# **Interferometry and Telescopes**

A practical guide to building and using your own interferometer

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Further Reading

Optical Shop Testing Second Edition, Edited by Daniel Malacara, John Wiley and Sons Telescope Optics, by Rutten and van Venrooij, Willmann-Bell

Modern Optical Engineering Second Edition, by Warren J Smith, McGraw-Hill

#### Preface

This booklet has been written to assist commercial and amateur telescope makers in discovering the modern testing technique of laser interferometry.

Much of the material dealing with interferometry found in the professional literature is very technical and does not deal effectively with the practical techniques and concerns of testing optics. This booklet will attempt to explain, in simple language, how interferometers work, how to build an interferometer and how to test telescope optics by interferometry. In writing this booklet, the emphasis was placed on presenting hard to find information in a easy to understand way.

It is assumed that the reader has had some experience with testing mirrors, or is familiar with optical testing techniques like the Foucault and Ronchi tests. If not, the persistent worker will still be able to assemble an interferometer and use it in experiments, and even engage in the testing of telescope optics.

Interferometry is a very technical subject with no shortage of specialized lingo and concepts which may be difficult to understand without having seen an interferometer in use. If you have difficulty understanding the technical matters, ignore them! At least for the time being. The best way to learn about interferometry is to actually do it. And do not be intimidated by the misconception that one needs finely machined components to do interferometry. The first time I laid out the interferometer described in this booklet I used masking tape to hold everything together!

Remember, during those frustrating times when things don't seem to work, *fringes are fun!* I recall how thrilling it was to see fringes when I first slapped together my first interferometer, even though I routinely work with high-tech commercial units. There is something special about making a piece of equipment which does essentially the same job as a commercial instrument costing tens of thousands of dollars!

#### Introduction

The optical tests amateur telescope makers use have changed little in the last hundred years. The Foucault test, invented in the mid 1800's, is unusual in that even a crude apparatus made of wood, a razor blade and a light bulb becomes an extremely powerful device capable of magnifying otherwise invisible defects on a mirror many thousands of times.

Unlike amateur testing techniques, the last thirty years have seen great advances in professional optical testing techniques, and the invention of the laser revolutionized the field of interferometry. However, these modern techniques were largely out of reach of the amateur telescope maker because of the very expensive equipment and extensive engineering know-how needed to perform these tests. Today, due to the availability of inexpensive lasers and computers, modern interferometry can now be practiced by advanced telescope makers in their home workshops.

Interferometry offers many advantages over the well known Foucault knife-edge and Ronchi tests, the main fault of the latter two being their subjective nature. The Foucault test's shadow pattern is qualitative; figure errors are easily detected, but their magnitude is not easily measured. In contrast, interferometry easily lends itself to objective computer analysis, avoiding the biases and inexperience of the operator.

While the Foucault and Ronchi tests easily reveal small errors in figure, the magnitude of aberrations can be difficult to measure accurately, particularly when the aberrations are subtle. Non-rotationally symmetric aberrations such as coma and astigmatism can be difficult to see and impossible to measure accurately. The interferometer's fringe pattern is quantitative in nature. The distortion of the fringes from straightness is directly related to the magnitude of aberration. While the intensity of shadows in the Foucault test is hard to quantify, the straightness of a fringe in an interferogram is easily measured.

Another drawback of the Foucault and Ronchi tests is the variability of sensitivity with the focal ratio of the optic being tested. The greater the focal ratio, the greater the sensitivity. A 1/4 wave figure error on an f/8 mirror will be more apparent than a 1/4 wave figure error on an f/2 mirror. However, the sensitivity of interferometry is constant with respect to the focal ratio of the optic being tested. One type of optical testing that is not done with interferometry is the testing of color correction in refractors. By its very nature, interferometry requires monochromatic light. Only aberrations which reveal their presence at the particular color being used will be seen.

Interferometry is also more difficult apply to optical testing than the Foucault and Ronchi tests. It is convenient to slap together a Foucault setup by stacking phone books to get the tester at the right height, but interferometry requires more care in making sure the optics and tester are held firmly in place without flexure, since excessive motion of the interference pattern can make testing difficult, if not impossible.

#### **Interferometry Basics**

In the Foucault test, a razor blade cuts into the converging beam reflected off a concave mirror. If the lights rays reach a common focus, a smooth graying of the mirror will be observed. If, however, the mirror is flawed, the knife edge will intercept some rays while letting others pass by, causing defects on a mirror to appear as shadows on its surface. With the Foucault test, the spherical mirror at the center of curvature is tested "against itself" since no additional optics are required.



The Fringe Pattern

Interferometry is different in nature. The light reflected off the test mirror (the test wavefront) is compared to the light reflected off a reference surface (the reference wavefront) of known quality. When the test and reference wavefronts are combined they form interference fringes whose form are an indication of the optical quality of the mirror under test. A telescope's optical performance can be assessed by analyzing the degree of straightness of the fringes: the straighter the fringes, the higher the quality.

The interference pattern contains *quantitative* information derived from a measure of the spacing of the fringes. When a telescope mirror is tested at the center of curvature, one fringe spacing corresponds to 1/2 wave on the mirror's surface. If a depression on the mirror's surface causes a fringe to distort by one fringe spacing, the defect is 1/2 wave deep.

In order for interference fringes to be clearly visible the light source must be monochromatic. If the test surface can be placed in contact with the reference surface, as when checking a Newtonian diagonal against an optical flat, a simple, reasonably monochromatic low pressure sodium vapor lamp (i.e. an outdoor security light) can be used, since the test and reference surfaces are nearly in contact. But when non-contact interferometry is required, as when testing the wavefront quality of a complete telescope for example, a laser must be used. The highly monochromatic nature of laser light allows a large separation, or optical path difference, between the test and reference surfaces. Optical systems as a whole, not just their individual elements, can then be analyzed by interferometry.

Interferometry is much more sensitive to environmental disturbances than the Foucault or Ronchi tests. Even slight air currents and vibration can make interferometry difficult. While it is easy to jury rig a Foucault test, an interferometer requires solid optical mounts to reduce vibrations, and a shrouded optical path to dampen air currents. Even so, interferometry is not beyond the means of the resourceful hobbyist.

#### **Types of Interferometers**

Over the decades many types of interferometers have been designed to fulfill a variety of testing requirements. The original and simplest interferometer is the Newton interferometer. It is commonly known as the "test plate method" of testing optical surfaces, where the test and reference surfaces are in contact. The fringes are formed by the narrow air gap between the test and reference surface, and are generally viewed by the eye alone. Test plates have been used by opticians for at least a century and are still in wide use today, especially in high volume production optical shops.



# Newton (test plate) Interferometer

One of the main disadvantages of the Newton interferometer is the possibility of scratching surfaces when they are in contact. Test plates are also only useful for checking the quality of individual surfaces. It is not possible to check the total system quality of a telescope with the Newton interferometer.

One of the first modern interferometers was the Tymann-Green modification of the Michelson interferometer. Monochromatic light is collimated by a lens and is then split in two by a beamsplitter to form the reference and test beams. The beams reflect off the master and test flats, to be recombined by the beamsplitter. The fringes are viewed at the focus of the imaging lens. The Tymann-Green interferometer is capable of producing fringes without the necessity of having contact at the test and reference surfaces.



