THE PERFORMANCE OF GROUND BASED TELESCOPES

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The paper identifies causes of degradation of image quality in astronomical telescopes, describes how the effects of these can be calculated using MTFs, considers the validity of multiplication of MTFs for this purpose and gives the results of measurement of external and dome seeing, system MTF and image quality obtained during the commissioning of UKIRT.

A large astronomical telescope is expensive to build and operate and it is important that its performance should be maintained at the highest possible level. In the past there have been few attempts to predict operational image quality and compare the results of calculation and measurement, but during the last few years knowledge of atmospheric turbulence and the available methods of calculation have advanced to the point where both calculation and measurement are possible. The main sources of degradation of telescope performance are:

1. Atmospheric turbulence both external and within the dome.
2. Aperture diffraction.
3. Mirror surface errors.
4. Optical alignment.
5. Image movement.
6. Detector properties.

Calculation of system performance requires a method of combining the effects of the sources of degradation. In many other optical applications the use of the modulation transfer function (MTF) has proved to be the most convenient way of doing this and since the intensity distribution in the image of a point source can be readily calculated from the system MTF,[1,2] it appears to be a suitable choice. The main advantage of using the MTF method is that the system MTF at any spatial frequency is the product of the individual MTFs of the system components. To deal with the same problem using the point spread function (PSF), the individual PSFs must be convoluted to obtain the system PSF. This is much more laborious than multiplication even

C. M. Humphries (ed.), Instrumentation for Astronomy with Large Optical Telescopes, 85–92.

if the individual PSFs are known. To determine the individual PSFs may also be difficult since calculations must be diffraction based if the results are to be valid.

The MTF approach relies on the validity of the point by point multiplication of individual MTFs to obtain the system MTF. Multiplication appears to be valid for most of the expected sources of degradation of telescope performance. The problem of validity can be approached as follows:

For an optical system with wavefront errors W_{xy} the MTF is given by:

$$M_F = \iint \cos(2\pi\delta W_F/\lambda)$$

where $\delta W_F = W(x,y) - W(x + \lambda F,y)$

If the wavefront errors are the sum of two components (A and B) the term $(2\pi\delta W_F/\lambda)$ can also be replaced by (A + B) and the expression for M_F becomes:

$$M_F = \iint \cos(A + B) = \iint \cos A \cos B - \iint \sin A \sin B$$

The condition for valid multiplication of MTFs is then:

$$\iint \sin A \sin B = 0$$

This is valid if both A and B are wavefronts with rotation symmetry and also if either wavefront has random errors. When calculating telescope performance all of the sources of degradation are likely to be symmetrical or random (or both) except the mirror surface errors and wavefront errors due to optical misalignment. The case where multiplication of MTFs is likely to lead to significant error is that where a wavefront with significant spherical aberration or astigmatism is combined by multiplication with coma introduced by optical misalignment. In this case the wavefront errors due to the optical surfaces and the misalignment must be added and the combined MTF obtained before combining the result with other MTFs by multiplication. If the telescope system is known to be free from significant astigmatism and spherical aberration the effects of misalignment and surface errors can be dealt with by multiplication of MTFs.

The system performance can only be calculated if the individual MTFs for the sources are known. For aperture diffraction, mirror surface errors and optical misalignment, the measurement or calculation of MTF presents no difficulty[3]. The MTF of a uniform image movement of small angular extent is simply derived from the expression for surface error. Detector performance is too complex to be considered in a short paper but degradation introduced by detectors can be dealt with in a similar way to that proposed for the other sources.

https://doi.org/10.1017/S0252921100083391 Published online by Cambridge University Press

Source	MTF Expression	To combine
Aperture Diffraction	$M = 4A/(D^2 - d^2)\pi$	Multiply MTFs
(approximation for $\lambda F << D$)	$M = 1 - 4\lambda F(D + d)/(D^2 - d^2)\pi$	Multiply MTFs
External Seeing	$M = \exp. - 3.44\ (\lambda_o F/r_o)^{5/3}$	Multiply MTFs
(wavelength dependence of r_o)	$r_o = r_z\ (\lambda_o/\lambda_z)^{6/5}$	
Dome Seeing	As external seeing?	Multiply MTFs
Mirror Surface Errors (and optical alignment)	$M = \int\int \cos(2\pi\delta W/\lambda)$	Combine then multiply MTFs
Image Movement	$M = \sin(\pi\alpha F)/\pi\alpha F$	Multiply MTFs

D = aperture diameter, d = central obstruction

F = spatial frequency (angular), r_o = atmospheric coherence length

α = image trail length (angular)

A = overlap area for aperture sheared by distance λF

M = modulation at spatial frequency F

δW = difference in wavefront height for pairs of points with lateral separation λF.

