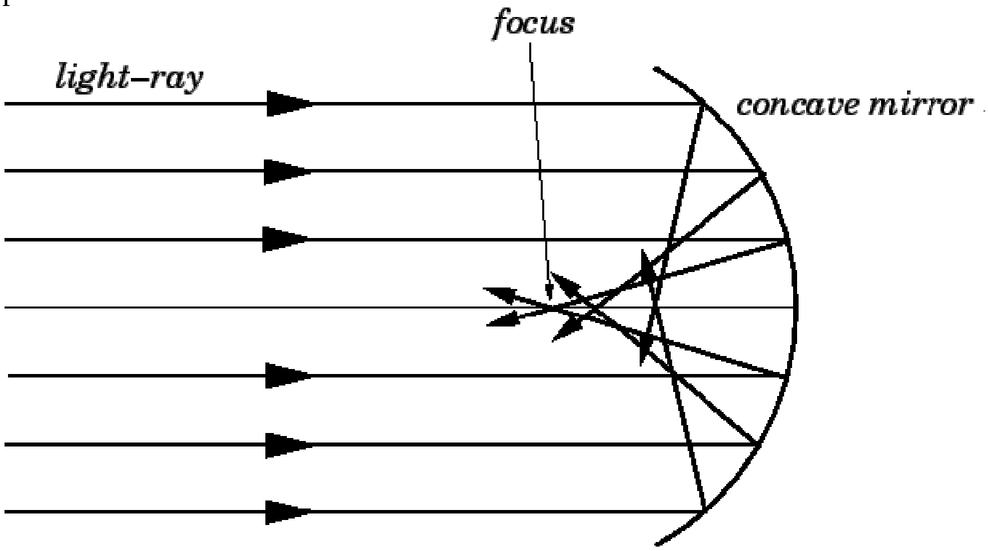
Optical Standards

John Nichol BSc MSc

The following notes are presented to explain:

Spherical Aberration
The Airy Disk
Peak to Valley, RMS and Strehl Ratio
Standards of Optics produced by Nichol Optical

Light rays arriving at Earth from any astronomical object are to all intents and purposes parallel. Unfortunately, this light cannot be brought to a common focus by a spherical mirror; this is due to the fact that such a mirror brings lights from its outer zones to a focus closer to the mirror surface than light reflecting from the inner zones. This is known as spherical aberration.

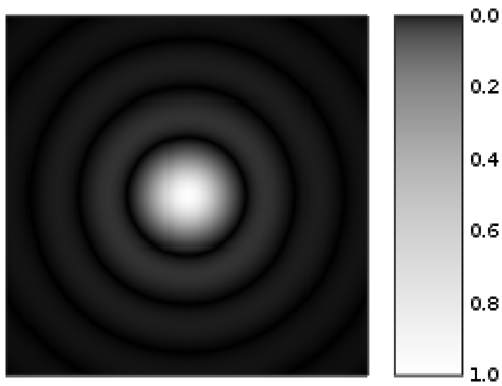


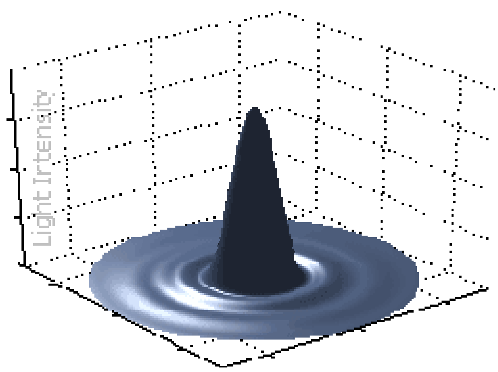
If the surface of the spherical mirror is deformed to a parabola light from all zones striking the mirror are brought to a common focus. Hence, the parabolic mirror is found in certain types of astronomical telescope (e.g. the Newtonian). Not all telescopes use parabolic mirrors, but any telescope regardless of the types of curves employed must eliminate spherical aberration, or at least bring it to acceptable levels if the telescope is to have an acceptable performance. If a telescope is described as ¼ wave or 1/8 wave, it is the residual amount of spherical aberration that is being measured, just how much is acceptable will be discussed here.

If it was possible to produce a parabolic mirror with zero spherical aberration the image formed would not be a point source. Due to the wave nature of light any image formed by an optical system suffers from diffraction, as a result the image of a star will appear to have a central disk of light surrounded by fainter rings. This is know as the Airy disk,

George Biddell Airy

and is named after the once astronomer royal George Biddell Airy. The size of the disk is determined by the aperture of the telescope. The best we can hope for is 84% in the central disk and 16 % in the rings. A 1/10 wave mirror has 81.6% of the light in the central disk, more on this shortly. The images below are computer generated representations of the Airy disk.