## Tymann-Green Interferometer

Non contact testing without laser light was possible because the optical path length, or distance the light travels, in the test and reference arms of the interferometer were made nearly identical. As far as the light is concerned, the test and reference surfaces are effectively in contact, allowing fringes to form. This balancing of the light path permitted the Tymann-Green interferometer to test complete telescopes, not just their individual surfaces. The significant difficulty with the Tymann-Green interferometer is the requirement of very high quality beamsplitter and auxiliary optics in the test arm.

Of the many types of interferometers that can be applied to optical testing, the simplest to build and the one that is found in most modern optical shops is the Fizeau interferometer. The important difference between the Newton test plate method and the Fizeau interferometer is in the lens used to collimate the light striking the reference and test surfaces.

If the fringes in the Newton interferometer are viewed from too close a distance they will be distorted. For maximum accuracy the monochromatic light must strike the surfaces at normal incidence, or perpendicularly, which basically means that the wavefront of the illuminating light must have roughly the same shape as the optics being tested. In the case of testing flats, the wavefront of the illuminating light must be flat. The lens in the Fizeau interferometer collimates the light rays diverging from the source, causing them to strike the flats at right angles.



The fringes in the Fizeau interferometer are observed at the focus of the collimator. This viewing position ensures that the eye (or camera) is seeing properly collimated light, eliminating the possibility of distortion caused by incorrect viewing distance.

The Fizeau interferometer design requires that only the reference surface of the interferometer to be of high quality; all surfaces before it may be of lesser quality because they only affect the collimation of the light. The collimation optics can be as bad as several waves before otherwise straight fringes suffer a significant amount of distortion. Remember, the fringes are formed in the interferometer "cavity", the space between the reference and test surfaces. The Tymann-Green interferometer requires very high quality optics in the cavity, mainly the beamsplitter and any focusing lenses. The quality of these optics have a direct affect on the fringes. The Fizeau interferometer requires no optics in the interferometer cavity to function.

The Fizeau modification of the Newton interferometer was limited to testing flats in near contact since the fringes would disappear when using conventional monochromatic lamps and when the air space between surfaces was increased beyond a millimeter or so. Using a laser with its high purity light allowed the simpler Fizeau interferometer to test spherical and flat surfaces which are widely separated from the reference. The laser Fizeau quickly superseded the Tymann-Green interferometer as the instrument of choice in optical shops.

There are a number of other unique interferometer designs that have been developed which excel in simplicity and effectiveness. Two that stand out are the point diffraction interferometer (PDI) and the Shack cube interferometer. The PDI is known as a common path interferometer; the reference beam is generated by the same optics being tested, so it is much less sensitive to vibration and air currents. The PDI requires a pinhole in a semi-transparent medium, such as partially exposed film, and a small, high quality beamsplitter. The pinhole must be smaller than the Airy disk of the system being tested. Such a small pinhole is difficult to make and alignment can be difficult.

One great advantage of the PDI is its ability to form fringes under polychromatic, or "white, light. In fact the PDI has been used to test large telescopes in the observatory using starlight. Amateur use of the PDI was described in the February, 1985 issue of Sky and Telescope magazine. Despite its simplicity, the PDI can be difficult to implement and has not seen widespread use.

The Shack cube interferometer is of the Fizeau type, but it is dedicated to testing the converging wavefronts of a mirror at the center of curvature, or of a telescope under autocollimation. The Shack cube interferometer inherited its name from Roland Shack, of the University of Arizona, who combined a beamsplitter cube with a high-precision plano convex lens. The Shack interferometer is capable of producing a high quality, very fast cone of light for testing strongly curved wavefronts. The Shack interferometer is described in the SPIE conference proceedings, Interferometry, vol 192 (1979), pg. 35.

The spherical wave interferometer to be discussed in this booklet is of the Fizeau type and is similar in nature to the Shack interferometer, but considerably easier to build. The spherical wave interferometer, like the Shack, is limited to testing converging wave fronts. It can be used everywhere a Foucault tester is used, and since it is simple in design it is ideal for amateur construction. The spherical wave interferometer was developed by the author to meet in-house testing needs at Ceravolo Optical Systems.

# The Spherical Wave Interferometer



Kitchen table interferometry!

The spherical wave interferometer is well suited to amateur construction since it is relatively simple in principle and requires a minimum of precision components. Because this interferometer is located close to the telescope's focus it can be physically small and compact, thus reducing the cost of the precision optics required. In fact, the interferometer can be designed to slide into the telescope's focuser tube, thus making testing very convenient by reducing the extra mounting hardware necessary to support the interferometer.

This interferometer is of very simple construction when compared to the instruments used in professional optical shops. The interferometer's simplicity is the result of specifically tailoring it to the testing needs of telescope mirrors and complete telescopes. As stated earlier, this interferometer can be used wherever the ordinary Foucault tester is employed.

The interferometer consists of a small laser for the light source, a polarizing filter, a gradient index (grin) lens to diverge the laser beam, a beamsplitter to make the fringe pattern accessible, and the reference element, whose convex surface is the master surface the test wavefront is compared to. All items, except the reference element, can be purchased from optical and surplus house catalog listings.



The optical elements will be described in detail later on, but let's briefly go over the way the interferometer works. The laser beam passes through a rotatable polarizing filter used to adjust fringe contrast (see the chapter "The Laser"), and is then made to diverge from parallelism by passing through a gradient index (grin) lens. The diverging beam travels through a beamsplitter and onward to the reference element. The concave surface of the reference element causes the cone of light to diverge a little more, but without introducing aberrations. The light then passes through the convex master surface of the reference element, without further deviation, toward the telescope or test mirror.

Some of the light is reflected off the reference surface and retraces its path back into the interferometer. This is the reference wavefront. The remainder of the light returning from the telescope or test mirror retraces its original path back through the interferometer and interferes with the reference wavefront, thus generating the fringe pattern. The interfering test and reference beams pass through the beamsplitter, and are reflected 90 degrees to the secondary focus where the fringes are viewed or photographed.

The target screens placed around the grin lens, laser and the secondary focus of the interferometer will greatly aid in the alignment of the interferometer components, and also aid in aligning the optics to be tested. The function of the target screens is explained in the chapter, "Assembling and Aligning The Interferometer".

The nature and function of the optical components will now be described in detail.



The experimental laser interferometer fashioned from bits and pieces of aluminum lying around the shop. A very short focus test mirror is mounted in an adjustable holder, and both are mounted on a small optical bench.



The light path in the interferometer is revealed by smoke blown into the light beam in this time exposure.

The Grin Lens

The grin lens is a tiny glass rod about 2mm in diameter and about 4mm long. The index of refraction of the glass is not constant within the rod, but varies radially. This variation in refractive index causes the rod to act as a lens, even though it has flat, not curved, surfaces.



The Gradient Index (Grin) Lens

The use of a grin lens provides a very simple and convenient way to generate a diverging cone of light. The faces of the grin lens should be anti-reflection coated, otherwise spurious background interference fringes will form. Such spurious fringes may seriously affect the accuracy of test results.

The focusing power of the grin lens is described by its numerical aperture (NA). The NA can be converted to a focal ratio by the simple equation:

f/# = 1/2 NA

Since the grin lens must full illumination across the reference element, it must be carefully selected so as to match the reference element's f/#. In fact it is better to over-fill the reference element since "noise" at the outer edge of the beam is "filtered" out of the interferometer.

