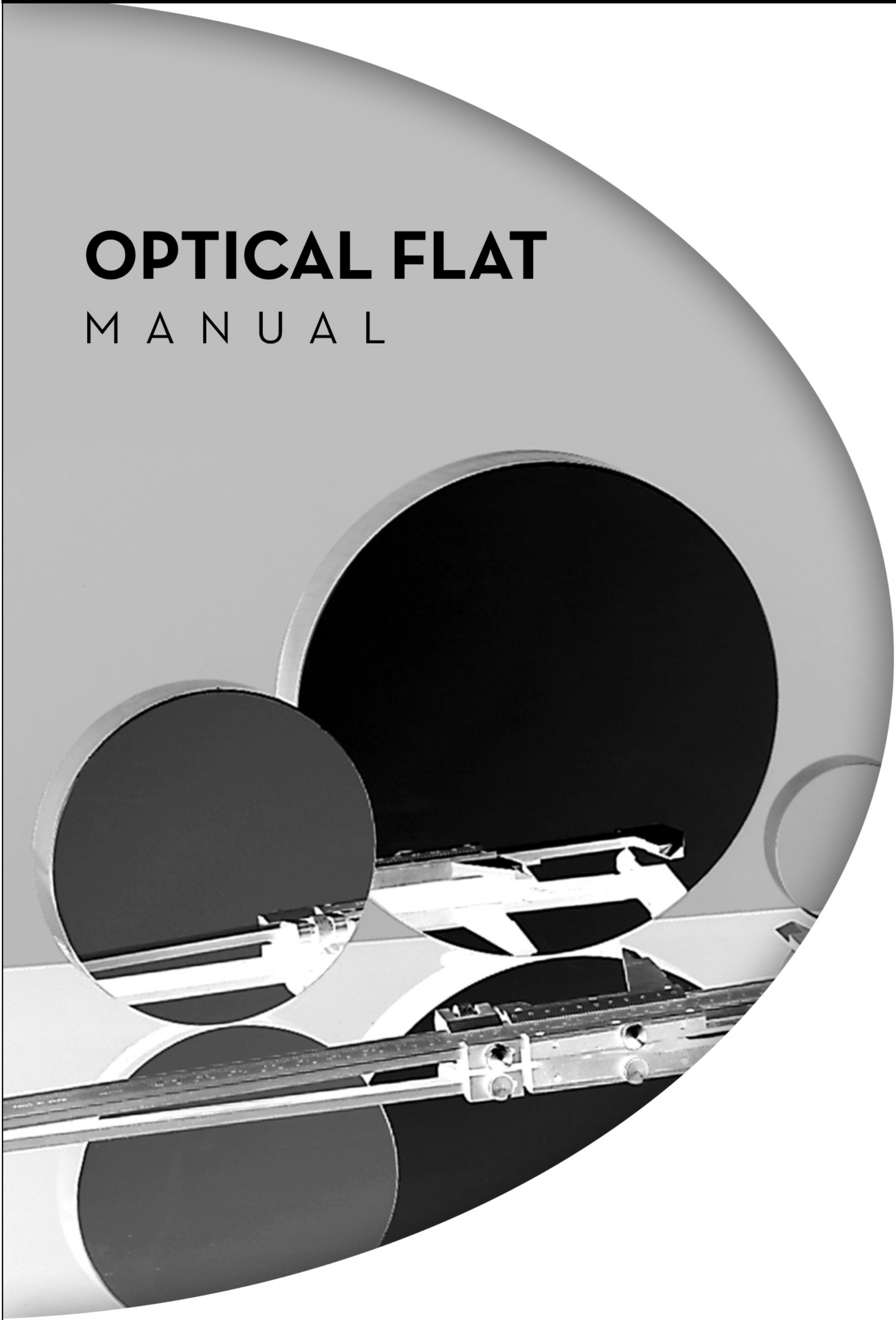
OPTICAL FLAT

MANUAL



Edmund optics | worldwide

CONTENTS

LIST OF ILLUSTRATIONS

STANDARD WAVELENGTHS

SOURCE	WAVELENGTH (in angstroms)	WAVELENGTH (in millionths of an inch)	ONE FRINGE (in millionths of an inch)
Helium	5876 (yellow) 7065 (deep red)	23.1 27.8	11.5 13.9
Hydrogen	4861 (blue) 6563 (red)	19.1 25.8	9.5 12.9
Mercury	4047 (violet) 4358 (blue) 5461 (green)	15.9 17.2 21.5	8.0 8.6 10.7
Cadmium	4800 (blue) 6439 (red)	18.9 25.4	9.5 12.7
Sodium	5893 (yellow)	23.2	11.6
Helium - Neon Laser	6328 (red)	24.9	12.4

1. Introduction

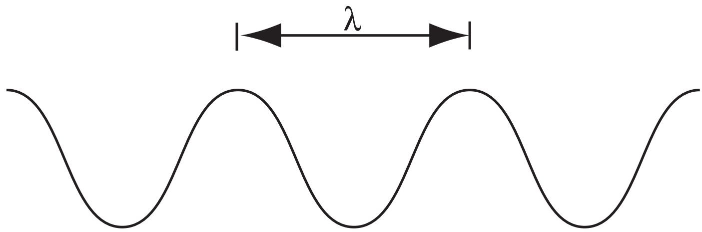
There is an old saying in the optical world - "If you can measure it, you can make it." Accordingly, the effort to make more accurate components must be paralleled by a similar effort to create standards of measurement and to manufacture suitable test equipment. As time passes, the ability to take accurate measurements has gradually increased. For example, a normal ruler can be used to measure to an accuracy of about 1/54th of an inch. A vernier caliper, on the other hand, can measure to about 1/1000th of an inch, while a good micrometer caliper extends the range further - down to 1/10,000th of an inch.

Extremely high levels of measurement accuracy become possible when the interference effect of light is used. Light interference techniques enable measurements within a few millionths of an inch. Such techniques involve the use of high quality reference standards called Optical Flats, used in conjunction with supplementary test equipment.

This booklet will familiarize readers with the effects of light interference and the necessary techniques for measuring flatness using optical standards. Proper use of optical flats requires an understanding of the theories they rely on and this is detailed herein.

It should be pointed out that some optical components must be tested by non-contact methods to prevent being scratched. A detailed explanation of this testing is covered in Section 5 of this guide.