We can now go on to look at established optical standards. The original standard was first described by Lord Rayleigh, it states “If the light coming to a focus has no optical path difference error exceeding ¼ of the wavelength of light, the optical system will be sensibly perfect”. If an optical system has errors much more than ¼ wave we start getting more light in the rings at the expense of the central disk.

When we have been talking about ¼ wave, we are talking about wavefront error, take care not to confuse this with surface error. In order to produce a wavefront with errors of ¼ wave the surface must have an accuracy of at least 1/8 wave, and surface errors are doubled as a result of reflection.

Another optical standard is that of Danjon and Couder, they state; “If the circle of least confusion is smaller the Airy disk AND the max wavefront error does not exceed ¼ wave and defects should not be much less that this over the entire surface.” If you refer to the first image showing spherical aberration you will see that an area of ‘confusion’ exists at the focus, if this area is smaller than the Airy disk then the Danjon and Couder criterion has been met.

Peak to Valley (PV) Error

A telescope mirror may be described has having ¼ wave PV wavefront error. This means that the distance between the highest and lowest point on the mirrors surface is 1/8 wave. Remember that the surface error is halved at the wavefront due to reflection. On the face of it this mirror meets the established criterion for a good mirror. Consider this, we have two mirrors both ¼ wave PV (wavefront) 1/8 wave on the surface, one has a small bump ¼ wave high, the other has several bumps ¼ wave high. Both meet the established criteria but the first mirror will out perform the second mirror. Clearly, a PV rating is not giving the full picture it fails to take into account the size of the surface defects.

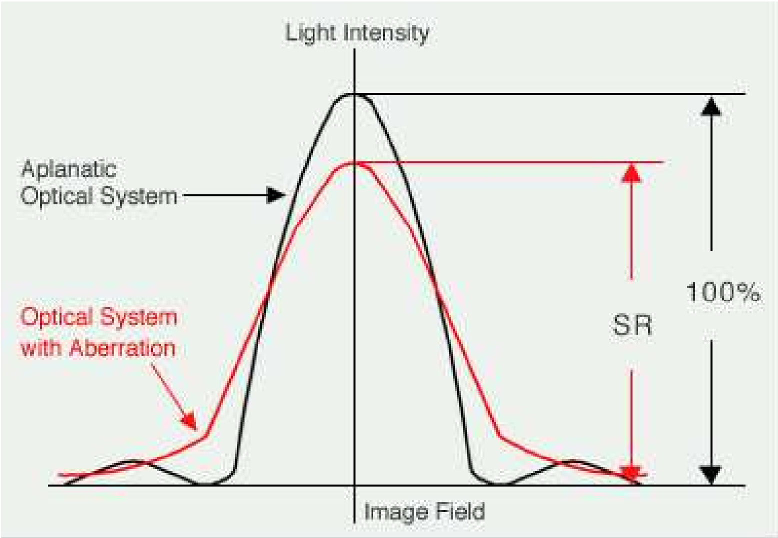
RMS (Root Mean Square)

With RMS the intention is to better characterise, in one number, the entire mirror surface (or wavefront) by accounting for the relative size of defects, this done by measuring the difference between the actual and measured surface in many different places. This is the same technique used to obtain standardised variation of a population of random variables, and is know as standard deviation. Importantly, for RMS to provide its potential, the mirror surface should be sampled by many equal, preferably small, increments of areas across the entire surface (or wavefront). Really, this can only be done with an interferometer, a device that compares the entire wavefront of the optic under test against a reference wavefront on know quality.

It can be shown mathematically that a mirror that is <u>smooth</u> but under / over corrected by ¼ wave at the wavefront calculates to an RMS value of 1/14 wave. (1/13.856), note that RMS value is approximately 3.5 times the PV value. Despite its obvious advantage in quantifying an optical system there is no accepted standard RMS number unlike the ¼ wave PV standard.

Strehl Ratio

Perhaps the best way to quantify the errors in any optical surface is by use of the strehl ratio. The strehl ratio is the ratio of intensity of the peak of the diffraction pattern of an aberrated image compared to the intensity at the peak of an unaberrated image, values ranges from 0 to 1, 1 being a perfect mirror. Strehl ratio (SR) is sometimes expressed as a %, 100% being an ideal optical surface with 84 % of the light in the central ring of the Airy disk. In the illustration below the red line indicates the distribution of light in the Airy disk for an optical system with some aberration. An aplanatic optical system is one that is free from spherical aberration and coma. The principle aberration limiting telescope performance is spherical aberration; usually coma is not a problem however, in certain instances like fast Newtonian telescopes coma can become a problem showing itself in the form of fan shaped star images towards the edge of the field.