A 1.8mm diameter grin with an NA = 0.46 has a focal ratio of f/1. But this is only true if one is filling the full 1.8mm aperture with laser light. Most lasers emit a very narrow beam, typically 0.5 mm. The grin, when used with such a laser, is underfilled and yields about an f/4 cone of light.

# The Beamsplitter

To allow the fringe pattern to be viewed, the return beams from the reference element and the optic under test must be separated or "split" from their original paths and then be redirected to an accessible observation point. A beamsplitter accomplishes this by both partially transmitting and reflecting light passing through it.



A cube beamsplitter is made from two identical right angle prisms cemented together at their hypotenuse faces. On the hypotenuse of one of the prisms is applied either a partially reflecting coating of aluminum or a modern multi-layer dielectric (non metal) coating. Unlike a dielectric beamsplitter, a metal coated beamsplitter will absorb a significant portion of the light. This is unimportant, however, since even a low power laser will deliver plenty of light for most testing requirements.

The cube beamsplitter has two significant effects on the light cone emanating from the grin lens, and which must be considered when designing the interferometer.

First and most important is the introduction of spherical aberration. A cube beamsplitter is essentially a thick glass plate. When such a plate is inserted in a converging (or diverging) cone of light, the outer rays strike the flat surface of the beamsplitter at a greater angle than those rays close to the optical axis. This causes spherical aberration, which worsens with "faster" beams. Because the laser light passes through the beamsplitter twice in the interferometer, the aberration is doubled.

The spherical aberration introduced by the beamsplitter can be minimized by doing one or both of the following. Reduce the size of the beamsplitter and place it closer to the interferometer's focus, or limit the speed of the cone of light emerging from the interferometer.

The second effect to consider is the shift of focus along the axis caused by the glass thickness of the beamsplitter, the magnitude of which is given by the simple formula:

focus shift = t (n-1)/n,

where t is the cube beamsplitter's thickness, and n is its refractive index.



# Focus Shift (highly exaggerated) with Beamsplitter

Cube beamsplitters are expensive purchased new, however inexpensive 12mm (1/2 inch) cubes can be purchased from surplus suppliers listed at the end of this document. An alternative is the plate beamsplitter, a thin glass plate tilted at 45 degrees. This plate must be thin, otherwise a significant amount of astigmatism will be generated by the inclined plate, and which may affect test results.

The plate beamsplitter should only be used for checking slow cones of light. An f/4 or slower mirror checked at the center of curvature (i.e., an f/8 beam) should not pose a problem with a beamsplitter plate that is no more than several millimeters thick. The plate should be placed close to the focus so that only a small area of its surface is used—plate beamsplitters are seldom very flat.



Beam displacement with plate bemsplitter

The plate beamsplitter causes, in addition to an axial shift of focus, a lateral displacement of focus away from the optical axis which should be considered when the interferometer is laid out.



There are many unwanted reflections which occur in the beamsplitter, causing spurious fringes and a general fogging of the fringe pattern. This source of noise can be largely blocked by a screen pricked with a pinhole. The pinhole passes the light from the reference element and test optics, while the screen blocks the stray light from getting to the eye or camera. Such a card with a pinhole is called a "spatial filter" by optical engineers.

#### **The Reference Element**

The reference element, the heart of the spherical wave interferometer, is essentially a small, high-precision negative lens. The light diverging from the grin lens passes through the concave surface of the element. This is what is known as an aplanatic surface; it causes the light to diverge slightly without introducing aberrations, provided it is figured well.

Because a laser is used in the interferometer, many spurious interference patterns are generated between beamsplitter and lens surfaces. Coating all glass surfaces except for the test and reference surfaces will help to reduce these undesirable fringe patterns. The aplanatic surface of the reference element should be coated with a high efficiency (less than 0.5% reflectivity) multi-layer dielectric coating.



The Reference Element

The convex side is the master surface. Its radius is chosen such that light will pass through it without further deviation. A fraction of the light is reflected off the master surface and back into the interferometer; this is the reference wavefront. The rest of the light proceeds to the optic under test where it is reflected back to the interferometer so that it may interfere with the reference wavefront. Since the reference element is a negative lens, it shifts the focus back from its origional position and slows the apparent focal ratio of the mirror or telescope being tested by a factor equal to its refrative index. In other words, an f/8 beam will appear as an f/12 beam if the index of the reference element glass is 1.5.

# **Designing and Making the Reference Element**

Designing the reference element is very simple. But making it can be quite difficult. For those who wish to purchase the reference element, CERAVOLO Optical Systems is making a limited number available for the price of \$375. The 1" clear aperture reference element, made from optical grade Zerodur, generates an f/3.2 diverging beam. The critical master surface is tested by computerized interferometry to meet or exceed the  $\lambda/10$  criterion over the full f/3.2 aperture, and is even better at slower focal ratios. Each reference element is supplied with a quality assurance test data sheet specifying that particular reference element's optical quality.

When designing the reference element there are two parameters which must be established. The first is the limiting focal ratio of the interferometer, and the second is the diameter of the master surface.

The COS reference element is designed to yield an f/3.2 beam, since most telescopes are not faster than f/4. Also remember an f/4 mirror at the center of curvature produces an f/8beam. So the COS reference element can actually test a mirror as fast as f/2 at the center of curvature. It is always advisable to make the interferometer faster than the fastest telescope likely to be tested so as to provide a "buffer" around the edge of the interferometer field. The 1" clear aperture implies the master surface will be placed about 3.2" inside focus (or ahead of the radius of curvature) of the mirror being tested.



# Designing the Reference Element

Given that we have established the distance inside focus (S), determining the reference element's two surface radii is easy:

The master surface radius (R1) is equal to the distance inside focus,

# R1 = S

The radius of aplanatic concave surface (R2) is given by,

R2 = n(S - t) / (n + 1)

where n equals the refractive index of the material used, and t is the center thickness of the element.

Note: the reference is a negative lens, causing the focus to shift farther back. The resultant back focus, from the vertex of R2 to the focus is

BFL = n (R1 - t).

The reference element must be made of an optical grade material, since variations in homogeneity of the glass will distort otherwise straight fringes. The crown glass normally used in refractor objectives can be used, but a more thermally stable substrate like ultrahigh quality fused silica or Zerodur is preferred, especially if the reference element is larger than 2" in diameter.

The lens should also be thick enough to resist any stresses when mounted in the interferometer. The standard 1:6 aspect ratio will be sufficient if care is exercised in its mounting. Lenses smaller that 2" may be difficult to figure with the traditional ATM techniques, so make it at least large enough to be comfortable to work on.

The master surface is the most critical part of the reference element, since the test optic is directly compared to it. In order for the interferometry results to be accurate, the master surface must be made as precisely spherical as possible.

The concave surface of the reference element is not as sensitive to errors as the reference surface, and provided that the radii and glass thickness are strictly adhered to, need only be accurate to 1/2 wave or so. This is because this surface only affects the collimation of the light relative to the master surface.

The master surface is convex and therefore cannot be tested directly by reflection with the Foucault test. However, if the reference element is made precisely, that is by grinding the radii and the thickness of the lens as close as possible to the design parameters, and by figuring the concave side as accurately spherical as possible, we can then test the convex master surface through the concave surface with the ordinary Foucault test.