Figure 1
Concept Wavelength



2. Light Waves and Interference

From the earliest times, speculations have been made as to the mechanism by which vision occurs. Many theories have evolved, the net result being that different theories accommodate different phenomena. To explain the effects of interference and diffraction, and to study the behavior of optical instrumentation more closely, it is necessary to consider light as a wave motion. The study of these effects is termed "Physical Optics" and you can consult one of the many excellent textbooks on this subject for more in-depth coverage of that field.

If we consider light traveling as a wave motion with a constant velocity (186,000 miles a second), then the wavelength is defined as the distance between successive peaks. The units of wavelength in the visible spectrum are angstroms (Å) (1Å = 10^{-9}meters). Each color corresponds to a different wavelength. For example, green light typically has a wavelength of 5500Å. The visible wavelengths range from violet light with a wavelength of 4000Å to red light with a wavelength of approximately 6500Å. Light of a single wavelength is said to be monochromatic. Isolating one wavelength from those produced by a light source (an interference filter placed in front of a Mercury Vapor Lamp, for example) can produce this. The various standard wavelengths emitted by mercury, hydrogen, sodium and helium lamps are itemized in Table 1. To achieve the effects that follow, a monochrome light source is needed. When a particular wavelength is required, it is necessary to select a suitable light source and filter combination.

Let us now examine the effect of two being superimposed. When two waves come together, there are three possible situations that may result:

(1) The waves may come together in such a way that the crests and troughs of both waves coincide.

