The Testing of Astronomical Telescope Optics
## by
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Introduction

The purpose of the following article is to give an overview of the various methods of testing astronomical telescope mirrors, it will be of interest to those seeking an overview of the test methods but not necessarily wishing to actually perform the tests. It is hoped that it will inspire those already using the more accessible tests to try something a little more advanced. It is sobering to think that tests like interferometry, once the province of professionals, is now becoming commonplace amongst amateur telescope makers. One thing that all of the tests have in common is that they benefit from experience and skill to give reliable results. The author has had experience in using all of the tests described.

The Foucault Test

In 1858 Jean Bernard Leon Foucault revolutionised the way telescope mirrors could be evaluated through the invention of a test we now call the Foucault or knife-edge test. In this test a light source in the form of a slit or pin hole is reflected off the test optics, the returning beam is intersected at the centre of curvature. If the eye is placed immediately behind the knife-edge the mirrors surface is revealed in apparent relief. Bumps, hills and zones are all easily visible. The Foucault test is a null test for a spherical mirror; this means that a perfect spheroid will darken evenly over its surface when seen under the knife-edge test. The problem is that telescope mirrors are not spherical they are parabolic.

*The Testing of Astronomical Telescope Mirrors*
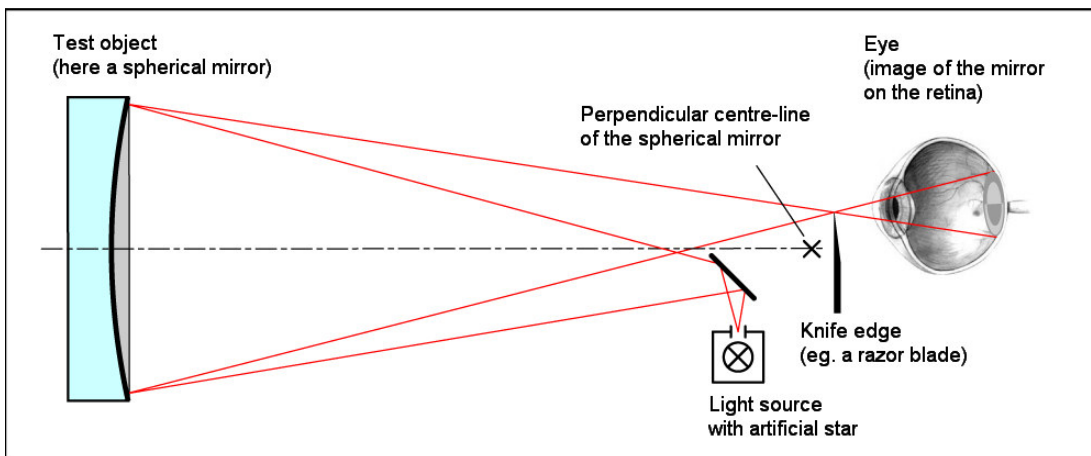
Under the Foucault test a parabolic mirror displays the so-called doughnut appearance, as the shadows produced resemble a doughnut. Incidentally, long focus telescope mirrors can be left spherical and work well, this is because at longer focal lengths the difference between a spherical and parabolic mirror can be less that ¼ lambda on the wave front, which in very general terms conforms with the definition of a good quality optical surface.
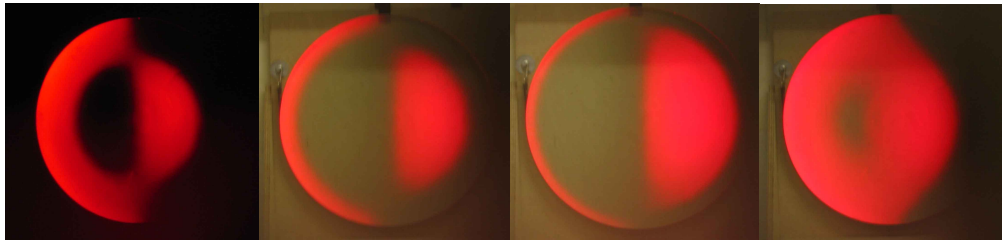

Foucault test images of a 22-inch F4 paraboloid showing 'doughnut' shadows.