A word of caution. The difficulty of making excellent spherical surfaces must not be underestimated. One of the myths of telescope making is that spherical surfaces come naturally. Take it from someone who has made hundreds of spherical surfaces—they do not always come easy!

The procedure for making the reference element is no different from that of making any other precision lens, so we will not go into any great detail here (see Telescope Making Magazine #3).

Both surfaces are first accurately ground, de-wedged and completely polished before any figuring is attempted. The concave side is first figured as accurately as possible with the

Foucault test. There should be absolutely no visible zones, since the sensitivity of the Foucault test is poor with fast cones of light. If the reference element is to cover an f/3 beam, the concave side of the lens will have approximately an f/2 curve at the center of curvature. It will be difficult to see the whole aperture because the cone of light is so steep.



Testing the Reference Element

With the concave surface accurately figured, we can now test the convex side through the concave surface as a Mangin or second surface mirror. The knife-edge should be positioned where the grin lens will be mounted. It is important to remember here that what appears to be a bump is in fact a depression on the surface, since we are checking this surface from the "other side". The internal reflection works in our favor because the visibility of zones is amplified by a factor equal to the refractive index of the lens. But this must be weighed against the fact that the light must first pass through the concave surface, whose test was nowhere near as sensitive.

The reference element is the most demanding part of the spherical wave interferometer. Once made, the job of assembling the interferometer is relatively straightforward.

## Mounting the Components

The mountings for the optical components of the interferometer do not need to be precision machined in order to work well. All that is required of the mounts is the ability to tip, pivot and adjust in separation and height. This can be accomplished by simply drilling oversized holes in some of the fixtures, and using large diameter washers with the machine screws to clamp the components together once alignment has been achieved.

The mounting hardware should be made of aluminum. No detailed dimensions are given since the mount designs can be easily adapted to readily available materials.

The laser should be mounted first, since the height of the laser beam will necessarily determine the height of the other components. The surplus bar code scanner lasers listed in the parts list are encased in a plastic box along with the power supply. The entire unit can be simply bonded with RTV (rubber cement) to a base plate long enough to hold the entire interferometer assembly. No provisions for adjustments are needed as long as the beam is reasonably parallel with the mounting plate. More conventional lasers housed in aluminum tubes should be carefully clamped to V-blocks mounted on the base plate.

The reference element should be mounted to a plate having a hole equal in diameter to the working aperture of the interferometer. No machining is required, since the reference element can be placed over the hole, with three small dabs of RTV spaced equally along the edge being all that is needed to hold the lens in place.



Mounting scheme for Reference Element

The grin lens is best mounted on a thin plate about half as thick as the grin lens is long, through which a hole slightly larger than the grin lens diameter is drilled. A small dab of epoxy cement will hold the grin lens securely, but be very careful not to get any cement on the faces of the grin lens. Don't be otherwise afraid to touch the faces since they can be cleaned later.



# Mounting scheme for Grin Lens

Clean both the plate and grin with alcohol. Rest the plate over a soft facial tissue and carefully place the grin in the hole with tweezers. Since there is no front or back to the grin, either end can be inserted in the hole. Scoop up a tiny bead of epoxy cement with a needle and carefully apply it to the edge of the grin and the aluminum plate (use a magnifying glass to see clearly) and allow the epoxy to set for the required length of time.

The beamsplitter can also be as simply mounted. Attaching it to a piece of U-channel aluminum using RTV is effective. The U-channel is ideal, since a spatial filter and camera can be easily supported on one arm of the "U".



# Mounting scheme for beamsplitter

A circular polarizing filter may be necessary to improve fringe contrast (see the chapter, "The Laser"), and must be mounted so that it can rotate easily. No fine adjustment of rotation position is necessary, since the polarizer will only have to be adjusted every several minutes or so depending on the stability of the laser.

#### The Laser

# CAUTION: NEVER STARE INTO THE CONCENTRATED BEAM OF ANY LASER OR EYE DAMAGE WILL SURELY RESULT!

The choice of a light source in interferometry is important. It must be as monochromatic as possible, otherwise interference fringes will not be visible. When the test and reference surfaces can be placed nearly in contact, a simple mercury vapor or low pressure sodium vapor lamp (i.e., an outdoor security light) will work very well.

While these light sources are not highly monochromatic, the spacing between test and reference surfaces is not very great when compared to the wavelength of light. If the spacing is increased to avoid contact between test and reference surface (to avoid scratches for example) fringe contrast will suffer, reaching a point where fringes will no longer be visible.

Testing a mirror that is widely spaced from the reference surface is known as large path difference interferometry, and is made possible by the use of a laser. Laser light, specifically from a common helium-neon laser, is ideal bacause it is highly monochromatic, allowing very large path differences on the order of many feet instead of micro-inches. In the case of testing telescopes and concave reflector primary mirrors, large path difference interferometry allows the master surface to be very small in comparison to the concave mirror being tested. This is a very important consideration— amateur telescopes are now approaching one meter in diameter!

The common, red helium-neon (HeNe) laser that one is likely to encounter is far superior to the sodium vapor lamp for interferometry work, but it is still not perfect. The only lasers which should be considered for interferometry are known as single transverse mode lasers (TEM<sub>00</sub>). Instabilities within the laser tube cause the fringe contrast to vary with time. These instabilities generate what are known as "longitudinal modes". When more than one longitudinal mode is present in the laser cavity, fringe contrast will suffer or the fringes may totally disappear. The longer the laser the greater the instabilities, and therefore the possibility of a greater number of modes forming in the laser cavity.

Fringe contrast will be increased if a single longitudinal mode is isolated from the rest of the modes by use of a polarizing filter placed in the laser beam immediately before the interferometer. The longitudinal modes are orthogonaly polarized. While one mode is vibrating in the plane of this paper, for example, the other mode is vibrating in a plane perpendicular to the plane of this paper. The polarizing filter is rotated until it allows the light from one mode to pass through the polarizing filter while light from the other mode is reduced in intensity. This filtering of extraneous modes can make the difference between seeing and not seeing fringes with a long, high power laser, and will make the fringes stand out in bold relief in a short, low power laser.

Used lasers are readily available at low cost from some surplus stores or surplus mailorder houses, although stock may be limited. The ideal laser will be non polarized and have a tube length of less than 10". The surplus bar code scanner laser module in the parts list at the end of this booklet is ideally suited for interferometry, although instabilities within the 6" long laser tube will cause fringe visibility to vary with time and changing environmental conditions, however a polarizing filter, rotated to suit, will increase fringe contrast.

The laser module is convenient since it has a power supply built into the case (normally they are separate units for higher power lasers) which requires just a 12 volt DC transformer as the power source. One laser module, purchased from Herbach and Rademan, was advertised as a 1/2 milliwatt laser but was found to be actually 1 milliwatt, powerful enough for most testing applications. Surplus lasers may vary significantly from advertised power levels.

Diode lasers are not suitable for interferometry. The diverging beam is usually very astigmatic (producing a rather elongated spot) and will adversely affect the test results. They are also not stable; the frequency of the laser light will vary with voltage and temperature, making the fringe pattern difficult if not impossible to see.

The standard red HeNe laser will do for most optical testing applications, particularly the testing of mirror and lens *surfaces*. However, when testing telescope tube assemblies having transmissive optics (such as refractors), careful consideration must be given to the wavelength of light being used. Most telescopes which use lenses suffer from what is known as chromatic aberration.

