Adaptive optics at the WHT

C.R. Benn [a]

[a] *Isaac Newton Group of Telescopes, Apartado 321, 38700 Santa Cruz de La Palma, Spain*

Abstract

The WHT is unusually well-placed for exploitation of adaptive-optics (AO) technology. The site seeing is excellent (median 0.7 arcsec), dome seeing is negligible, and preliminary studies indicate that most of the atmospheric seeing originates in a well-defined layer at low altitude, which bodes well for future laser-guide-star AO. The Durham group have built up extensive experience with natural-guide-star adaptive-optics experiments at the GHRIL Nasmyth focus, and the NAOMI common-user AO facility is due to be commissioned at this focus early in 2000. NAOMI will provide near-diffraction-limited imaging in the IR (Strehl $\sim$ 0.6, FWHM $\sim$ 0.15 arcsec in K) and is expected to give significant correction in the optical (poorer Strehl, but similar FWHM). NAOMI will perform better at short wavelengths than AO systems on other telescopes, and observers will require instrumentation that can exploit this crucial advantage.

Key words: WHT; adaptive optics; high resolution imaging

1 What is adaptive optics?

'Active optics' and 'Adaptive optics' improve image quality by correcting distortions imposed on the wavefront during its passage through the atmosphere and the telescope. 'Active optics' corrects for slow ($<\sim$ 0.01 Hz), low-order distortions, such as those caused by sagging of optics when the telescope is tipped.

Adaptive optics (AO) (Hardy 1994, Beckers 1993, Wilson & Jenkins 1996) improve seeing by ironing out some of the wrinkling of the wavefront caused by passage through turbulent layers in the atmosphere. Typically, the wavefront is corrected by making independent tip, tilt and piston movements to each of $\sim$ 10 - 100 elements of a deformable mirror in the collimated light beam, at $\sim$ 100 - 1000 Hz. The corrections required are obtained by analysing the wavefront from a bright star close on the sky to the object of interest, usually using a Shack-Hartmann wavefront sensor:

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                                            |-> science camera (IR)
  starlight -> deformable -> dichroic -|
                mirror                      |-> wavefront sensor (optical)
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The guide star must be bright enough for it to be detected in a fraction of a second using light gathered by one ($\sim r_0$-sized) sub-aperture, i.e. $m_{GS} <\sim 14$, with little dependence on telescope diameter, but depending strongly on the quality of correction required, and the local atmospheric conditions. The guide star must lie close enough to the target that the wavefronts from star and target suffer similar distortions. This 'isoplanatic radius', typically < 1 arcmin in the IR ($\propto \lambda^{6/5}$), determines sky coverage for a given AO system.

The quality of the seeing is parametrised by the Fried parameter r_0, $\approx$ the diameter of a telescope whose diffraction-limited resolution is similar to the seeing. $r_0 = 20$ cm yields optical seeing ~ 0.5 arcsec. $r_0 \propto \lambda^{6/5}$. For a telescope with diameter $D < r_0$, diffraction dominates. For $D \sim r_0$, image motion dominates (maximum gain for tip-tilt). For $D > 4r_0$, speckle dominates.

The quality of the correction is determined mainly by r_0, m_{GS} and the bandwidth of the AO system. This quality is usually characterised by the Strehl ratio of the resulting psf = (corrected peak intensity) / (unaberrated, i.e. diffraction-limited, peak intensity), maximum value 1.0 FWHM can be a misleading measure, because partial correction (e.g. tip-tilt only) may yield an image with a narrow core superimposed on a diffuse plateau of emission, the latter including most of the light.

With natural guide stars, and typical isoplanatic radii, sky coverage is $\sim 10\%$ in K and $\sim 0.5\%$ in V. The exact numbers depend strongly on atmospheric conditions and acceptable Strehl, and on galactic latitude (beware of values quoted out of context!). An artificial guide star, created by laser illumination of the mesospheric Na layer ~ 100 km up, allows observing anywhere on the sky. A laser guide star cannot be used to measure the tip-tilt correction (because of the symmetry of the path up and down), so a natural guide star is still needed for this. However, the radius over which guide stars can be used for tip-tilt, the isokinetic radius, is $>>$ the isoplanatic radius. No astronomical observatory yet has an effective laser-guide-star system, although several are at the prototype stage.

Compared with HST, ground-based AO can deliver better resolution and larger collecting area, but the dynamic range is poorer.

2 Science drivers

The potential of an advance in astronomical technology is often judged by how much it enlarges the observational parameter space. The range of measured optical angular diameters θ (Fig. 1) is small compared to say, the range of wavelengths used by astronomers, or the range of measured optical intensities (both > 10 decades). Thus, in terms of expanding the observational parameter space, an improvement of a decade in angular resolution (1 arcsec $\rightarrow \sim 0.1$ arcsec) is substantial. Fig. 1 also suggests that an AO system, like a large new telescope, will find application in many different areas, and this is reflected in the comparable amounts of space devoted in AO science cases to solar-system, stellar and extragalactic topics.

