Optical imaging in very large telescopes

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ABSTRACT

The imaging characteristics of a telescope depend, among other things, on its size, diffraction, telescope aberrations, atmospheric seeing and dispersion, and wavelength range. The interaction of these is considered for a very large telescope, as they affect the best use of the telescope.

Key words: atmospheric effects – telescopes.

1 INTRODUCTION

There are various quite different factors that interact to limit the optical performance of a telescope, and which are different in various ways in the new generation of very large telescopes from earlier practice. Four of these factors, diffraction, telescope aberrations, atmospheric seeing and atmospheric dispersion, will be considered, first severally and then in their interactions.

2 DIFFRACTION

Airy (1835) introduced the concept of diffraction-limited imaging, first applied as the Airy disc in microscopy, as the diameter of the image of a point. The corresponding concept for a telescope, the diffraction-limited angular resolution (DLAR), is given by

\[ \text{DLAR} = \frac{2.44\lambda}{D}, \]

where \( \lambda \) is the wavelength and \( D \) the diameter of the telescope aperture. DLAR is generally quoted in arcseconds. Table 1 shows values of the DLAR for different telescope apertures and wavelengths, assuming the absence of other effects affecting resolution, in particular atmospheric effects and telescope aberrations.

3 TELESCOPE ABBERRATIONS

Any aberrations in some way degrade the image quality, and all astronomical telescopes have some aberrations, but all the current wave of 8- to 10-m telescopes have optical configurations different from earlier practice in ways that materially alter their aberration problems. Earlier telescopes with apertures from 2 to 5 m provided two focal stations, a prime focus of around \( f/2.8 \) and a Cassegrain or Ritchey–Chrétien focus from around \( f/11 \) to \( f/8 \), a telephoto ratio of the \( f/ \) numbers of about 3 : 1. Such telescopes were commonly fitted with small lenticular field correctors to correct any residual spherical aberration or coma (an aberration increasing linearly with field angle). By virtue of their configuration they had very small field curvature and astigmatism, aberrations increasing quadratically with field angle. Wynne (1989) gives references to such corrector systems from around the world.

The current wave of 8- to 10-m telescopes depart from this configuration. To keep down the very large dome costs they have much faster prime focal ratios, around \( f/1.8 \) (and hence shorter telescopes), and to keep the secondary mirror small (for chopping and for fast fine guiding) they have a secondary mirror at around \( f/16 \), a telephoto ratio of around 9 : 1. The prime focal station is abandoned.

This change of telephoto ratio introduces field curvature and some astigmatism, so that the image field is approximately spherical and off-axis images out of focus. For the Gemini telescopes, with \( f/1.8 : f/16 \) Ritchey–Chrétien mirrors, this produces a geometrical image spread of some 0.1 arcsec at \( \pm 1\text{-arcmin} \) field (Wynne 1994), increasing quadratically with field angle, and larger if account is taken of diffraction.

The instruments planned for the Gemini telescopes require a field angle of \( \pm 3.5 \) arcmin (Allington-Smith & Davies 1995; Robertson 1995), where the geometrical image spread would be some 1.2 arcsec, 12 times larger than required.

4 THE SEEING

This is the effect whereby atmospheric turbulence dilates the image of a star, effectively a point in the absence of air, to a larger disc. It is always present on Earth, varying with atmospheric conditions and consistently better at some sites than others; and, until recently, a seeing disc of 1-arcsec diameter was considered good. More recently it has been found possible, by an adaptive optics (AO) process, substantially to reduce the seeing errors in some cases.

This correction process falls into two parts, corresponding to two components of the image dilation. First, the unexpanded stellar image is in continual random motion, the time average of which is an expanded disc. This may be due to fast telescope shake, and it can be reduced by high-speed precise guiding provided by a tipping mirror in the beam. In another component the instantaneous image is fragmented owing to deformation of the incident wavefront. To reduce this effect, some of the light from a star is analysed to determine its rapidly varying deviations from sphericity, and from this the shape of a flexible mirror in the path of the main beam is altered to correct or reduce its asphericities. The area of the image plane over which the asphericities of seeing-limited wavefronts are...
effectively the same, known as the isoplanatic patch, is very small, certainly less than 1 arcmin, and less still at shorter wavelengths. The limits within which AO will work are not year clear, but it is generally agreed that it will not be effective at the shorter wavelengths of the visible spectrum. At infrared wavelengths, however, it has been shown by McArthur, Rigaut & Arsenault (1966) to give valuable reduction in the seeing.

Extensive theoretical work about seeing has been published that is not much concerned with the practical problems of this paper, but work on the wavelength dependence of seeing by Fried (1966), Boyd (1978) and Selby et al. (1979) is relevant, and is capable of experimental checking, given by Boyd and Selby et al. It appears that dilation of an image owing to seeing varies as $\lambda^{-1/5}$, the seeing errors being less at longer wavelengths. This is a very low rate of change compared with the linear variation of DLAR (the seeing decreases by about 15 per cent for a doubling of $\lambda$), but it becomes significant for large changes of $\lambda$. A tenfold increase of $\lambda$ would reduce the seeing by a factor of 0.63.

5 ATMOSPHERIC DISPERSION

Since the refractive index of air varies with wavelength, light from a star removed from zenith is dispersed into a linear spectrum, in the direction of the star from zenith. For light in the visible wavelengths, at normal temperature and pressure (n.t.p.), the angular spread for $\lambda = 0.4$ to 0.8 $\mu$m at 45° zenith distance is 1.69 arcsec (Allen 1973), varying as $\tan z$ (zenith distance). It changes slowly with temperature and humidity, and faster with pressure; at 4205-m altitude, it is 60 per cent of the sea level value. It is therefore 0.1 arcsec at $z = 5^\circ.4$ at n.t.p.