(2) On the other hand, the crest of one set of waves may coincide with the troughs of the other set.

(3) Generally, a condition somewhere between these two extremes occurs and the waves are out of phase. This can occur if the waves originate at the same place and travel via different routes to the same particular point. The distance P as indicated in Fig. 2c is known as the path difference between the two waves.

If the crests of one set of waves coincide with the troughs of the other at a particular point and their amplitudes are equal, then the sets cancel each other out.

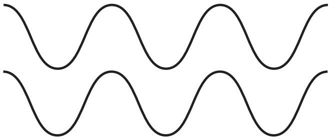


Figure 2a
Troughs and crests coincide

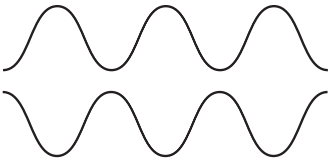


Figure 2b
Troughs coincide with crests

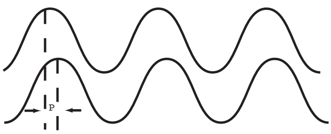


Figure 2c
Two waves out of step by a distance P

This phenomenon is known as destructive interference. It is the principle upon which flatness testing techniques are based. To completely extinguish light when two sets of waves are completely out of phase, it is necessary for the waves to have the same amplitude. If this condition is not met, regions of complete darkness will not be formed, but provided there is equality between both beams, an interference pattern will be noticeable.

If the two amplitudes are totally different, no effects are discernable. In addition, if the path difference introduced between the two sets of waves is made too great, no fringes are observable.

Now, consider an optical reference flat placed in contact with a test piece whose flatness we wish to determine. If both surfaces are clean, an air film is formed between the two surfaces. If this air film is illuminated by monochromatic light, an interference pattern will be formed. The pattern is formed by light waves being reflected from the test and reference surfaces as shown. Whenever twice the thickness of the air film is an integral number of wavelengths (e.g. 1,2,3,4), a dark fringe is formed. Such a fringe will be a line that joins all points where the film's thickness is the same.

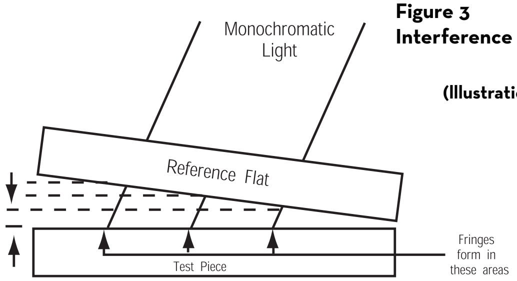


Figure 3
Interference from an air wedge

(Illustration exaggerated for clarity)

The resultant lines are not unlike contour lines on a map. Since the contact surface of the reference flat can be regarded as perfectly flat, the fringes form contour lines that reflect the surface characteristics of the area under examination. This proves particularly useful when it is necessary to identify imperfections in the test surface and determine whether that surface meets specific criteria.

8. Contact Methods For Testing Flatness

Optical flats can be used to measure the flatness of machine parts (bearings and seals, for example) or for measuring flatness of similar optical flats or mirrors. To perform this test for flatness, the following equipment is necessary:

(1) An optical reference flat of known quality

(2) A monochromatic light box

(3) Solvent and cleaning material

The surface flatness of the reference flat must be known and should be frequently calibrated by the supplier (who usually encloses a certificate indicating its traceability to the National Bureau of Standards). This is extremely important, since it would be meaningless to attempt to measure to one tenth of a wavelength using a reference which is only accurate to one quarter of a wavelength. Furthermore, flats in constant use do wear and can be damaged to such an extent that they no longer provide a reliable reference. It is important, therefore, to periodically check the flatness either by comparison with a second reference or, if this is not available, by sending the flat in question to a reliable test lab for certification.

Flats are usually supplied with the reference surface clearly marked on the edge by an arrow. This should be checked on each occasion the flat is used. It is not normal for both surfaces to be accurate to a fraction of a wavelength. Reference surfaces should always be used as the contact surfaces.