Refractors are typically designed to give the sharpest images in green light, the color range the eye is most sensitive to. The spherical aberration correction in refractors will vary with color—this is called spherochromatism, and can sometimes be as severe as 1/2 wave or more, depending on aperture and focal ratio. Apochromats may also suffer from this problem, even though the chromatic aberration is visually insignificant.

Schmidt-Cassegrain telescopes also suffer from spherochromatism. The Schmidt corrector plate, comprising a single lens, is not achromatic and therefore exhibts a large amount of color when analyzed with optical design software. Of course this color is usually not noticeable visually because the eye's insensitivity to red and blue light. The color aberration can be glimpsed, however, when a Schmidt optical system is tested by autocollimation with the Foucault or Ronchi tests.

Apperently, most producers of Schmidt-Cassegrain telescopes test their optics in red light, so testing the telescopes with a red HeNe laser would not be out of line.

Telescopes using refractive components may in general not test accurately with the red HeNe laser light. A green laser is therefore required. For further discussion on this matter please refer to the chapter, "Using the Interferometer".

## Assembling and Aligning the Interferometer

The mechanics of the interferometer should be designed so that the centers of all the mounted elements are at the same height. It is not necessary to make finely crafted mounts. Shimming, and bolting components together with oversized holes and washers will provide enough freedom of motion to properly align the optics.

Aligning the components of the interferometer is straightforward if done sequentially and in a darkened room. A piece of white cardboard mounted in front of the laser, and having a pinhole to pass the laser light, is very helpful in achieving alignment. Laying the system out on paper, with the proper spacings indicated, will also be of some help. Remember that a thick cube beamsplitter will cause a shift in focus. And do not confuse the focus of the interferometer with the center of curvature of the concave surface of the reference element.

First, the laser is fixed to a plate long enough to accommodate all of the components. The surplus bar code scanner laser can be simply glued in place with RTV cement. A cylindrical laser head should be mounted in a vee-block type holder for rigidity. The beamsplitter is fixed in place, then the reference element is positioned so the laser light is passing through its center. Use a ruler to center the beam within a millimeter or so.

The grin lens is then mounted and adjusted so that the pencil thin laser beam passes through its center. There will be a reflection from the grin lens' face bouncing back to the cardboard screen. The grin lens is tilted about until that reflection is positioned in the vicinity of the pinhole, but not too close, or spurious interference fringes may be generated within the grin lens and projected onto the reference element. Such fringes should be avoided, since they will interfere with the fringe pattern from the test optics.

The reference element should be evenly illuminated by the diverging laser light. If the light is slightly off center, make a fine adjustment of the grin lens to evenly illuminate the reference element.

If the initial positioning was reasonably accurate, the internal reflection at the master surface will cause the laser light to retrace its path and come to a focus in the vicinity of the grin lens. If not, the reference element's tilt and position must be adjusted until the spot falls back on to the grin lens. This alignment can be finessed, since the light retroreflected through the grin lens will form an out of focus spot on the cardboard screen fixed to the laser. This stage of the alignment is touchy. The reference element is moved slightly to and fro and tilted until the spot is focused on the screen fixed to the laser and is projected back to the vicinity of the pinhole. This fine alignment can be quite frustrating, but persistence will pay off.

The interferometer is now ready to go! But before you can test optics you will have to make some solid supports for both the interferometer and the test optic if the fringes are to be at all steady. If possible, mount both the interferometer and the test mirror on a common rail, so that if there is some motion they will at least move together.

If the path length is very long, place your mirror stand and interferometer stand on a concrete floor in the basement, or the next best solid surface. Keep in mind that you are trying to hold two wavefronts relative to each other to within a fraction of a wave! This is quite demanding on optical mounts, so build them stiff and heavy, otherwise the fringes will creep, never sitting still long enough to analyze them.

# Viewing and Recording the Fringe Pattern

The interference fringes generated by the test and reference beams may be viewed by several methods. The simplest and safest method involves switching off the room lights and projecting the fringe pattern on to a screen placed anywhere beyond the secondary focus of the interferometer.

With such an arrangement it is possible for a group of people to view the fringe pattern at one time. The farther the screen is placed from the focus of the interferometer the larger the fringe pattern becomes. The limit to the size of the fringe pattern occurs when the light is so spread out and dimmed that it is difficult to clearly see the pattern. A high power laser is desirable (one greater than 2 milliwatts) for fringe projection, since the more intense beam will permit a greater projection distance and a larger fringe pattern.

The fringe pattern may also be viewed directly by placing the eye at the focus of the interferometer, right up against the spatial filter.

# CAUTION: NEVER STARE INTO A CONCENTRATED LASER BEAM SINCE SERIOUS EYE DAMAGE WILL OCCUR!

When looking into the interferometer one is not staring into a concentrated laser beam since the cone of light is expanding and the fringe pattern is projected directly on to the eye's retina. Visual interferometers are not uncommon in optical shops and can be safely used provided proper precautions are exercised.

The laser light reaching the eye will be reduced in intensity by the polarizing filter (transmitting approximately 30%), the beamsplitter and by the bare glass reflections off the test and reference surfaces. Even with all this filtering, visual observation of the fringe pattern should only be performed with a low power laser of 1 milliwatt or less.

If the intensity of the fringe pattern is still too great, a suitable neutral density filter placed between the eye and the interferometer will make viewing the fringes more comfortable. If there is any doubt, be cautious. Better faint than sorry. *Be especially careful if the master surface has been partially aluminized to match the reflectivity of a coated test mirror. The laser light reflected back to the interferometer will too bright to be safely viewed by eye and <u>must be filtered</u>.* 

The actual intensity of the fringe pattern will depend on the focal ratio of the beam being tested. When an f/4 telescope is tested with an interferometer sending out an f/3.2 cone of light, the interference pattern will be bright because nearly all the laser light emerging from the interferometer is reflected back into the instrument. But if an f/6 telescope is

tested with the same f/3.2 interferometer the interference pattern will be about four times fainter (given the same projection size or apparent size when viewed by eye), since only a fraction of the light emerging from the interferometer is reflected back by the mirror.

The size of the fringe pattern visible in the interferometer will also depend on the relative focal ratios of the interferometer and test optics. The f/4 telescope will nearly fill the aperture of the f/3.2 interferometer. However the f/6 scope's fringe pattern will appear almost half as large in the interferometer.

To view small fringe patterns in the interferometer, a small telescope (a finder taken from a cheap department store telescope is ideal) placed at the focus of the interferometer will magnify the fringe pattern, making smaller zones easier to see. The focus of the viewing telescope is adjusted until the edge of the fringe pattern is sharp.

The fringe pattern may also be viewed on a video or television screen if a video camera, with its lens left in place, is mounted or positioned at the second focus of the interferometer where the eye would normally be placed. The fringe pattern can then be recorded on video tape for later study, or digitized by a frame grabber for computer processing.

The intensity of the interferogram may overwhelm the video camera if a fast optic is tested, and especially if the reference element has been partially aluminized for the testing of coated primary mirrors. The intensity of the pattern will not be affected by the iris in the camera lens. The iris will only stop down the interferometer's field of view. Reducing the interferogram intensity must be accomplished with filters in front of the camera or in the laser beam in the vicinity of the polarizing filter.