Although RMS and Strehl ratio are different, when the RMS is small they are related by an approximation such that an RMS value of 1/14 wave equates to a SR of .80. Using the relationships between PV, RMS and Strehl, R.F.Royce has produced the following table:

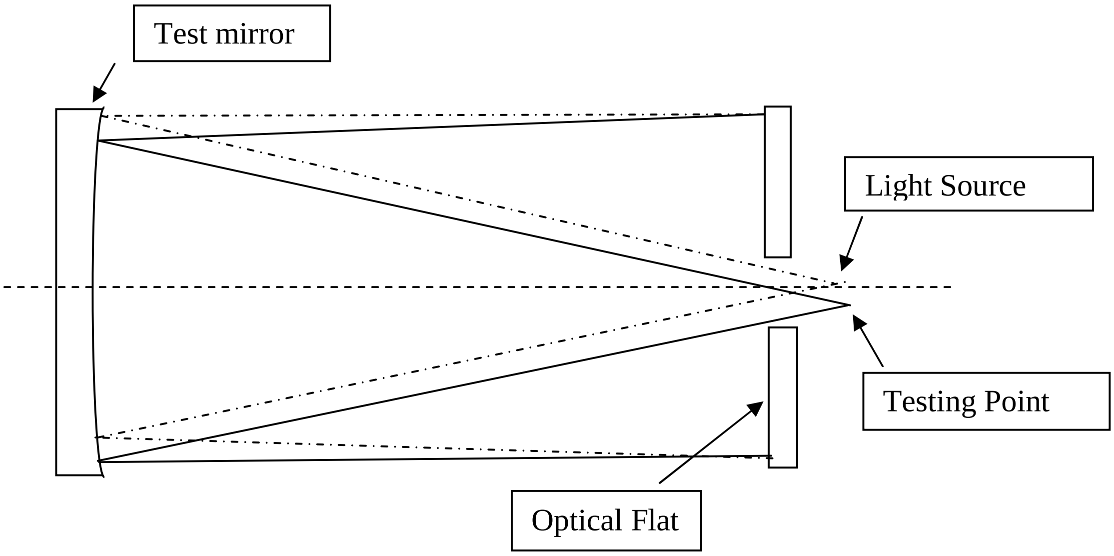
PV Fraction	RMS Fraction	RMS Decimal	Strehl Ratio
¼	1/14	.071	.82
1/8	1/28	.036	.95
1/10	1/35	.028	.97

Standards of Optics produced by Nichol Optical

I would now like to go on to discuss the test methods that I employ and how my mirrors are standardised. The following tests are used:

Ronchi test at the Radius of curvature
Knife edge at the Radius of curvature
Rochni test in combination with a flat mirror (Autocollimation)
Knife edge test in combination with a flat mirror (Autocollimation)
The Ross null test
Interferometry

In making any mirror at least two of the above tests are used and usually more. The principle test used is the Autocollimation, or double pass null test, this is used to test parabolic mirrors. In this test a parabolic mirror is tested in combination with a flat mirror.



The test is highly sensitive due to the fact that light reflects from the surface under test twice; making any errors appear twice as large as they would when testing at the Radius of curvature. This test is highly regarded by professional opticians and is widely used in the production of parabolic mirrors. The test in its pure form is qualitative and does not give any numerical information about the mirrors surface. The quality of the flat mirror used is important. It does not have to be optically flat, it can have a few waves of curvature, the important thing is that it is smooth. I employ two optical flats when testing with autocollimation. One was manufactured by Grubb Parsons so is of known quality; the other was made by me. In order to test the flat I first made a spherical mirror and figured it to a surface accuracy of at least 1/8 wave, verified by my interferometer. I then used the Ritchey-Common test to figure the flat until it was at least as good as the test sphere.

Under the autocollimation test a parabolic mirror appears to behave like a spherical mirror tested at the radius of curvature, as a result an ideal optical surface appears to grey or ‘null’ uniformly across it’s surface when tested with a knife edge. This is the test I use on a regular basis for the production of parabolic mirrors.

How can I be sure that mirrors produced using the double pass autocollimation test are at least 1/4wave PV, 1/14 wave RMS and have strehl ratio > .82. I have a Fizeau interferometer built with a Ceravolo reference lens. Experience has shown me that if I complete a mirror using the double pass autocollination test and then test it with my interferometer it always meets or exceeds the required standard which is 1/4 wave PV, 1/14 wave RMS and Strehl ratio of at least .82. Interferometric analysis is a time consuming and involved process and for this reason I do not provide an interferometer produced analysis with every mirror I make. I do offer it at an additional cost to cover the time involved in producing it. Please note that all of my mirrors are produced in the same way whether they have an interferometer analysis supplied or not. Interferometers are not normally used during the production of optics; they are normally used at the completion of the optic to verify the optical quality. The ultimate test of any optical surface is how it performs in a telescope; I am pleased to say the Nichol Optical has received much positive feedback for customers and has an ever increasing customer base reflecting the quality optics produced at realistic prices.