λ_o = wavelength (for which r_o applies).

Table 1. Telescope performance degradation

Table 1 lists the main sources of telescope degradation, gives an expression for MTF and indicates validity of MTF multiplication for that source.

Interferometric measurements of atmospheric MTF have been made by Dainty and Scaddan[1] and others, but the full potential of this method of investigation remains to be explored. The atmospheric MTF[4] is obtained from the fringe modulation in a long exposure interferogram and the remaining phase errors in the interferogram should be those due to the optical surfaces and their state of alignment. If short exposure interferograms are also taken, they contain additional information about phase errors due to the atmosphere. By measurement of phase and modulation on long and short exposure interferograms, it is possible to separate the effects of distant and local turbulence and derive MTFs for each of these. Information about dome seeing can also be obtained by comparison of Hartmann tests in the dome and during works' tests. The result of a single Hartmann exposure on a star usually indicates an image quality significantly degraded from works' test data (or from the mean of many site Hartmann tests). Unfortunately, such tests are usually made with rather long exposure time (in order to remove the effects of local turbulence) but some information about dome seeing remains. Long and short exposure Hartmann plates can, in principle, provide the same information as the interferometric method, but in this case the phase errors are obtained from measurements of position of the images on the plate and information about the more distant turbulence from the size and light distribution in the individual Hartmann images.

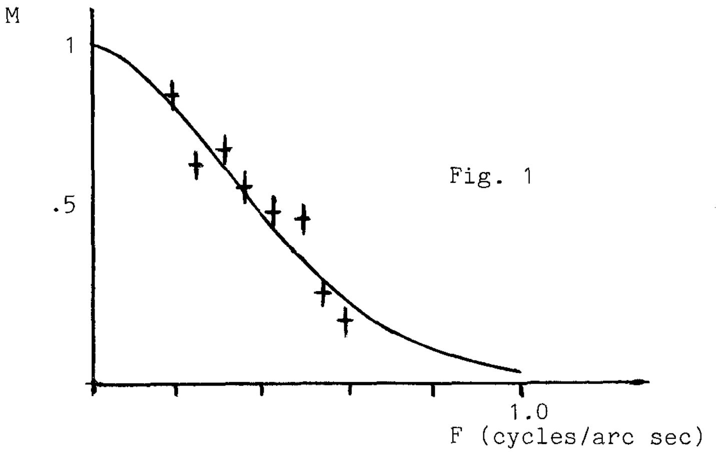

Fig. 1

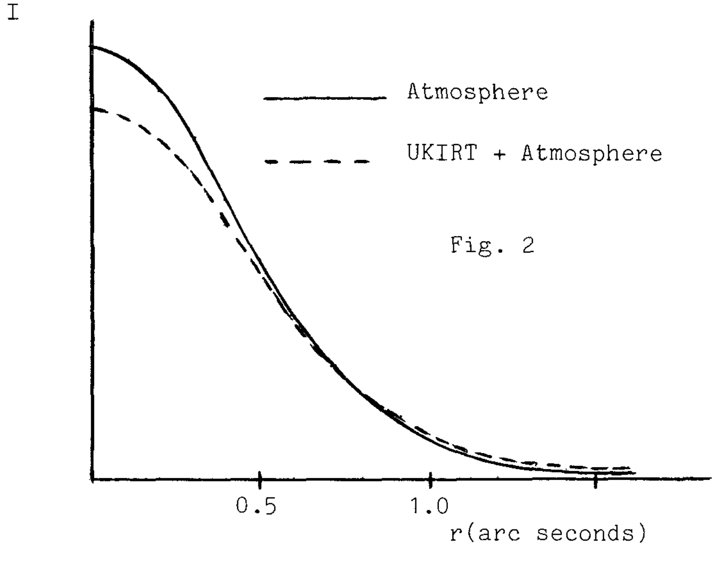

Fig. 2

Fig. 1 gives the results of atmospheric MTF measurements on a typical exposure in red light with the interferometer described by Brown[5] and Scaddan. The best fit Fried curve has r_o=12.8 cm at λ=610 nm.