The fringe pattern may also be photographed with a 35mm SLR camera. The use of a lens with any type of camera is important since the fringe pattern must be in focus. An out of focus fringe pattern will not have a clearly defined edge and diffraction effects will distort the fringes at the edge of the aperture, creating what might be interpreted as a rolled down edge.

The focal length of the lens is chosen so as to fill the camera's field of view with the fringe pattern, thereby maximizing resolution. This is very important if the fringe pattern is to be analyzed by computer, since the accuracy of the measurement is dependent on the number of points the computer can fit on a fringe. The larger the fringe pattern, the greater the number of points that can be fit to the fringes and hence the greater the accuracy of the measurement.

Depending on how the interferometer is designed and how fast the test optic is, a zoom lens may not work well since the interferometer's field of view may be reduced by the shifting lens elements within the zoom lens. A number of fixed focus lenses may be required in order to view the full range of focal ratio optics one is likely to encounter.

Undesirable, spurious fringes generated by the other optical elements can interfere with the test optic fringe pattern, likely causing erroneous test results. The minimal number of

optical elements in the spherical wave interferometer reduce the number of spurious fringes, but there are still some which can cause problems.

When a cube beamsplitter is used, a bright hot spot in the center of the field can cause problems with small interference patterns. This hot spot is the reflection of the grin lens off the surfaces of the beamsplitter, which then reach the eye or camera. The hot spot is a problem only when checking very slow beams with a fast reference element.

Dust on the optics can distort otherwise straight fringes and cause "bullseye" patterns to form. The interferometer must be kept clean in order to avoid these spurious fringes.

The spatial filter (semi-opaque screen with a small pinhole) placed at the secondary focus of the interferometer will let the light of the test and reference beams through, but block stray light which contributes to some of the spurious fringes. The pinhole should be very small, on the order of 0.02" or about 1/2 millimeter.

The spatial filter/screen combination is useful since it is also an alignment aid. If the test optic is slightly mis-aligned with the interferometer, the return beam will fall on the screen and be seen as a spot. The position of the interferometer or the test optic must be adjusted until the spot is made to pass through the pinhole. Only then will interference fringes will be visible.

#### Using the Interferometer

The spherical wave interferometer can be used to test any optical surface or complete telescope which can be tested with the standard Foucault test. As with the Foucault test, the testing of complete telescopes requires the use of an optical flat at least as large as the aperture of the telescope. The testing of concave spherical mirrors can be accomplished with the interferometer alone, just as with the Foucault test.

Testing a parabolic mirror at the center of curvature requires a null lens or autocollimating flat to test properly. The aberrated wavefront that produces the familiar donut pattern with the Foucault test will produce wildly distorted fringes in larger fast mirrors at the center of curvature. It is possible to remove the distortion (or artificially null) the distorted fringe pattern but special, not readily available, software is required.

When assessing the optical quality of a reflecting telescope or one of its components, the test results should be scaled to about 542 nm (green light) from 633 nm (the wavelength of red HeNe laser light). The eye is most sensitive to green light and will preferentially see aberrations in that wavelength regime. When the test results are scaled appropriately, the magnitude of any aberrations will increase.

Before you can successfully test optics with your new interferometer you will have to make some solid supports for both the interferometer and the test optic if the fringes are to be steady. If possible, mount both the interferometer and the test optic on a common bench since, if there is movement, they will at least move together and reduce the problems caused by vibration. If the path length is long, as is usual with telescope objectives, place your optic and interferometer stands on a concrete floor in the basement, or the next best solid surface.

If the optics and interferometer can be mounted on a single, solid bench, interferometry can (and has been) performed on a rickety kitchen table. But if the long path length dictates separate mounting benches, then a solid cement floor in the basement is required. Wooden floors, especially carpeted, are nowhere near as stiff as required for interferometry. Even on a concrete basement floor, the shifting of weight from one foot to the other, and people walking on the floors above, will affect the fringe stability. Interferometers make excellent seismographs! When setting up the test, keep in mind that you are trying to hold two wavefronts relative to each other to within a fraction of a wave.

Do not be discouraged by these warnings of extreme sensitivity. Interferometry, with all its problems, is definitely within reach of hobbyists.

To avoid confusion it should be remembered that an f/5 telescope mirror, when tested at the center of curvature, operates at f/10. The radius of curvature is equal to twice the mirror's focal length. Since telescope mirrors are generally checked at the center of curvature, when we consider an f/10 beam for testing purposes, it actually refers to an f/5 telescope mirror. Similarly an f/16 beam refers to an f/8 primary tested at the center of curvature.

## Testing a bare glass mirror at the center of curvature

Setting up a test for a mirror at the center of curvature should be done in a darkened room. Set the interferometer and mirror the proper distance apart, keeping in mind that the master surface must lie inside the center of curvature by an amount equal to its radius. Aim the interferometer so that the mirror is centered in the diverging cone of light. A white cardboard screen placed behind the mirror in a darkened room will help make the laser light visible.

If the interferometer is sending out an f/3.2 cone of light, an f/10 mirror (measured at its center of curvature) will be greatly "overfilled" and hence difficult to center in the beam properly. The diameter of the laser beam when it reaches the mirror will be about three times larger than the primary itself. To aid in centering the mirror, stop down the interferometer reference element by placing a paper mask in front of the master surface so as to reduce the size of the cone of light until only a little larger than the mirror being tested.

A large piece of cardboard, with a hole large enough to pass the laser light, is placed in front of the interferometer. This screen will help to align the mirror relative to the interferometer. The light reflected off the mirror is made to fall on the cardboard screen, then, by adjusting the mirror's tilt and tip, is directed to pass fully through the hole and back into the interferometer.

The return beam should be near the grin lens, and will probably be slightly out of focus if the initial spacing between the interferometer and the mirror was not accurately set. Move the interferometer until the beam is focused and falls back on the grin lens. The translucent spatial filter/screen, placed at the focus of the interferometer above the beamsplitter, will aid in fine alignment.

On this screen there will be one spot visible (the reference surface's spot is passing through the pinhole). The interferometer is adjusted until the spot is made to pass through the pinhole. Placing the eye up to the pinhole, circular fringes should be visible in the illuminated aperture. The interferometer (or mirror) is moved to and fro until the fringes are straight, and then tilted until a suitable number of fringes are seen across the aperture.



This picture illustrates an interferogram at best focus.



This picture illustrates a defocused interferogram.

Remember, if the interferometer has been designed to generate an f/3.5 cone of light, an f/10 beam will only use a small percentage of the reference element, and the test mirror will be seen as a small disk in the field of view.

The spherical wave interferometer can be teamed with the Ross null test (see Telescope Making magazine #39 and #41) to test Newtonian primaries at the center of curvature. The Ross null test utilizes a large, precision plano-convex lens to cancel the spherical aberration of a parabola at the center of curvature, making the mirror appear spherical when properly figured. The Ross null test is an "in line" null test. The null lens is simply placed between the mirror and the interferometer at the appropriate distance, and the fringes are interpreted in the same way as for a spherical mirror. The alignment technique is the same as discussed above.

The Dall null test is not suitable for adaptation to interferometry since the null lens is placed off axis, resulting in astigmatic effects which, while generally not serious with the Foucault test, will be most apparent with interferometry. Moreover, since the Dall null is not an "in line" test, the light emanating from the interferometer will not retrace its original path as required in order to produce interference fringes.