The Foucault knife-edge test is qualitative, that is it does not give us any numbers to describe the surface of the mirror. The test can be made quantitative by using it in combination with a zonal mask or Couder screen. Here a piece of cardboard is cut to expose zones as shown in the picture. As the knife-edge is moved backwards and forwards zones of the same radius are seen to null, or darken evenly as the knife edge moves. By carefully measuring the positions at which the null occurs using a micrometer and by knowing the positions of the zones it is possible to give a quantitative analysis of the mirrors surface. This method is widely used by amateur telescope makers. Unfortunately it is not without its problems. It requires considerable skill to make accurate judgments about when nulling of the zones occurs; the test looks only at certain areas of the mirror and not all of it. The mirror can be rotated to reduce this problem. This test is tedious and tiring to perform and becomes less dependable with decreasing focal length, never the less the test has been employed in professional optical shops to produce optics which have be been shown to give excellent images in the field. Useful software tools are available to assist with the analysis of the test optic.
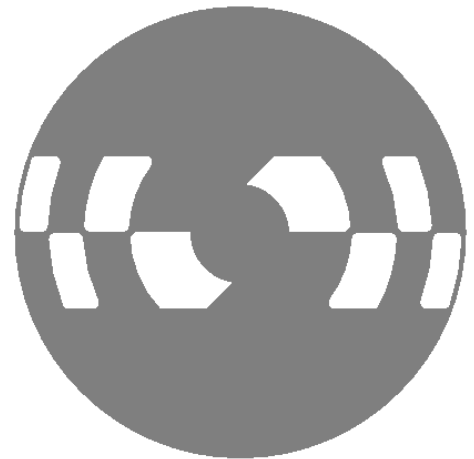
The Ronchi Test

In 1922 Vasco Ronchi proposed the test now named after him. It is a variation on the Foucault test. The light source is a slit which is reflected off the test optic, and the returning beam is allowed to pass through a transparent screen with a series of dark parallel lines marked on its surface. The appearance of the Ronchi bands reveals much information about the surface of the optics under test. Again, the test is qualitative; no numbers describing the mirrors surface are produced. It is possible to use a computer to generate the appearance of the Ronchi bands at different positions either side of the centre of curvature, these can be compared with the observed images and judgements made about the surface of the optic. For someone new to telescope mirror making this is perhaps the easiest test to perform that can be regarded as semi-quantitative.
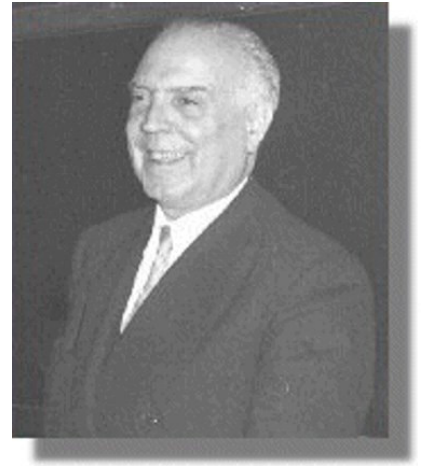
Examples of ronchi bands

	A spherical mirror tested at the centre of curvature, the Ronchi bands appear as straight lines.
	A parabolic mirror with the Ronchi ruling just inside of the centre of curvature.
	A parabolic mirror as seen with the Ronchi ruling just outside of the centre of curvature.
	A parabolic mirror showing a turned down edge, Ronchi ruling just inside of the centre of curvature.

