The Prediction of On Site Telescope Performance

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The acceptance tests of an optical mirror are most often based on measurements of the slopes on its surface and the geometrical concentration of light. However, the result depends rather critically on the way of sampling and, furthermore, the final quality of the telescope is a combination (convolution) of many parameters: the optical quality, seeing, guiding, etc.

Dr. D.S. Brown is responsible for the manufacturing and testing at Grubb Parson's workshop in Newcastle upon Tyne, which has recently polished the 1.5 m mirror for the new Danish telescope on La Silla and the optics for the 3.6 m CAT. Having spent most of his working life in the manufacture of astronomical optics, he has a keen interest in the prediction of actual telescope performance, based on tests in the optical shop. He explains—with a clear direction towards observing astronomers—that better test methods are now available which will let the future user know with good confidence how good (or bad) his new telescope will be, long before the first real observations are made.

In a recent *Messenger* article (No. 17, p. 14) describing the optical performance of the Danish 1.5 m telescope at La Silla, Drs. Andersen and Niss refer to the scepticism with which seasoned observers respond to predictions of image quality based on works tests. This response is historically well justified since there are many accounts of works tests on mirrors indicating levels of performance not achieved by the telescope when operational. They give some reasons why operational performance falls short of that achieved during works tests (flexure, misalignment, seeing, guiding errors) but do not explore the reasons why the effects of these are not allowed for when predictions are made.

In the past, several factors have made reliable prediction difficult, but recent advances in knowledge and technology make it possible to overcome these difficulties. One major problem has been the lack of reliable quantitative descriptions of the image deterioration due to seeing, a second has been the widespread use of geometrical formulae in converting test data (usually in the form of wavefront slopes) into an intensity distribution in the star image. A third, less well known difficulty is the occurrence of systematic errors in some tests. Several test methods (i.e. Hartmann, Gaviola, shearing interferometer) determine the mean wavefront slopes over finite areas of wavefront. These mean slopes can be significantly less than the "true" slopes at the centres of the averaging areas. Finally the astronomer usually prefers to define optical quality in terms of image size, which appears convenient and direct. Unfortunately it is then necessary to combine the effects of the various sources of degradation by convolution

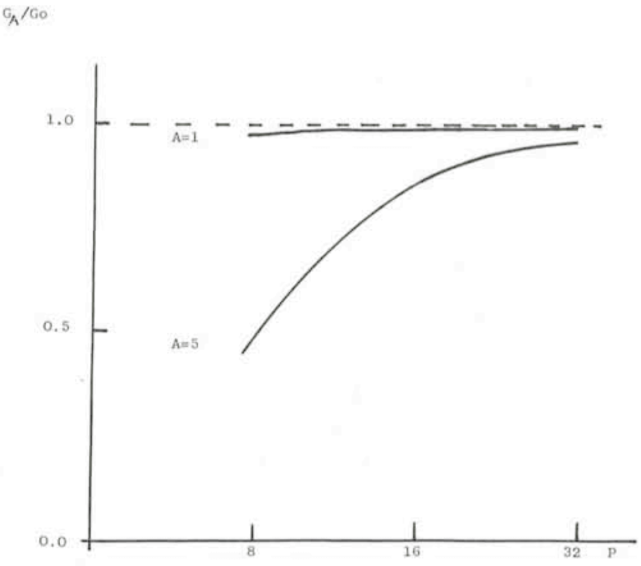

Fig 1. Loss of sensitivity for test methods averaging information over width A in the aperture, for periodic errors of period P.

and for many astronomers and opticians this is an unfamiliar, time-consuming and often inaccurate process.

Some idea of the scale of the problems can be obtained by considering one-dimensional sinusoidal errors of differing period (P). Simple expression can be deduced for the relationship between the "true" and averaged geometrical slopes, for the diffracted image spread and for the Strehl Intensity. Figure 1 shows the relationship between "true" geometrical image width (Go) and the measured width (G_A) obtained by averaging over an area of width A, for values A = 1 and A = 5. For A = 1 the loss of sensitivity is small but for A = 5 it is relatively large. In many Hartmann or shearing interferometer tests, values of A between 2 and 7 cm would be used and in the upper part of this range significant loss of sensitivity would be expected for errors with periods less than 20 cm. Figure 2 shows the relationship