Several AO systems are now up and running. What are they being used for? In the years 1993, 94, 95, 96, 97 and 98, the numbers of AO-science papers published were 3, 2, 5, 8, 24 and 19 [1], indicating a fast-growing field. The titles of the 19 AO-science publications in 1998 cover, as expected, an eclectic range of topics: comets, asteroids, HII regions, circumstellar disks, dwarf galaxies, AGN and starburst galaxies, QSO hosts and gravitational lenses.

The use of AO to study a wide range of physical phenomena suggests that AO systems will require general-purpose science cameras i.e. both imaging devices and spectrographs operating over the full range of wavelengths at which there is appreciable correction.

3 What are other observatories doing?

AO systems are being built for most of the ≈ 29 operating or planned optical telescopes with primary-mirror diameter > 3.5 m. The Calar Alto 3.5-m, CFHT, ESO 3.6-m and Keck II all have functioning AO systems.

CFHT's AO system, PUEO, has been operating successfully since 1996, and comprises a 19-element deformable mirror operating at 1 kHz (suited to the weak, fast turbulence over Mauna Kea), feeding an IR camera and an integral-field spectrograph. Recently, AO correction has been extended to the optical, achieving 0.24 arcsec FWHM in V (Strehl 0.1) (Rigaut et al. 1998). This shows that correction in the optical is achievable, and bodes well for NAOMI, with its design emphasis on operation at short wavelengths.

Calar Alto's ALFA has also been in operation since 1996, and delivers high Strehl (0.6) in K band. Spectroscopy of two objects separated by 0.26 arcsec

