telescopes and observatories can be found in Beckers[3].

5. INTERFEROMETRIC IMAGING

Even with the use of adaptive optics, astronomical telescopes will be limited in angular resolution by their diameter. The largest telescopes, with diameters of 8 to 10 meters, presently in existence or being planned, approach probably the limit of what can be achieved in single mirror telescopes. As happened in radio astronomy a few decades ago, optical astronomy is therefore relying on interferometric imaging with arrays of telescopes to achieve higher resolution. Major efforts are presently under way to implement interferometric imaging in optical astronomy. Interferometric arrays are in operation in Australia (Culgoora), England (Cambridge), France (CERGA) and in the USA (Mt Wilson, MMT). Others are under construction or in advanced planning stages, in Europe (the VLT Interferometer, or VLTI) and in the USA (Mt. Hopkins, Anderson Mesa, the CHARA array, the Keck Interferometric Array or KIA). Both the VLTI and the KIA involve the use of large 8 to 10 meter telescope to achieve the highest possible sensitivity. To do so optimally these telescopes will be equipped with adaptive optics. Figure 2 shows the layout of the VLTI. It will have a maximum baseline of 130 meter for the 8 meter telescopes only, and 200 meter for the full array which includes a minimum of three 1.8 meter diameter telescopes.

6. OTHER METHODS FOR HIGH RESOLUTION IMAGING

Even with interferometric arrays angular resolutions will be probably be limited to milli-arcsec levels because of atmospheric and possibly physical limitations. Interferometers in space or even on the moon have been proposed to remove these limitations. Even without them higher angular resolutions of stellar surfaces can be achieved by using the temporal photometric and spectroscopic variations associated with the stellar rotation to infer stellar surface structure. Differential interferometry in different colors or spectral positions can also give information at the micro-arcsec level as can careful astrometric measures of eg binary stars.

7. REFERENCES

1. R.N. Wilson, F. Franza and L. Noethe, "Active Optics : I A System for Optimizing the Optical Quality and Reducing the Costs of Large Telescopes," *J. of Modern Optics* **34**, 485 - 509, 1987.
2. H.W. Babcock, "The Possibility of Compensating Astronomical Seeing," *Publ. Astr. Soc. Pacific* **65**, 229 - 236. 1953
3. J.M. Beckers, "Adaptive Optics for Astronomy : Principles, Performance and Applications," *Ann. Rev. Astron. & Astrophys.* **31**, 1993, in press = ESO Scientific Preprint No. 877.