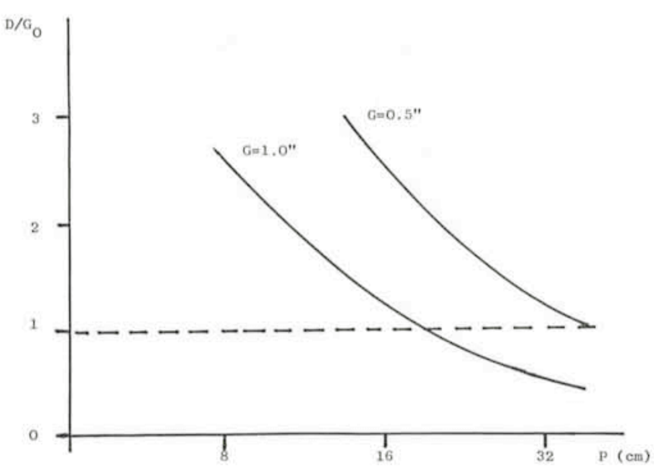

Fig 2. Ratio of diffracted to geometrical image widths as function of period.

between the diffracted image width D (separation of first-order maxima) and Go for errors with Go = 0.5 and 1.0 arc-second. Since D is independent of the amplitude of the wavefront error, but dependent on period, the curves show strong dependence on both Go and period.

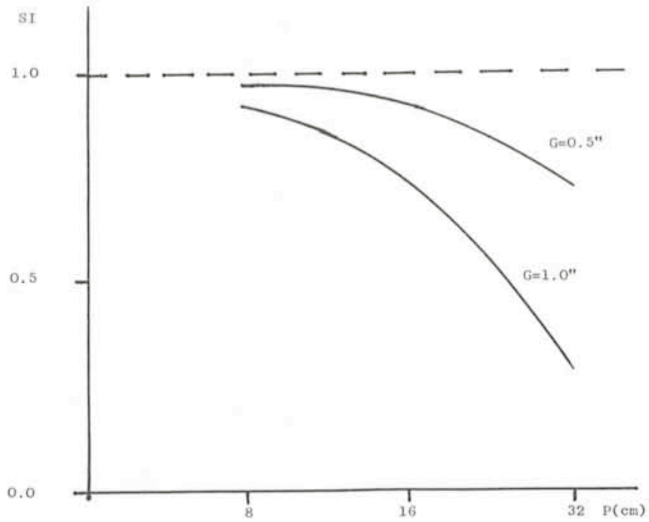

Fig 3. Strehl intensity for periodic errors of geometrical spread 0.5 & 1 arc second.

The Strehl intensity (ratio of the intensity in the central maximum to that for an aberration-free wavefront) is shown in figure 3 for errors with Go = 0.5 and 1.0 arc-second. For short periods the first-order maxima lie outside the geometrical image, but for the periods where D/Go<1, the two first-order images lie within the geometrical image. Figure 4 shows the fractional energy (E) within the geometrical image width Go for Go = 0.5 and 1.0 arc-second.

To obtain an accurate prediction of performance it is necessary to combine the effects of aperture diffraction, seeing and telescope aberrations using diffraction-based calculation. A possible approach is to calculate the point

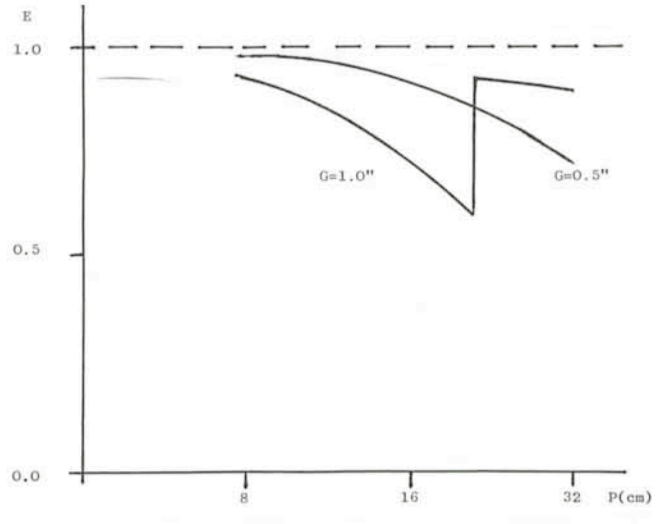

Fig 4. Encircled energy for periodic errors of geometrical image width 0.5 and 1.0 arc second. The discontinuity at P=20 in the curve for G=1.0 is due to the movement of first order diffracted images into the geometrical width when P exceeds this critical value.