## Testing a bare glass mirror by autocollimation

In order for high contrast fringes to be seen, the reflectivity of the test and reference surfaces must be reasonably equal. The 4% reflectivity of a bare glass mirror tested at the center of curvature equals the 4% reflectivity of the bare master surface in the spherical wave interferometer, so high contrast fringes will be seen (provided a suitable laser source is used).

When testing a bare mirror by autocollimation (with a coated flat) there are two 4% reflections from the mirror being tested. The laser light returning from these multiple bare glass reflections has been reduced to 0.16% (4% of 4%) intensity. The difference in intensity between the 4% reference beam from the master surface and the 0.16% beam from the test optic is a factor of 25. The result is low contrast fringes which are difficult to see and record.

The disparity in intensity between the test and reference beams can be reduced by having the master surface coated with a high efficiency, multilayer antireflection coating whose reflectivity is less than 0.5%. Of course the reference element will no longer be usable for testing mirrors at the center of curvature, or for that matter any other configuration which delivers a 4% reflection.

# **Testing Coated Mirrors**

If the test mirror is aluminized, its reflectivity will be 88% or more. When this mirror is tested with a master surface reflecting 4%, the fringes will have very poor contrast and may not be visible at all. Also the aperture under test will be extremely bright and not suitable for visual observation and will overwhelm a video camera. To solve the fringe contrast problem we can either aluminize the reference element's master surface with a semi- transparent layer of aluminum so as to provide a closer match with the coated test

mirror, or we can use a "filter" and effectively cut down the reflectivity of the test mirror by reducing the intensity of the laser light reaching it.

A glass filter is problematic in that it must be of very high optical quality. Another option that is both simple and an excellent coversation piece is a section of ladies' nylon stocking, or less interestingly, a piece of window screen. The material is stretched over a frame and placed in the light path close to the optic under test. The screen does cause diffraction effects, but otherwise does not affect the interference pattern.

Ideally, an autocollimating flat will be bare glass, matching the reference elements 4% reflection.

# **Testing Telescopes**

As with the Foucault test, the testing of complete telescope tube assemblies with the spherical wave interferometer requires an optical flat of high quality and as large as the aperture of the telescope. The autocollimating mirror need not be precisely flat—a few waves of curvature are unimportant—but it must be very smooth. Zones on the autocollimating flat will affect the test result of any telescope tested with it.

Since completed reflecting telescope mirrors are coated, and refracting telescopes transmit nearly 95% of the light passing through the objective, the autocollimating flat should be bare glass so as to reflect only 4% of the light back to the interferometer. Testing with a coated autocollimating flat will produce a bright test beam that must be reduced in intensity. The screen netting or stocking can be stretched over a frame and placed in front of the coated autocollimating flat to more or less match test and reference beam intensities.

The autocollimating flat should be aligned relative to the telescope before the interferometer is positioned. Center your eye in the telescope's focuser and adjust the flat so that you can see your eye's reflection centered in the optics. The flat and telescope are now in coarse alignment. Place the interferometer ahead of the focus position by an amount equal to the radius of the master surface. Move the interferometer about until the return beam falls back on the grin lens and the fringes become visible.

The easiest way to fine tune the alignment of the telescope, flat and interferometer is to work with circular rather than nearly straight fringes. Circular fringes are obtained when the interferometer is slightly defocused by moving it closer or farther away from the telescope. If there is an alignment problem the fringes will not be round but flared to one side. Adjustments are made by trial and error until the fringes are round. If the fringes appear oval, no amount of adjustment may make them appear circular. In this case the telescope's optics are at fault.

Oval fringes are a sign of astigmatism due to improperly made optics, optics being pinched in their cell or, depending on the design of the telescope, a misalignment of the telescope's optics. Coma is the most dominant off-axis aberration in telescopes. Fringes flared to one side are usually a sign of coma. Typically, a collimated telescope will show the best fringes when the light is passing through the center of the focuser. However, when testing some commercial Schmidt-Cassegrains, the author has found that the best fringes are obtained when the light is far off-axis, even though the optics appear collimated when checked with an eyepiece and artificial star. Apparently this may be due to a decentered corrector.

The testing of refractor telescopes requires special consideration. Refractors suffer from chromatic aberrations in addition to the more common secondary spectrum that astronomers are most familiar with. Secondary spectrum is the result of the red and blue rays not focusing at the same point as the yellow or green light rays. This is seen as an out-of-focus purple halo surrounding bright objects.

Another color aberration present in ordinary refractors which is not commonly known is spherochromatism, or the variation of spherical aberration with color. Simply put, the average refractor is spherically corrected in the green part of the spectrum, but blue light is overcorrected and red light is undercorrected.

The degree of spherochromatism in a refractor will depend on the objective diameter and its focal ratio. The faster the objective the greater the problem. Apochromat refractors are generally well corrected for secondary spectrum but the spherochromatism correction may not be as well corrected.

*One should not test conventional refractors or apochromats with red lasers* since these instruments are generally designed to work best in green light. Green lasers are commercially available, but they tend to be very expensive when compared to the more common red laser. Green lasers are also harder to find in the surplus market.

# **Analyzing the Fringe Pattern**

The fringe pattern by its very nature contains quantitative information. It is important to note that the fringe pattern is representative of the interaction of two interfering wavefronts. The fringe separation is directly related to the wavelength of light. When two wavefronts (from the test and reference optics) combine, the interference fringes are 1 wave apart. If the fringe distortion is measured to be equal to the fringe separation, the wavefront error is 1 wave.

This "one fringe spacing equals one wave" rule is true for all interferometers. The only cases where this rule changes is when we are interested in surface quality instead of wavefront quality, or when the test configuration changes.

TEST SET UP:	FRINGE SPACING (in waves):	
	surface	wavefront
Surfaces in contact (Newton Int)	0.5	
Concave mirror at center of curvature	0.5	1.0
Concave mirror by autocollimation	0.25	0.5
Complete telescope by autocollimation		0.5

With the Newton interferometer, or test glass interferometry, we are generally interested in the surface quality of optical elements (remember, the Newton interferometer cannot test complete telescopes, only their surfaces), so the distance between fringes equals 0.5 waves. If a zone in the pattern traverses one fringe spacing, the surface quality is 1/2 wave.

When complete telescopes are being tested, such as, say, a Schmidt-Cassegrain, we are interested in the final wavefront quality. Unlike a Newtonian primary which can function alone, the Schmidt corrector and the mirrors in the telescope do not function by themselves. Their performance as a group is what is important.

Understanding how the fringe spacing varies with the test set up is important in order not to misinterpret the test results. One cannot analyze a fringe pattern properly unless one knows which test set up was used to create it.

The fringe pattern produced by the interferometer can be analyzed in a number of ways, each of differing accuracy. The quickest and cheapest is the eyeball method.

#### Manual fringe analysis

The experienced optician can determine the degree of fringe distortion to within 1/10 wave or so just by looking at the fringe pattern. The accuracy is increased to about 1/20 wave when the fringe spacing and distortion are manually measured with the aid of straight lines drawn on the hard copy.

The example fringe pattern illustrates a smooth wavefront, but the curved fringes indicate spherical aberration. Guide lines are drawn down the fringe centers and their separations are measured. Another guide line is drawn as illustrated to define the fringe distortion. The fringe distortion is devided by the separation which gives us the wavefront error.