[1] http://www2.keck.hawaii.edu:3636/public/realpublic/ao/ao_sci_list.html

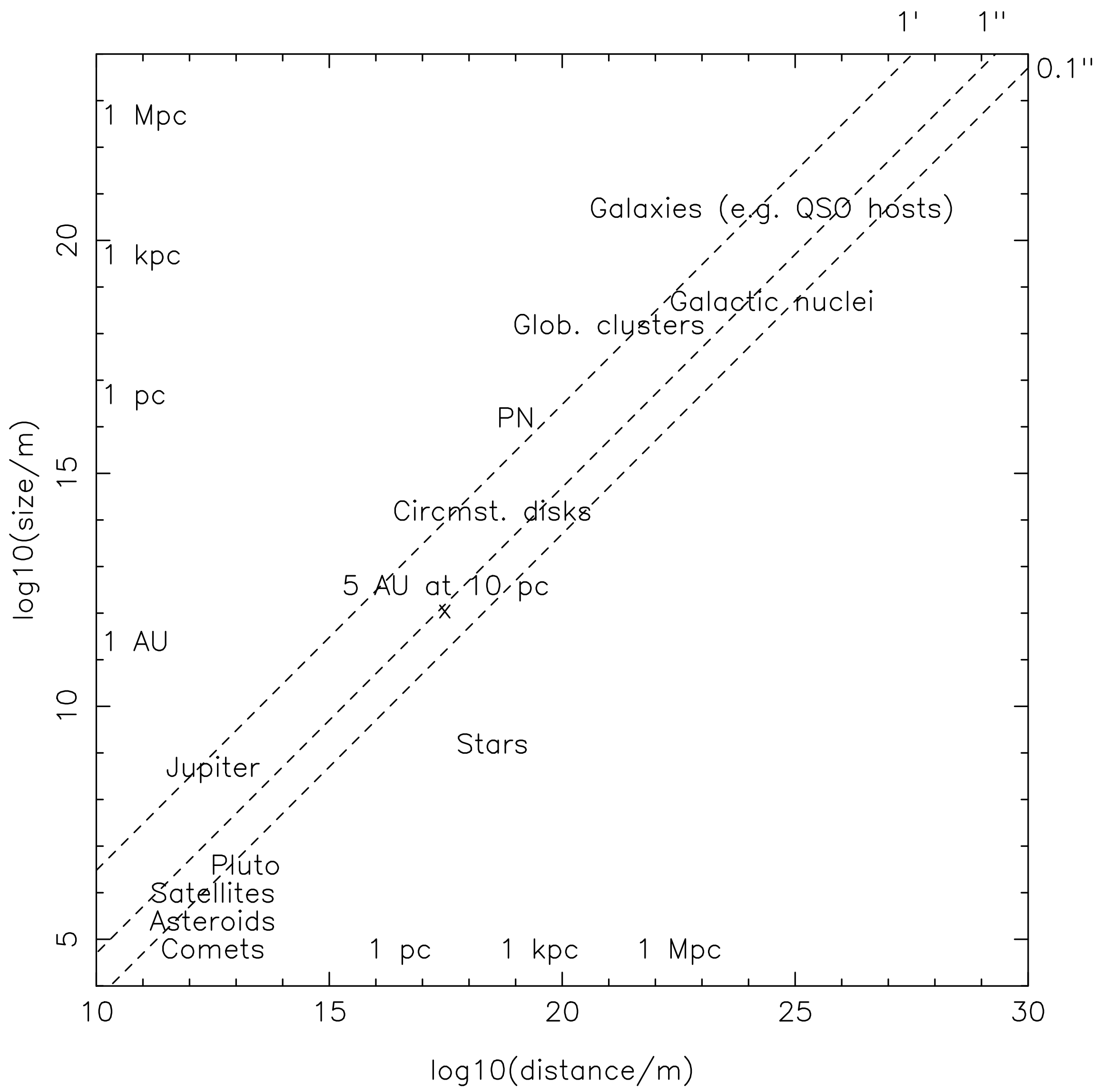

Fig. 1. Measured angular sizes of astronomical objects span a small range in the optical. Gravitational stability imposes the requirement that astronomical objects are generally much smaller than their separations i.e. the nearest other planets, stars and galaxies typically subtend $\theta << 1$ radian, while the earth's atmosphere limits measured $\theta >\sim 1$ arcsec. The dashed lines indicating angular size do not take into account cosmological distortions at large scales.

was recently reported (Davies et al. 1999). Calar Alto is also well advanced with a laser-guide-star system. The main driver for AO at Calar Alto is alleviation of the poor site seeing, usually > 1 arcsec.

Keck II's AO system has just been commissioned (Feb 1999) and delivered 0.04 arcsec FWHM in K band (Strehl 0.3). The deformable mirror has 349 actuators. A similar system (currently in Waimea) exists for Keck I. One of the drivers for AO at Keck is the need to maximise wavefront correction before using the light for interferometry between Keck I and II.

4 Quality of the La Palma site

The quality of the seeing at the WHT has been measured as part of ING's 'Half-arcsec programme', under which causes of dome seeing have been identified and minimised. A Shack-Hartmann camera (JOSE) was used at the Nasmyth focus to measure the distribution of r_0 (Wilson et al. 1999), and it was found to be almost indistiguishable from distributions measured at CFHT and in Chile, median seeing 0.7 arcsec. The distribution of r_0 at the WHT is also identical to that measured by a DIMM seeing monitor outside the WHT, implying that dome seeing is negligible.

The vertical structure of the turbulence is not well known at any site, but the few measurements available for La Palma (JOSE, see also Muñoz-Tuñon et al. 1997) suggest that the turbulence is dominated by low-lying layers, which bodes well for correction using laser-guide-stars.

5 NAOMI - adaptive optics at the WHT

NAOMI, the WHT's common-user AO system [2], is scheduled for commissioning early 2000. Its predecessor ELECTRA has had several successful commissioning runs at the WHT, achieving FWHM 0.15 arcsec in J, H and K.

NAOMI is designed to deliver near-diffraction-limited performance at a wavelength of 2 μm using natural guide stars. Specifically, it should deliver, under median-seeing conditions, Strehl > 0.25 over 50% of the sky, and Strehl $>$ 0.7 over 5% of the sky. At shorter wavelengths, the performance will not be diffraction limited, but there will be partial correction, probably FWHM $>$ 0.2 arcsec at 0.7 μm. The isoplanatic radius at K (where the Strehl ratio falls to half its on-axis value), will be $\sim$ 20 arcsec.

NAOMI is expected to perform well in the optical, compared to other AO systems, thanks to the (76-element) segmented deformable mirror (most AO systems use a mirror with continous face-sheet) and to the unusually accurate positioning of the mirror segments. NAOMI will operate at the Nasmyth focus and will have separate ports for optical and IR cameras. Initially, imaging will be available at the IR port using ING's new IR camera INGRID (0.04 arcsec/pixel, field 40 arcsec), and may be available at the optical port using

[2] http://www.ing.iac.es/~crb/wht/ao.html

a test camera (field 15 arcsec). Optical spectroscopy will be available via the TEIFU fibre feed to WYFFOS, (field 6 arcsec, at 0.25 arcsec/pixel, or 3 arcsec at 0.13 arcsec/pixel). TEIFU was partly commissioned June 1999. No IR spectrograph is currently planned, but a number of inexpensive options are being considered, including the possibility of IR spectroscopy with WYFFOS, or with a warm grating in front of INGRID.

6 What next?

With natural guide stars, NAOMI will offer sky coverage of only a few % in the IR, and $< 1\%$ in the optical, and this coverage is biased to low galactic latitudes. Some improvement in coverage is possible through enhancements of the existing system e.g. by conjugation to image the dominant turbulent layer at the deformable mirror, or by deployment of a wavefront-sensor detector with very low readout noise (allowing use of fainter guide stars). Laser guide stars (LGS), however, offer the best chance of obtaining reasonable sky coverage in the optical. A team from IC/Durham will use a (weak) LGS in autumn 1999 to characterise the sodium layer above La Palma. LGS AO could be available at the WHT sometime after 2002. LGS AO in the optical will be much more difficult to achieve on an 8-m telescope because of the severe shrinking of the isoplanatic patch caused by laser and starlight traversing different paths through the atmosphere ('cone effect'). Michaille et al (2000) and Longmore (2000) discuss LGS AO in their presentations (this volume).

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