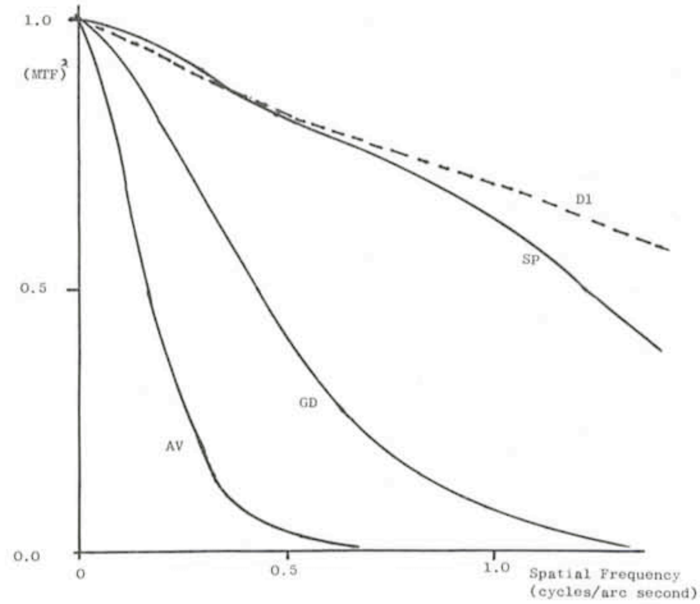

Fig 5. Squared MFT data for average seeing (AV), good seeing (GD), a typical specification (SP), and diffraction by an aperture of 1 metre diameter (D1).

spread function (PSF) for the telescope and convolute this with the atmospheric PSF. An alternative is to make the calculations in the spatial frequency domain, describing all the contributions in terms of modulation transfer function (MTF). The second method is much easier to carry out and is well established in other optical applications, but produces a result which astronomers do not easily relate to the point imaging characteristics of the system. It is not difficult to transform the MTF for the system into a PSF but this is often unnecessary since the intensity at the centre of the image can be obtained very simply from the MTF data.

The value of central intensity for the image of a point source is approximately equal to the integrated value of $(MTF)^2$. Central intensities so obtained can only be relative values and a useful basis for comparison is the central intensity for atmospheric seeing alone. Since the image degradation produced by the telescope will usually be significantly less than that produced by the atmosphere, the

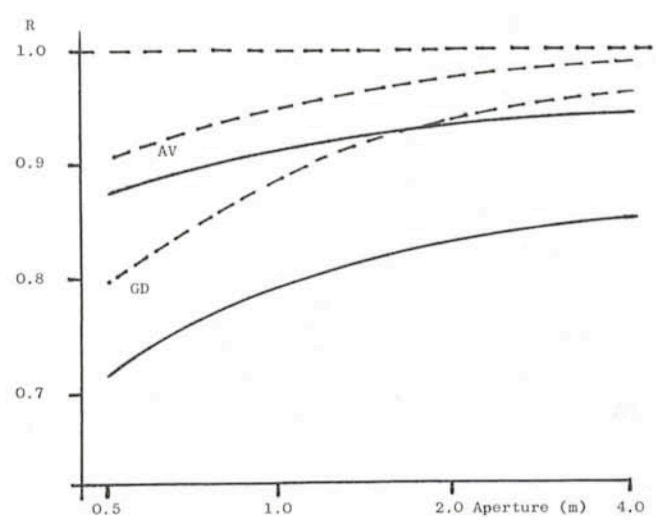

Fig 6. Ratio of central intensities of image after and before degradation by telescopes for average and good seeing. Dashed curves are for aberration free telescopes, full curves for telescopes just meeting the typical specification.

increase in image diameter will be small. The change in central intensity is relatively larger and provides a sensitive and conceptually useful indicator of image quality.