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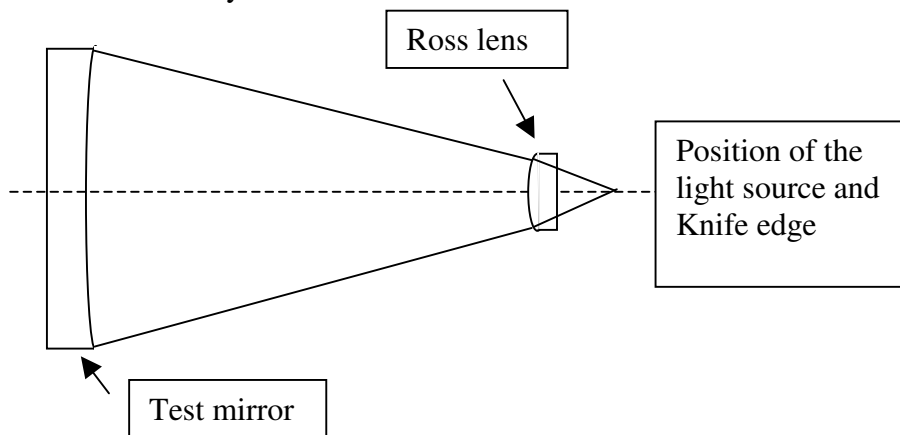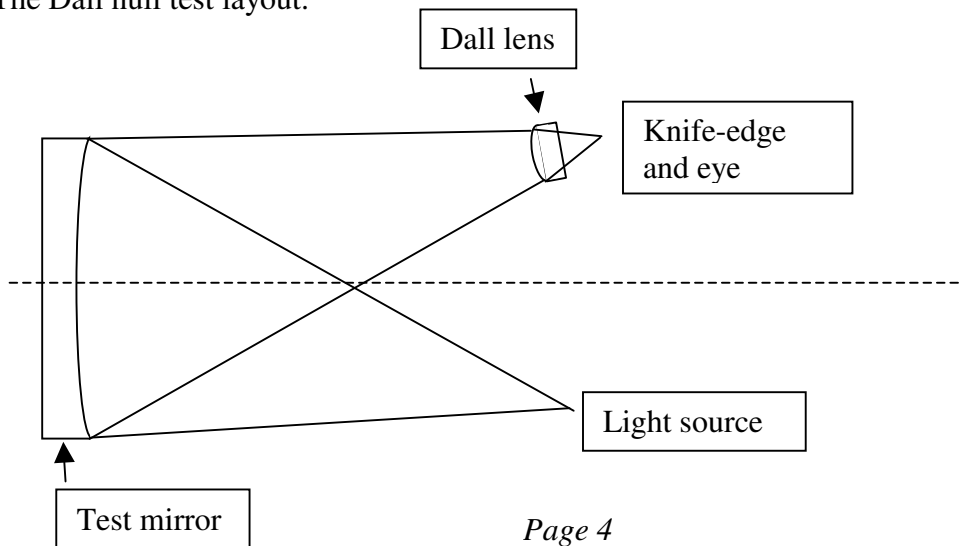
For further information see:

The Dall and Ross null tests.

Both of these tests require additional optics in the form of a high quality plano-convex lens. This lens is used to introduce spherical aberration equal in size but opposite in sign to that produced by the parabolic mirror under test. The result of this is that the parabolic mirror under test appears like a spherical mirror when it is fully figured. The arrangement for the Dall test is such that the returning image is viewed off axis, as a result unwanted astigmatism arises which complicates interpretation of the results. The test works best with longer focal lengths (approximately F6 and above).

The Ross null test layout.

Ross lens

Position of the
light source and
Knife edge

Test mirror

The Dall null test layout.

Dall lens

Knife-edge
and eye

Light source

Test mirror

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The advantage of the Ross test is that it is on axis, the light from the source passing through the lens before and after reflection therefore, assuming correct alignment, the off-axis effects present in the Dall test are not seen. Being null tests both of these tests offer the advantage that interpreting the result is relatively straight forward for example, when used in combination with a ronchi ruling the ideal parabolic mirror shows straight bands when correctly figured. When under corrected the bands appear bowed towards the centre, when over corrected the bands appear bowed towards the edge. Both tests are qualitative in nature yet are generally well regarded and are used by professional opticians as an aid to testing parabolic mirrors.