The only other piece of test equipment which is required is a monochromatic light box. Interference fringes are usually only formed in monochromatic light. If white light were to be used, for example, a rainbow effect would be observed and the fringes would merge into each other, making actual measurement impossible. Monochromatic light can be obtained from various light sources, including helium tubes, sodium lamps, lasers, mercury vapor lamps. If the lamp being used emits more than one discrete wavelength (mercury, for instance), then the required wavelength must be isolated by means of a filter. The best type of filter for this purpose is an interference filter, although less expensive absorption filters can be used. The filter can be fitted to the lamp or can take the form of a beamsplitter, as shown in Fig. 4. Vertical illumination is extremely important, as is viewing at normal incidence. The arrangement shown in Fig. 4 is highly desirable. In addition, the box should be shielded from stray light and the interior should be painted black or lined with black velvet to avoid unwanted reflections and give the best viewing conditions.

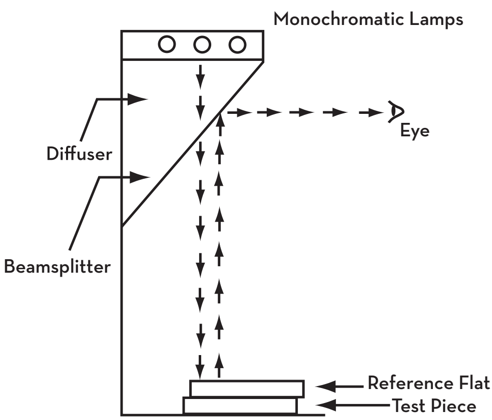


Figure 4
Monochromatic Light Box

A third piece of equipment that frequently proves useful is a camera. Although it may not be necessary, a photographic or digital record can prove helpful, particularly when comparing many fringe patterns to accurately calculate deviations from flatness. In addition, permanent records of the fringe patterns can be used for the certification of the test pieces.

Before contacting the reference and test surfaces, remove all grit and dust from the two surfaces. Cleanliness is critical and dust particles that are not removed can affect the accuracy of the results. Cleaning requires the use of solvents and an anti-static dust brush. Great care should be taken to prevent scratching the surface of both the test piece and the reference flat.

After cleaning, but prior to contacting, the two pieces must be left to reach the same temperature. The reference flat is usually manufactured from a low expansion glass (like quartz or Pyrex®) and should be resistant to local temperature variations. Test pieces, on the other hand, can be manufactured from almost any material and temperature gradients can greatly affect the fringe pattern. It is important, therefore, to ensure that stable thermal conditions prevail during the evaluation.

Both the reference and the tested component can now be placed in contact and the interference fringes can now be observed. This is accomplished by placing the test piece in the light box with the test surface uppermost and centrally located under the monochromatic source. A piece of lens tissue is now placed on the surface of the test piece and reference flat laid carefully on one edge. The flat is lowered gradually as the tissue is removed. When the tissue is finally removed, a thin air wedge remains between the two pieces. This air wedge gives rise to fringes, which should be straight if the surface under test is flat. If this is the case, the wedge must be reduced by light pressure on the reference flat. The number of fringes present is dependent upon the air wedge and is not in any way indicative of the surface flatness. It is the straightness of the fringes that is used to determine the flatness of the surface in this configuration.

If any asymmetry exists in the pattern, the air wedge should be rotated through 90 degrees. It is good practice to do this, even if no apparent asymmetry is present, as asymmetry might show up in one direction, much more than in another.