Calculations of telescope-induced degradation of image quality are easily carried out if the MTF is available. It is interesting to note that the effects of aperture diffraction alone can be calculated in this way once the atmospheric MTF is determined. Figure 5 shows curves of $(MTF)^2$ for average and good seeing, diffraction by a 1 metre aperture and for the aberrations of a telescope mirror just meeting a typical modern specification. Figure 6 shows the relationship between R (the ratio of central intensities after and before degradation by the telescope) and telescope aperture, for average and good seeing. The curves are plotted for diffraction only and for telescopes with aberration corresponding to the typical specification. From figure 6 it is clear that at small apertures and in average seeing, aberrations are responsible for only a minor part of the telescope-induced image degradation. For larger apertures and good seeing the telescope aberrations are more important and it could be argued that the specification used is appropriate for small apertures but is not sufficiently stringent for larger telescopes.

The principal advantage of the use of MTF is the simplicity of the calculations needed for reliable derivation of the image quality of a complete system, which can include the atmosphere, telescope aperture and aberrations. Measurement of MTF for large mirrors does not appear to present any major difficulty since any test method capable of producing reliable wavefront-height data can give the MTF. To produce data of high accuracy in the spatial frequencies of greatest interest (those where the atmospheric MTF is appreciably greater than zero), some revision of test details may be needed. Calculation of central intensity via MTF provides a simple method of expressing image quality, and the ratio of the central intensities of the system (atmosphere + telescope) to that of the atmosphere alone, provides a numerical measure of optical performance that is practical, easily visualized and appropriate to the conditions of use.

Neutron Stars

E. J. Zuiderwijk

It is a common trick among astronomers who give popular lectures to shock the audience with large numbers. The statement that a matchbox of material from a white dwarf weighs as much as several large locomotives (or elephants if there are influential ecologists present) is always of great effect. But that is all antique by modern comparison. Now, one cubic millimetre of a neutron star (about the size of the head of a pin) weighs one million tons! Dr. Ed Zuiderwijk of the ESO Scientific Group in Geneva is engaged in a theoretical and observational study of these incredible objects. There is still much to be learned from them, both for physicists who look for the ultimate properties of matter and for astronomers who wonder how stars end their life.

Neutron stars are among the more exotic objects in the sky. Their mass is comparable to that of our sun, but their diameter is as small as 15 kilometres. The matter in these stars is therefore extremely dense—the density is of the order of 10^{18} kg m^{-3}—and is mainly composed of degenerate neutrons, thus making the star look like a giant atomic nucleus.

The prediction that neutron stars should exist was made by the famous physicist Landau in 1933, immediately following the discovery of the neutron as a constituent of the atomic nucleus. It took, however, more than 30 years before they were discovered. Direct evidence for their existence was found in 1967 when the first radio pulsar was detected. This kind of objects turned out to be rapidly rotating neutron stars. The widely-accepted idea is that they originate from supernova explosions where in a final collapse of the stellar core the exploding star comes to the end of its evolution. With only one (or possibly two) exceptions all neutron stars, appearing to us as radio pulsars, are found to be single, isolated objects. An accurate, direct mass determination for many of these compact stars is therefore not possible.

The discovery of X-ray binaries with the UHURU satellite in 1970 revealed, however, that neutron stars also occur in binary systems. In such a system the neutron star is orbiting a "normal" star, the latter being often detectable from ground-based observatories. The X-rays are produced when kinetic energy of infalling gas is converted into heat at the surface of the neutron star. This matter originates from the "normal" optical star; the mass transfer occurs either because this star overflows its Roche lobe or loses mass by means of a stellar wind. The gravitational potential at the surface of the neutron star is very large (as the stellar radius is very small) and causes the gas to arrive with a velocity of up to one half of the velocity of light ($=3.0 \times 10^8$ m sec^{-1}). Subsequently the gas is heated to a temperature of about 10^7K, which is high enough for the gas to radiate strongly in the X-ray region of the spectrum.

Mass Limit

Theoretical models predict the existence of an upper limit to the mass of a neutron star, above which no stable configuration can exist. A compact object more massive than this upper limit is expected to collapse completely, presumably to become a black hole. The numerical value of this mass limit can be computed from a neutron-star model; the result depends, however, on which particular model is used. To be more specific, the choice of the so-called "equation of state", which describes the relation between the physical quantities pressure, temperature and density of the degenerate nuclear material, is of crucial impor-