The disadvantage of both tests is that they require careful and accurate measurements of certain spacings in the test set up to be made. In the case of the Dall test the lens to light source slit has to be accurately set up, this may be accomplished by mounting the lens and light source in a sliding tube with lugs on the outside. These may be used to make measurements about the spacing of the lens and light source slit. The lens used in the Ross test is much larger than the Dall lens, typically 80 mm in diameter as opposed to the 25mm or so of the Dall lens. In the Ross test, accurate measurements of the distance between the test mirror and lens, together with the distance between the lens and knife-edge and light source, must be made. In practise these measurements are not too difficult to make with a little care. Both tests have the advantage of being able to test a range of aspheric surfaces other than parabolic curves including ellipsoids and hyperboloids which are employed in some cassegrain telescope configurations. For reliable results lenses used in either of these tests must be well made or from a reputable source. A lens tested with an interferometer and having certification is preferable.
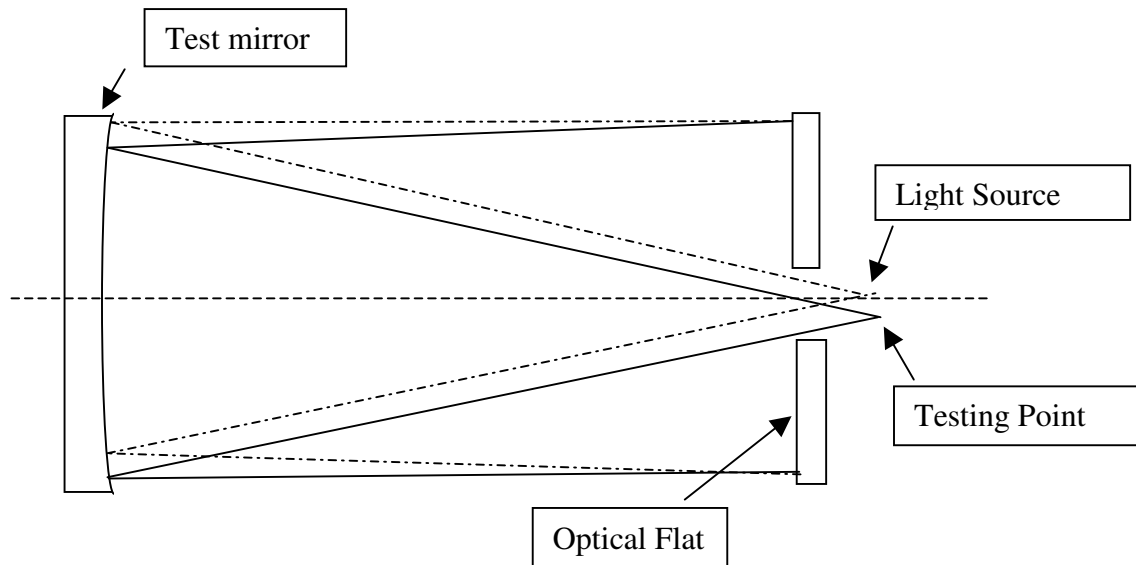
For further information see:

http://www.ceravolo.com/testing/ross_null.pdf
http://www.atm-workshop.com/dall-null.html

The Autocollimation Test

The autocollimation or double pass null test is well regarded and widely used in professional optical shops for testing parabolic mirrors. Like the Ross and Dall tests it is a null test so the ideal parabolic mirror shows straight bands when use with a Ronchi ruling or is seen to darken uniformly when viewed with the knife edge. However, the test is twice as sensitive as the other null tests as light is reflected off the test optic twice, this makes it a very powerful test. The price to pay for this sensitivity is that the test set up requires a high quality optical flat at least as big as the mirror under test, such an item is difficult to make and very expensive to buy. With the autocollimation test the mirror is tested at it's focus unlike the Ross and Dall tests which are at the centre of curvature.

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Optical layout for the Autocollimation test

Test mirror

Light Source

Testing Point

Optical Flat

In fact the flat reference mirror does not have to be perfectly flat it can be slightly convex or concave but it must have a very smooth surface at least as good as that expected of the test optic. The advantage of a null test is that at any given point it is very easy to interpret the condition of the mirror's surface and take appropriate remedial action. An optician proceeds as if he is figuring a spherical mirror and is looking for straight bands with a Ronchi ruling or a null with the knife-edge.

A parabolic mirror as seen under autocollimation with a Ronchi ruling.

	Ideal situation, straight bands indicate a well corrected optic when viewed at the focus.
	Seen just inside the focus bands that bow outwards indicate an over corrected mirror.
	Seen just outside the focus bands that bow inwards indicate an under corrected mirror

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The double pass autocollimation test is not a quantitative test, but none the less it is widely used in professional optical shops as it allows the production of high quality optics within a sensible time scale.

The Star Test.

The star test is a very powerful means of assessing the optic performance of a telescope. It does have some disadvantages, it needs the optics to be in a telescope and properly collimated (aligned) and needs to be performed on a star under good seeing conditions. For these reasons it cannot be regarded as a bench test and is generally not used by professional optical shops. The basis of the test is that a star image is examined both inside and outside of best focus; the resulting images should appear essentially the same, any difference in the intra and extra focal images gives an indication of the nature of the fault in the system. In this test the entire optical train, flat and primary mirror are under scrutiny, on finding a fault further steps will need to be taken to determine in which optic the fault resides.

