ADAPTIVE OPTICS; PRINCIPLES, PERFORMANCE AND CHALLENGES

Adaptive Optics

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Abstract

There are several good reviews of adaptive optics (AO) as well as a few textbooks (Hardy(1988), Roddier(1999), Tyson(2000)). The proceedings of earlier Cargese Summer schools also serve as a good introduction. While it is necessary to briefly explain the principles of AO, I will try to emphasize some particular aspects in more detail than the existing reviews. The more recent developments in AO will also be examined in some detail. These include Multi-Conjugate AO (MCAO) and the development of AO for the next generation of Extremely Large Telescopes (ELTs).

Keywords: adaptive optics, multiconjugate adaptive optics, extremely large telescopes

1. INTRODUCTION

One of the basic tasks of observational astronomy is to make images (or ‘maps’) of distant sources. The angular (and hence spatial) resolution of these images will depend on the optical quality of the telescope and camera we use and at best it will be limited by diffraction at the entrance aperture. This diffraction-limited resolution is given approximately by $\frac{\lambda}{D}$ radians, where $\lambda$ is the wavelength of observation and $D$ is the aperture diameter. Using the fact that 1 arcsecond corresponds to approximately 4.85 $\mu$rad, we could expect a 10m telescope to have a resolution of 0.01 arcsecond when observing at 0.5 $\mu$m. However, no matter how carefully we make the telescope we never obtain resolution which is this good. In fact, the resolution will be in the range of approximately 0.3-3 arcseconds and will not depend on the telescope diameter if the diameter is larger than about 10cm. This is due to the effects of the Earth’s
turbulent atmosphere on the amplitude and phase of electromagnetic waves passing through it. The effect of atmospheric turbulence on images is described in several texts and also in this book (Ch. 1). Here we repeat the definitions of the parameters of turbulence which are of most importance to adaptive optics. The most important parameter is $r_0$, the Fried parameter, which can be defined as the radius of a circle over which the mean square wavefront variance is 1 rad$^2$. A telescope of diameter less than $r_0$ will be diffraction-limited when observing through the turbulence, while a telescope of diameter larger than $r_0$ will be seeing-limited i.e. the resolution will be poorer than the diffraction limit. The value of $r_0$ depends on the integrated strength of turbulence along the line of sight. It also depends on the zenith angle of the observation, since the effective path through the turbulence is longer at higher zenith distance. Since it is defined in terms of radians, it will also depend on the wavelength of observation. For Kolmogorov turbulence the expression for $r_0$ is as follows:

$$r_0 = \left[0.423k^2(\cos \gamma)^{-1}\int C_n^2(h)dh\right]^{-\frac{2}{5}}$$

where $k = 2\pi/\lambda$ is the wavenumber, $z$ is the zenith angle and $C_n^2$ is the turbulence structure function. The dependence of $r_0$ on wavelength and zenith angle are $r_0 \propto \lambda^{\frac{6}{5}}$ and $r_0 \propto (\cos \gamma)^{-\frac{2}{5}}$. As useful figures of thumb, the value of $r_0$ increases by a factor of three from the visible to the J band (1.25 µm) and a factor of 6 from the visible to the K band (2.2 µm). The full-width at half-maximum of a seeing-limited image is given by

$$fwhm_{\text{seeing}} \approx 0.97\lambda/r_0$$

which implies that the full-width at half maximum depends on wavelength as $\lambda^{-\frac{1}{5}}$ and is therefore slightly better in the near infrared than in the visible.

Atmospheric turbulence is a dynamic process and the wavefront aberrations are constantly changing. A characteristic timescale may be defined as the time over which the mean square change in wavefront error is less than 1 rad$^2$. If the turbulence were concentrated in a single layer with Fried parameter $r_0$ moving with a horizontal speed of $v$ ms$^{-1}$ then the characteristic time, $\tau_0$, is given by

$$\tau_0 = 0.314r_0/v$$

For example, a layer with $r_0 = 10$ cm at 0.5 µm moving at a speed of 10 m/s will give rise to wavefront errors having $\tau_0 = 3.1$ ms at 0.5 µm. This will scale with wavelength in the same way as $r_0$, so that the corresponding value of $\tau_0$ at 2.2 µm is approximately 19 ms.

Another parameter of the turbulence which strongly influences the performance of an adaptive optics (AO) system is the isoplanatic angle. The light