3. Typical Interference Patterns and Their Interpretation

The wedge method just described is only applicable to surfaces that are almost comparable in flatness to that of the reference flat. Furthermore, the reference and test flats must be of approximately the same diameter, otherwise this necessitates moving the reference flat across the surface of the test flat. This should be avoided

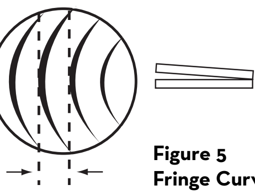


Figure 5
Fringe Curvature

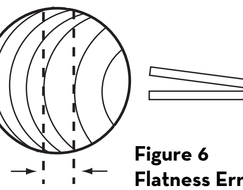


Figure 6
Flatness Error of 2 Fringes

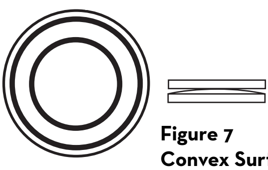


Figure 7
Convex Surface

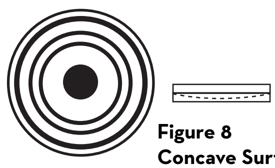


Figure 8
Concave Surface

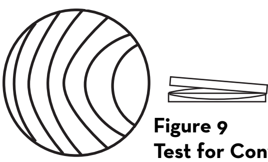


Figure 9
Test for Convex Surface

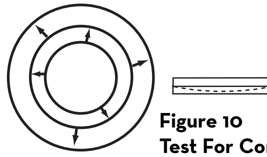


Figure 10
Test For Concave Surface

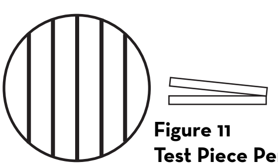


Figure 11
Test Piece Perfectly Flat

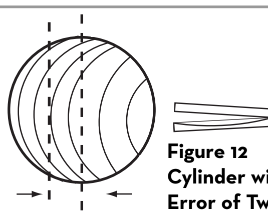


Figure 12
Cylinder with Flatness Error of Two Fringes

if at all possible, to minimize the possibility of scratching either or both surfaces.

If the surface to be tested is irregular, as shown by the curvature of the fringes in the air wedge, it is then necessary to place the reference flat down vertically on top of the test flat. In this situation, the flat sits on the high zones (peaks of the hills) and the resulting fringes indicate the valleys present in the test piece. To obtain an accurate evaluation of the tested surface, the two pieces should be contacted with light finger pressure, until the number of fringes is a minimum.

Once fringes have been determined, it is possible to assess the surface flatness of the component being tested. In the wedge technique, the curvature of the fringes is a measure of the departure from flatness, while the overall number of fringes is indicative of the wedge and has no relationship to the flatness. The resultant unit of measurement is the wavelength of light being used for viewing, one fringe being equivalent to a separation of one half of a wavelength between the two surfaces. If the fringes are sufficiently far apart, it is actually possible to estimate to 1/10th of a fringe, corresponding to a flatness of 1/20th of a wavelength. To assess the actual flatness using the air wedge configuration, reference should be made to Fig. 5, which represents an interference pattern formed between two flats. At any particular zone, the flatness is determined by joining the ends of a particular fringe by either an imaginary line or by placing a straight edge across the rear surface of the reference flat. If a photograph of the pattern is available, then the photograph can be accurately measured. The particular situation in Fig. 5 indicates a curvature of 1 fringe, or half a wavelength, and an air wedge of 4 fringes, or 2 waves. The actual dimensions in micro inches are dependent upon the wavelength of the illumination. For all practical purposes this can be taken to be approximately 23 microinches. Fig. 6 displays a surface out of flat by slightly over two fringes; the air wedge being 8 fringes (4 wavelengths).

In the contact method, where the reference flat is pressed onto the highpoint(s) on a surface, rings of equal air thickness are displayed. The total number of rings visible across the surface between the point of contact and the edge (for a symmetrical pattern) is an indication of the total departure from flatness of the surface. The fringes are contours of equal air thickness and it will be obvious that non-uniformities will show up as departures from circles in the ring pattern.

A convex surface displays a bright patch in the center, while a concave surface displays a dark patch in the center of the pattern. To determine whether the surface is concave or convex, a simple procedure is used. The test flat will always roll on a convex surface. If one edge is subjected to light pressure, the flat will roll about the apex and the so called bull's eye will move in the direction of the edge where the pressure is applied. If this effect is observed, the surface under test is convex.