For further information see:

http://www.willbell.com/tm/tm5.htm
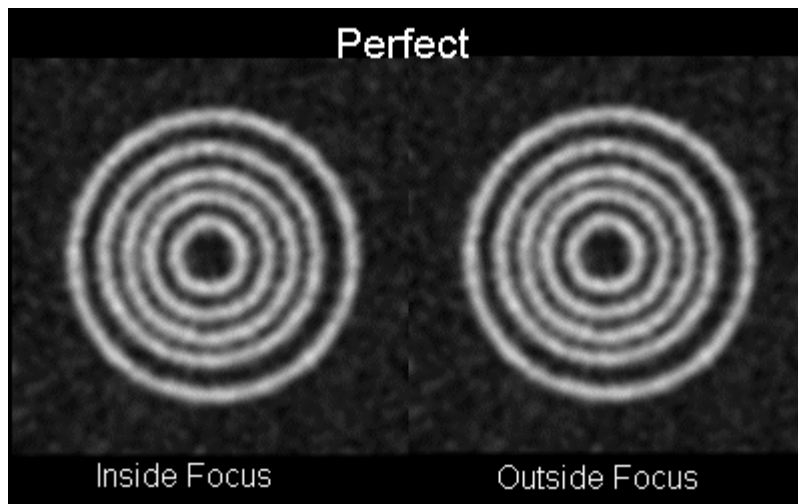
Interferometric Testing

Of all of the methods of testing interferometry is potentially the most informative. It gives a profile of the entire optical surface and is quantitative, the numerical analysis of any optical surface may be expressed as a P-V (peak to valley), RMS (route mean squared) or as a Strehl ratio* value. This test method is widely used in professional optical shops.

Most people are familiar with Newton's fringes produced when two pieces of flat glass are squeezed together (contact interferometry), the resulting fringes are in effect a contour map of the touching surfaces.

The principle of non-contact interferometry involves the bringing together of two wave fronts and the resulting creation of interference fringes. One of the wave fronts is produced by a reference element of known optical quality, the other is produced by the test piece, and the resulting interference fringes represent a contour map of the surface of the test piece. The reference wave front is spherical and as a result such interferometers are best suited to testing spherical surfaces, in such cases the fringes of an ideal surface would appear as straight fringes. Those of a parabolic mirror will appear as anything but straight fringes. There are methods for dealing with this as we shall see presently.

In the early 1970's Karl Ludwig Bath published a paper detailing the construction of a simple interferometer suitable for the testing of telescope mirrors, at the time cheap lasers were not as readily available as they are now. Analysis of the resulting interference fringes had to be done manually, a far from ideal situation. The ensuing years saw the development and availability of the relevant hardware and software needed to make interferometry accessible on a modest budget to anyone who cared to investigate it. Today we have amateur telescope makers regularly making interferograms of their optics and performing analysis with freely available software. The parts needed to assemble the Bath interferometer can be picked up quite cheaply on the surplus market. High quality optics are not required as the outgoing and returning wave fronts pass through the same optical components twice. The geometry of the set up results in the introduction of some astigmatism which is not serious in longer focal length mirrors. Some of the software available takes this into account when performing analysis, and compensates for it.
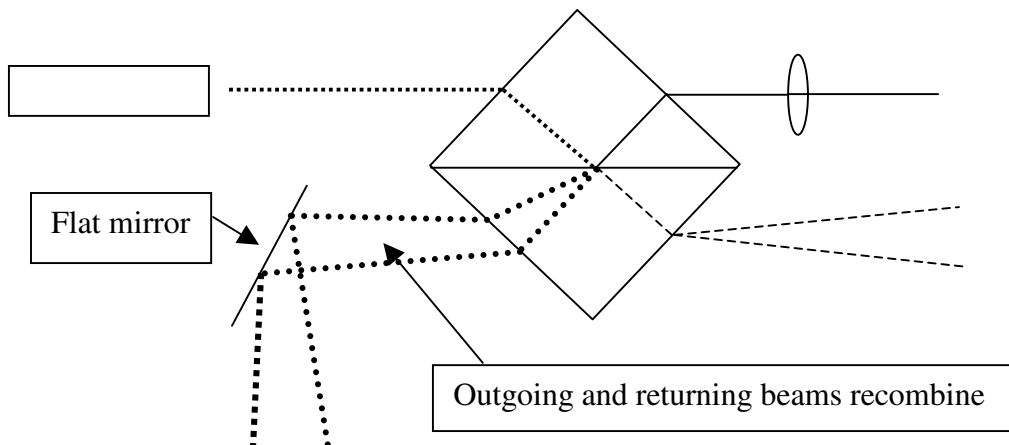
Strehl ratio expresses the performance of a mirror in comparison to the ideal performance. A perfect mirror has a Strehl ratio of 1, a mirror meeting diffraction limited performance has a Strehl ratio of 0.8

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The optical Layout of the Bath Interferometer.