Manual Fringe Analysis

# **Computerized fringe analysis**

The fringes are relatively easy to read if the aberrations are simple, but if there is a mixture of aberrations, especially asymmetric aberrations caused by irregular polishing, coma or astigmatism, the task of quantifying the total wavefront quality manually can be very difficult, if not impossible. Advanced optical manufacturers use fringe analysis software to analyze the fringe pattern and make a very accurate and objective evaluation of optical quality.

The first step in the analysis is to plot data points along the fringes. The position of each point relative the others tells us something about optical quality. Starting at one end of an interference fringe, the evenly-spaced points are plotted as close as possible to the center of the fringe. The position of each of these points is measured as an X-Y coordinate by the analysis software, and that data is reduced to a usable form, such as a numerical value for PV or RMS wavefront error or a three dimensional plot of the wavefront.

The fringe analysis software's modelling process uses a set of equations called Zernike polynomials. These polynomials have a number of interesting features. They can be used by the computer to calculate and display the amount of spherical aberration, astigmatism, and coma. Each polynomial, and the aberration it represents, is independent, so it is possible to ask the computer what an optic would look like if an aberration were removed. To find out how an astigmatic telescope would perform if the optics were not pinched, one could easily subtract astigmatism to reveal any spherical aberration. Coma is usually caused by misalignment— assuming it is not severe it can be instantly removed to see how the properly aligned instrument would perform. These added features provide a useful diagnostic tool for solving problems with an optical system. Having said that, for a definitive analysis the optics should be properly mounted and aligned.

The fringe analysis software used in the professional optical shops is extremely expensive, in excess of \$5,000 for the lower end software. These packages utilize a frame grabber to digitize the video image of the interferogram, from which the software automatically traces the fringes for rapid evaluation of optical quality. Such software, with its hardware requirements, is out of reach for most small optical shops and hobbyists. Diffraction Limited developed a much less expensive software package called Quick-Fringe, still at \$1500 it is beyond the reach of most hobbyists.

To make these professional fringe analysis techniques more accessible, Ceravolo optical Systems, and Diffraction Limited will be offering a less expensive fringe analysis package suitable for hobbyists in the later part of 2003. Check in the COS web site periodically for news.

The combination of an interferometer and fringe analysis software takes the guesswork out of optical testing. Using these modern tools, a truly objective, unbiased measure of an instrument's performance is now possible.

# Peak to Valley or RMS?: Optical Quality Revisted

How sharply defined a celestial object will appear through the eyepiece is determined largely by the telescope's optical quality. In the popular astronomy literature, optical quality is almost always expressed by one number, the peak to valley (PV) wavefront error. Stating a 1/4 wave optical quality, for example, implies that the difference in height between the highest high point and the lowest low point on the aberrated wavefront converging to a focus is 1/4 of a wavelength of light. Can one number fairly describe the imaging potential of an optical system? Yes--but it is not PV!

While it is informative to know the difference between the two worst spots of a wavefront, the PV value alone cannot adequately predict the resultant image quality. This has been acknowledged in the professional literature. Quoting from the industry bible, <u>Optical Shop Testing</u> edited by D. Malacara, 2nd edition, pg. 485, "The PV error must be regarded with some skepticism... Because the PV error is calculated from just two data points out of possible thousands, it might make the system under test appear worse than it actually is."

In fact it is possible for two different telescopes, each with 1/4 wave PV optics, to vary significantly in imaging performance! For example, two 200mm aperture unobstructed telescopes are rated at 1/4 wave PV wavefront quality. The first telescope has a 10mm radius bump in the center of the aperture, and the second has a roll-off at the edge 10mm wide. Which one will provide better images? While both telescopes have the same magnitude of aberration, the second telescope's edge roll occupies an area 19 times greater than the first telescope's central bump, throwing 19 times as much light into places where it shouldn't be, and having a more detrimental effect on image quality.

A more even-handed method of appraising optical quality would use what is known as the RMS, or root mean square, wavefront value. To quote <u>Optical Shop Testing</u> again, "The RMS error is a statistic that is calculated from all of the measured data, and gives a better indication of the overall system performance." In other words the RMS value offers some indication of what percentage of the light collected by the optics is affected by the defective zones, giving one a better handle on the resultant image degradation.

To obtain the RMS value, the deviation of a large number of data points (numbering from hundreds to tens of thousands) is measured uniformly over the entire area of the wavefront, the errors are squared and averaged, then the square root is extracted. Because most of the wavefront will deviate less than the total PV value, the RMS value is usually much smaller than the PV value.

Due to the wave nature of light, there comes a point when increasing optical quality offers diminishing returns in image fidelity. A telescope this good is regarded as diffraction limited. The spherical aberration in a diffraction limited telescope does not exceed 1/4 wave PV or 0.075 wave RMS.

Correlating PV and RMS is relatively straightforward, but the relation does vary with different aberrations such as coma and astigmatism. In general, the RMS value is typically 3.5 times smaller in magnitude than the PV value when the surface is smooth and suffers only from pure spherical aberration. Such a simple rule of thumb breaks down when the surface suffers from irregular, or very localized aberrations. In fact, a telescope that is much worse than 1/4 wave PV can still be better than diffraction limited from an RMS point of view!

In the past, I, like most amateur astronomers, only considered the PV wave value when assessing a telescope's optical quality. But after observing with a 1/2 wave PV Maksutov-Newtonian telescope that passed the star test and yielded excellent images of Saturn and double stars, I felt compelled to reconsider how I evaluated optical quality.

The mystery of that telescope's excellent performance is largely solved when one examines the wavefront plot. The irregularities in the wavefront which caused the large PV value occupy a relatively small area and thus only affect a small percentage of the light forming the image. So at 0.067 wave RMS, the 1/2 wave PV telescope was still slightly better than the diffraction limit.

Knowing the wavefront quality alone is still not enough to accurately appraise a telescope's imaging performance. One must consider image degrading factors such as the size of the central obstruction in reflecting telescopes, and stray light in the tube assembly, to name but a couple. The 1/2 wave PV instrument that yielded good images sported a very small 18% by diameter central obstruction. Such small obstructions reduce contrast very little. A similar 1/2 wave telescope with a central obstruction twice as large, such as a Cassegrain type telescope, would exhibit significantly worse performance due to greater diffraction around the larger obstruction.

Amateur astronomers may resist the adoption of the RMS value for characterizing wavefront quality because it may make the optics appear too good. Unfortunately the PV value may make the optics appear worse than they really are! In adopting RMS wavefront analysis, one is not encouraging mediocre optics, rather one is promoting a much more realistic method of appraising how a telescope will perform in actual use.

Realistically, both PV and RMS values together should be used to assess the optical quality of an imaging system.

# Spherical Wave Interferometer: The optical parts and where to get them

Optical parts needed

Reference Element	Make your own or, Ceravolo Optical Systems \$375
Gradient Index Lens	Melles-Griot
	Cat #06 LGT 114
Lasers	Herbach and Rademan
	Cat # TM91LSR1827
	Meridith Instruments Glendale, AZ 85301

**MWK Industries** 

Beamsplitter (cube type) Surpl

be) <u>Surplus Shed</u>

Polarizor

Edmund Scientific Co. Cat # P34,881