If, on the other hand, light pressure is applied at the center and the fringes move outward towards the periphery and reduce in number, then the surface under test is concave.

A few typical examples will be used to illustrate the type of fringe pattern that will occur in practice.

1. AIR WEDGES

A. Flatness error of zero

If the fringes are straight, parallel and equally spaced, the piece under test is perfectly flat and the resulting fringe pattern will be similar to that shown in Fig. 11.

B. Cylinder with flatness error of two fringes

Fig. 12 shows a typical interference pattern obtained by forming a slight air wedge between the reference flat and the surface that is weakly cylindrical. The overall wedge in this case is 6 fringes and the departure from flatness 2 fringes. It is important to note that when the surface is convex the fringes curve around the thin part of the wedge.

2. CONTACT METHOD

A. Convex Cylinder

A convex cylinder placed in contact with a reference flat is shown in Fig. 13. In this case, there is a bright area in the center and a symmetrical fringe pattern, as shown, with the spacing between successive fringes being unequal. The departure from flatness at the edge is slightly greater than 2 fringes.

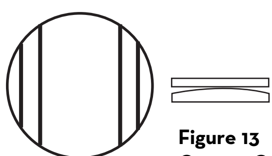


Figure 13
Convex Cylindrical Surface

B. Concave Cylinder

A similar situation exists with a concave cylinder, as shown in Fig. 14. It will be noted that a dark fringe exists in the center and the distance between successive fringes reduces as the

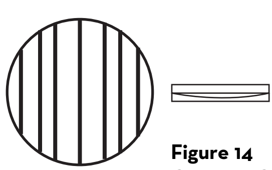


Figure 14
Concave Cylindrical Surface

periphery is approached. In the example given, the departure from flatness is approximately 4 fringes.

C. Convex Sphere

An example of a convex spherical surface, Fig. 15, shows a surface with a curvature of just over two fringes. The test described above is conducted to determine whether or not the surface is convex.

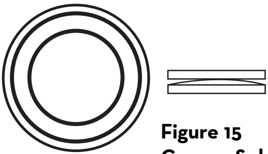


Figure 15
Convex Spherical Surface

D. Concave Sphere

If the test for sphericity indicates that a concave surface has been produced, then the pattern shown in Fig. 16 will result. Here the departure from flatness is about 4 fringes. As in the case of the concave cylinder, a dark fringe is present in the center.

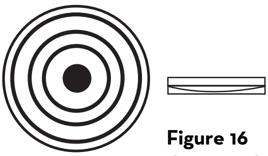


Figure 16
Concave Spherical Surface

E. Convex Spheroid

A surface very close to spherical, but slightly elliptical in shape is called a spheroid. A typical fringe pattern for a convex one is shown in Fig. 17. In this case, the fringes are, as expected, slightly elliptical.

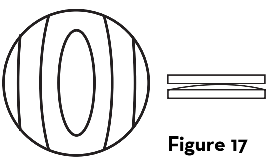


Figure 17
Convex Spheroidal Surface

F. Concave Spheroid

The fringe pattern for a concave spheroid provides no surprises, being comprised of an elliptical array of fringes with a dark center as shown in Fig. 18.

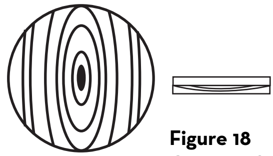


Figure 18
Concave Spheroidal Surface

G. Saddle

An extremely interesting fringe pattern is the one that is usually induced into stretched pellicles and gives rise to what is known as a saddle type interference pattern. Derived from the nature of a saddle, the pattern is indicative of a surface possessing both positive and negative curvatures about the central point, in mutually perpendicular directions. The form that this usually takes is shown in Fig. 19.