Fig. 2 shows image intensity profiles for the atmosphere and for the UKIRT coudé focus including atmospheric degradation. Table 2 gives the results of the analysis of the atmospheric and two sheared interferograms[6] with long (40 seconds) and short (1 second) exposures. In analysis it is assumed that the difference between long and short exposure phase errors is due to dome turbulence. The information isolated in this way will include the effects of dome turbulence and also the phase part of external seeing which is not transformed into fringe modulation by averaging during the short exposure. For external air velocities greater than 1 metre/second, transformation from phase to modulation in the interferogram should be essentially complete for exposure of 1 second or more.

Fig. 3 shows the atmospheric interferogram, the long and short exposure sheared interferograms and a zero shear interferogram which provides a photometric reference for obtaining modulation data.

Table 3 gives turbulence data obtained from measurements of single Hartmann plates obtained during commissioning of the AAT. To obtain data about dome seeing requires gross extrapolation to correct for averaging during the long exposure time used. Little reliance can be placed on the result but the fact that significant degradation remained after an exposure time of 1 minute is a clear indication of the presence of significant dome seeing. Significant improvements in dome seeing have resulted from the recent installation of additional fans in the AAT dome.

The central intensity of a star image can be obtained from the MTF data as well as the normalised intensity profile. The central intensity is a useful measure of telescope efficiency and if the UKIRT system (external seeing + dome turbulence + aperture diffraction + telescope wavefront errors) is used as a standard of comparison, the central intensity for external seeing alone is 1.42 and the central intensity for the system excluding dome seeing is 1.14.

Conclusions

The interferometric data gives a clear indication that dome turbulence can be measured effectively using long and short exposure sheared interferograms. The Hartmann test data indicates that long and short exposures Hartmann tests can produce the same information although the data in Table 3 does not allow useful results to be deduced because of the lack of short exposure tests.

The simplicity of the interferometric equipment and the ease with which the normal shear and atmospheric units can be interchanged makes

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$F=0.47c/\Uparrow$	Long Exposure	Short Exposure	Atmos. Turb.	Dome Contrib.	External Contrib.	Aperture Diff.	System
$\delta W(M)$	0.07λ	0.14λ	-	-	-	-	-
$\delta W(0.5)$	0.09λ	0.12λ	-	0.08λ	-	-	-
$M(0.5)$	0.86	0.74	0.37	0.87	0.42	0.98	0.31
$r_o(0.5)$	-	-	10.1	33.0	11.0	-	9.2
$F=0.94c/\Uparrow$							
$\delta W(M)$	0.11λ	0.20λ	-	-	-	-	-
$\delta W(0.5)$	0.13λ	0.16λ	-	0.10λ	-	-	-
$M(0.5)$	0.69	0.51	0.04	0.80	0.05	0.96	0.03
$r_o(0.5)$	-	-	10.1	49	10.6	-	9.4

$\delta W(M)$ = rms wavefront difference, measured at 0.61 μm with long exposure or 0.42 μm with short exposure.
$\delta W(0.5)$ = rms wavefront difference at $\lambda=0.5$ μm.
$M(0.5)$= modulation value at $\lambda=0.5$ μm.
$r_o(0.5)$ in cm for $\lambda=0.5$ μm.

Table 2. Analysis of interferograms obtained at coudé focus of 3.8m UK Infrared Telescope

$F=0.40c/\Uparrow$						(Scaled)	
	α	$\delta W(0.5)$	$\delta W(T)$	$\delta W(A)$	A	$\delta W(A)$	M
Pℓ1800	.160	$.065\lambda$	$.042\lambda$	$.049\lambda$	.95	$.19\lambda$	.37
Pℓ1809	.133	$.054\lambda$	$.042\lambda$	$.034\lambda$	.98	$.13\lambda$	.69

α = rms wavefront slope (arc seconds).
$\delta W(0.5)$ = wavefront difference for $\lambda=0.5$ μm, $F=0.40c/\Uparrow$ from α.
$\delta W(T)$ = rms wavefront difference (at $\lambda=0.5$ μm) from works tests.
$\delta W(A)$ = contribution to αW from atmospheric (dome) turbulence.
Scaled data assume a coherence timescale of 4 seconds for dome turbulence compared with exposure time of 1 minute.