The diagram shows the paths of the outgoing rays from the interferometer to the test surface.

Beamsplitter cube

Biconvex lens

Laser pointer

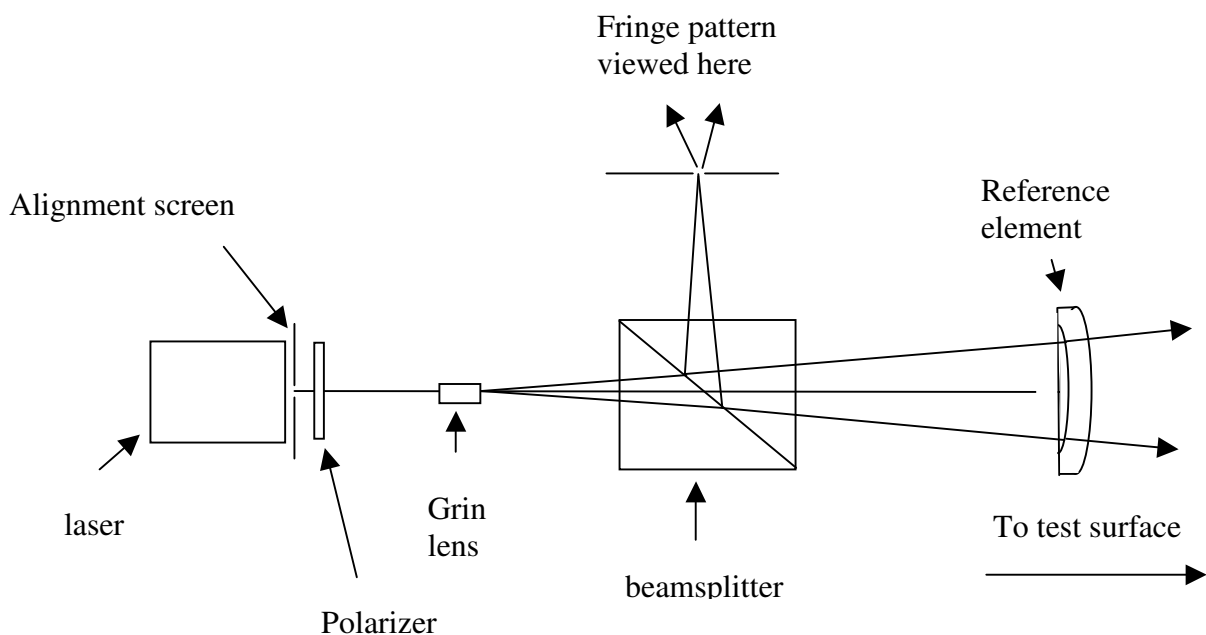Mirror under test
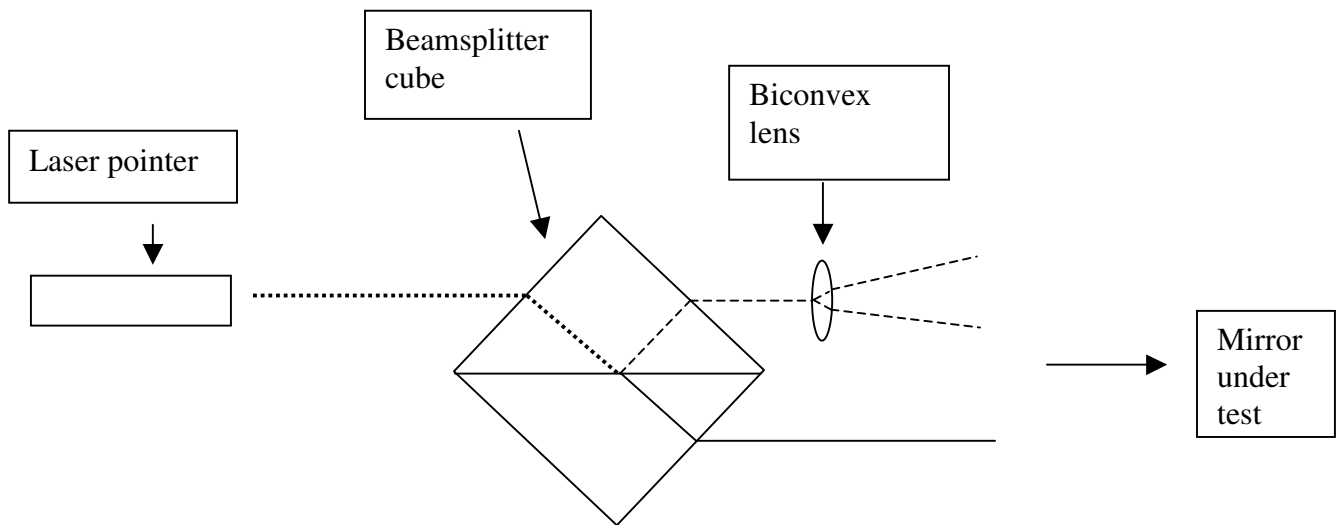
The diagram below shows the paths of the rays returning from a test surface. The rays from the bottom of the cube re-enter the beam splitter through the biconvex lens. The rays from biconvex lens re-enter the beam splitter at the bottom without passing through the lens again.