Since AO acts wholly with mirrors, it cannot detect or correct chromatic effects, so, if the 0.1-arcsec seeing is to be secured over a field greater than $\pm 3^\circ.4$, atmospheric dispersion must be separately corrected to that level.

Airy in 1869 described a simple correcting device that he used for observing transits of Venus and Mercury, and more sophisticated correctors tunable for $z$ have been described since, but hitherto there has been no requirement for 0.1-arcsec precision. Wynne (1997) has described a simple form of corrector which meets this need, over a wide range of wavelength and $z$.

6 DISCUSSION

Which of these factors sets a limit to the telescope performance depends on the wavelength range, the field size and the conditions of use.

Considering first imagery over the very small field angle of good resolution set by the telescope aberrations, or the still smaller field angle possible with AO, it is possible to make estimates of the angular resolution variation with wavelength under good seeing conditions, making the assumption that the seeing image spread is 1 arcsec at a wavelength of 0.5 $\mu$m. The seeing is a property of the atmosphere, independent of telescope size. Using the Fried $\lambda^{-1/5}$ rule, and the value of seeing at $\lambda = 0.5$ $\mu$m, the corresponding seeing at other wavelengths can be calculated. The image spread owing to seeing and diffraction is the sum of these effects; light from every point of the diffraction image will be expanded by the seeing.

Table 1 shows the effect of diffraction, for wavelengths of 0.35 to 5.6 $\mu$m, in the absence of other effects, for a space telescope. Fig. 1 is a plot of seeing against wavelength, the seeing at 0.5 $\mu$m being taken as 1 arcsec. Table 2 shows the combined effect of diffraction and seeing, from $\lambda = 5.6$ to 0.5 $\mu$m, for telescopes of 8- and 4-m apertures, using data from Fig. 1.
These tables show that, for a given size of telescope, the diffracted image increases with wavelength; for a given wavelength, the image size decreases as the telescope size increases; and the seeing disc decreases slowly with increasing wavelength. Therefore, as the diffraction image expands at longer wavelengths, the seeing disc contracts, the effects almost balancing on an 8-m telescope over the range shown.

There are two reasons for building large telescopes. First, they collect more light from a star, and so make possible the study of very faint stars not otherwise accessible; or, for less faint stars, make shorter exposures possible. The second reason is that the diffraction-based angular resolution is improved.

The first reason is always welcome to astronomers, but the value of the second depends on the wavelength used. For an Earth-bound telescope, and visible wavelengths, a smaller DLAR is no advantage because seeing prevents it being used. This applies also to the range of wavelengths over which AO can be used, there being no reason for thinking that AO will be more effective on a large telescope.

For longer infrared wavelengths, where the seeing improves with increased wavelength, increased telescope size can bring improved resolution. To make use of this higher resolution, over a range of wavelengths relatively little studied in astronomy, requires quite different instruments, since optical glasses and detectors commonly used at visible wavelengths will not work at these infrared wavelengths. By a fortunate chance, however, during the past few decades work in quite another field, and a much more copiously funded one than astronomy, has been active on work at these infrared wavelengths: namely the military. This has led to the development of new infrared materials, giving the possibility of good chromatic correction over the 1–5 \( \mu \)m range, and detector arrays. More recently still, much of this work has been released from military secrecy, and the new materials and detector arrays are now available commercially.

This opens the way for the development, on very large telescopes, of high-resolution infrared spectroscopy of comparable sophistication to existing work at visible wavelengths. This may well prove to be one of the most scientifically significant uses of large telescopes.

### REFERENCES

Allington-Smith J., Davies R., 1995, Spectrum, June
Robertson D., 1995, Gemini Project Newsletter, June

### Table 2. Stellar image size \( R \) in arcseconds, in the presence of diffraction and seeing (for 1-arcsec seeing at 0.5 \( \mu \)m), for 8- and 4-m telescopes, from \( \lambda = 5.6 \) to 0.5 \( \mu \)m.

<table>
<thead>
<tr>
<th>( \lambda ) (( \mu )m)</th>
<th>( R = \text{DLAR} + \text{seeing} )</th>
<th>For an 8-m telescope</th>
<th>For a 4-m telescope</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.6 ( \mu )m</td>
<td>0.35 + 0.62 = 0.97</td>
<td>0.70 + 0.62 = 1.32</td>
<td></td>
</tr>
<tr>
<td>4.0 ( \mu )m</td>
<td>0.25 + 0.66 = 0.91</td>
<td>0.50 + 0.66 = 1.16</td>
<td></td>
</tr>
<tr>
<td>2.8 ( \mu )m</td>
<td>0.18 + 0.71 = 0.89</td>
<td>0.35 + 0.71 = 1.06</td>
<td></td>
</tr>
<tr>
<td>2.0 ( \mu )m</td>
<td>0.13 + 0.76 = 0.89</td>
<td>0.25 + 0.76 = 1.01</td>
<td></td>
</tr>
<tr>
<td>1.4 ( \mu )m</td>
<td>0.09 + 0.81 = 0.90</td>
<td>0.18 + 0.81 = 0.99</td>
<td></td>
</tr>
<tr>
<td>1.0 ( \mu )m</td>
<td>0.06 + 0.86 = 0.92</td>
<td>0.12 + 0.86 = 0.98</td>
<td></td>
</tr>
<tr>
<td>0.5 ( \mu )m</td>
<td>0.03 + 1.00 = 1.03</td>
<td>0.06 + 1.00 = 1.06</td>
<td></td>
</tr>
</tbody>
</table>