Table 3. Analysis of Hartmann data obtained at Anglo-Australian Telescope

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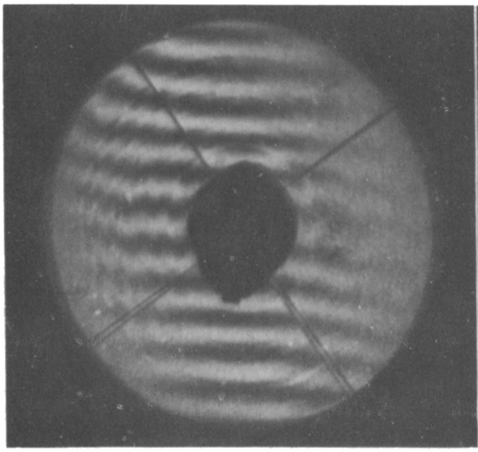
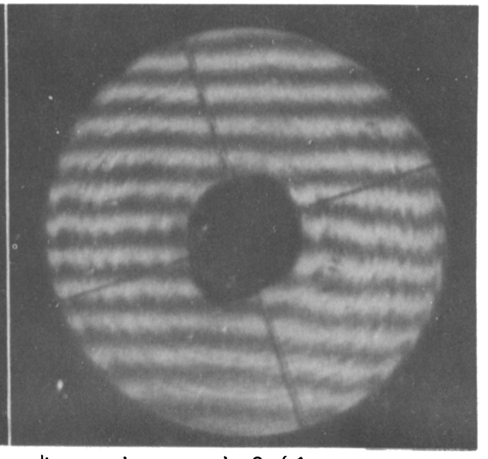
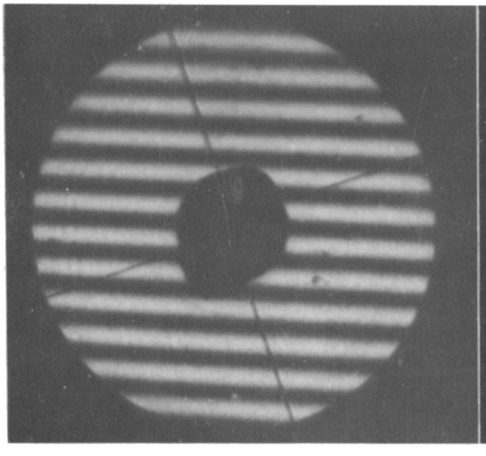


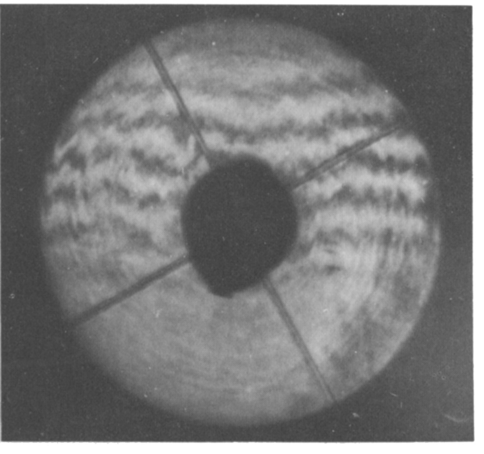
MTF configuration λ=0.61 μm
Long exposure (40 seconds)



4 cm shear. λ=0.61 μm
Long exposure (40 seconds)



Zero shear. λ=0.61 μm
Long exposure (40 seconds)



4 cm shear. λ=0.42 μm
Short exposure (1 second)

Fig. 3

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this a powerful method of investigation of dome seeing and external turbulence.

My thanks are due to R J Scaddan who measured the modulation of the UKIRT interferograms, to R V Willstrop for providing AAT Hartmann plate measurements and to C M Humphries for help in obtaining the interferograms at UKIRT coudé focus.

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