Flat mirror

Outgoing and returning beams recombine

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The outgoing and returning rays re-combine in the beam splitter to produce the interference fringes.

The Ceravolo Interferometer.

An alternative to the Bath interferometer is the interferometer popularized by optician Peter Ceravolo. This version employs a high quality reference element, the outgoing and returning beams follow the same path therefore astigmatism is not introduced. The disadvantage of this setup is that the reference element is quite expensive and beyond the means of some amateur telescope makers. The optical layout of the interferometer is shown below:

Fringe pattern
viewed here

Alignment screen

Reference element

laser

Grin
lens

To test surface

beamsplitter

Polarizer

The reference surface is spherical which means that straight fringes are seen when an ideal spherical mirror is tested.

The authors Ceravolo Interferometer
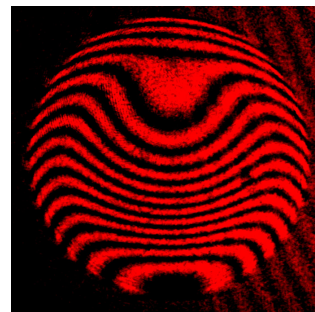
Interferogram of a parabolic mirror

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Testing an aspheric mirror with a spherical wavefront Interferometer.

The objective of interferometry is to produce an image of the fringe pattern, called an interferogram, this is usually in the form of a digital image which can be used by appropriate software to calculate the surface profile. In practice, when using the software, the edge of the mirror is defined and the fringes are then traced either manually or automatically, once this is done the software calculates Zernikes, these are numbers that quantify the various aberrations present in the optic. An overall view of the optics is presented in terms of it's Strehl ratio, RMS and PTV values.

Both of the interferometers discussed so far are best suited to testing spherical mirrors as these show straight fringe patterns which are relatively easy to interpret. Unfortunately, many surfaces employed in astronomical telescopes are not spherical; they are aspheric surfaces such as paraboloids, ellipsoids and hyperboloids.

For longer focal length mirrors this is not a problem as software can employ artificial nulling, a process which compensates mathematically for the difference between the test optic and a spherical one. This process starts to become less reliable with decreasing focal length and as a result alternative solutions must be found. From the notes on the autocollimation test you will recall that this is a null test for a paraboloid, one solution is to use an interferometer in conjunction with the autocollimation test, an ideal parabolic mirror produces a spherical wavefront in the autocollimation test, and such a wavefront will produce straight fringes when viewed with the interferometers described here. It should be noted that in practice very careful alignment of the optics in needed in order to avoid the introduction of aberrations, which can potentially confuse the analysis. Testing in this mode can result in the test wavefront being fainter than the reference wavefront due to the double reflection off the flat and the fact that the test mirror is uncoated, as a result fringes may be faint making analysis difficult if not impossible.

Another useful combination of tests involves the use of a Ross null lens and an interferometer. This combination has the advantage over autocollimation in that it can be used with aspheric surfaces other than a paraboloid. This is achieved by varying the spacing of the elements. Again the setup is quite sensitive to alignment problems.

For further information see;
http://www.ceravolo.com/testing/interferometer.htm
http://starryridge.com/mediawiki-1.9.1/index.php?title=Bath_Interferometer

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