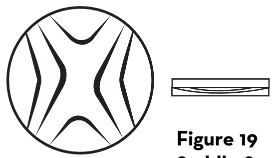


Figure 19
Saddle Surface

H. Highly Irregular

Fig. 20 shows a surface, which is very highly irregular, such as that found on particularly thin glass. The reference flat, when placed in contact with the surface, rests on the high spots and the fringes form contours of equal or unequal thickness. To calculate the maximum depth of the valley between the high spots, the number of fringes formed between the spots is divided by a factor of 2. For example, if there were 12 fringes between high spots, the departure from flatness would be 6 fringes.

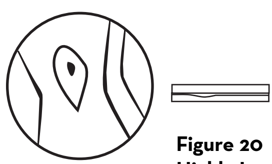


Figure 20
Highly Irregular Surface

5. Non-Contact Methods of Measurement

A. Twyman and Green Interferometer

Optical components can be tested by making use of a modified form of the classic Michelson Interferometer known as the Twyman and Green Interferometer. Its principle of operation is best understood by referring to Fig. 21.

Monochromatic light is used to illuminate a small pinhole H, situated at the focal point of a lens, L_1. The collimated beam emerging from L_1 strikes a beamsplitter inclined at 45 degrees to the axis, with its purpose being to reflect a portion of the beam towards M_3 and transmit the remainder to M_2. The two beams are reflected back from M_3 and M_2 respectively, pass through a second lens, L_2, and are brought to a focus at point E where the eye is placed. By adjusting M_1M_2, and M_1M_3, the optical lengths for the two paths may be made equal. By fine tilting one of the two mirrors, the two images of the pinhole may be made to coincide exactly. When the instrument is adjusted to this, the eye will see a uniform field of illumination. In this situation, the system can be thought of as providing two perfectly plane wave fronts that coincide to interfere.

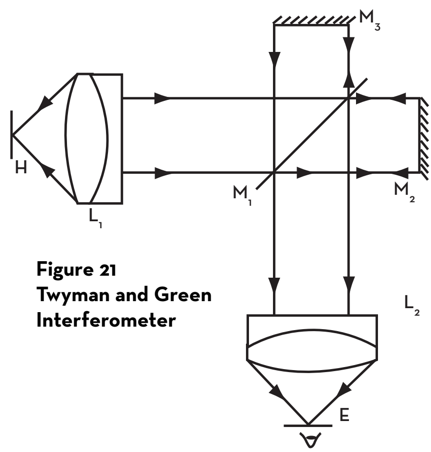


Figure 21
Twyman and Green Interferometer

If a test mirror is introduced in place of M_2, the return beam from M_2 will not have a plane wavefront and interference will take place. The field at E is no longer uniform, and dark interference fringes will be observed when the path difference between the beam from M_2 and M_3 is a half wavelength or an odd number of half wavelengths. The interferometer can thus be used to observe contours of the surface to enable the optician to perform final figuring of the high spots. To determine which are the high and which are the low regions of the test sample, it is necessary to increase either one of the paths, M_1M_2 or M_2M_3, while observing the fringes.

Increasing the path is accomplished by applying a slight pressure with the finger on the metal base of the instrument near M_2. After several minutes of practice, the inexperienced operator soon learns to determine which are the high and which are the low regions.

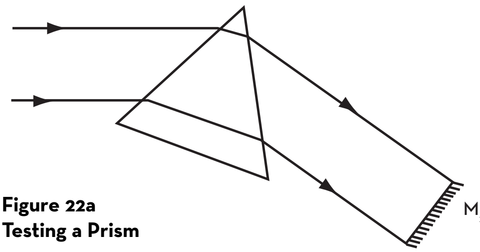


Figure 22a
Testing a Prism

Apart from using the interferometer for testing flat surfaces, it may also be used for testing plane parallel pieces of glass, which can be inserted in the path M_1M_2. The interferometer is extremely useful for checking the regularity of the optical path when light passes through a prism or lens. Fig. 22a and Fig. 22b show the arrangement necessary when testing a prism and lens respectively. In the case of the lens, a convex spherical mirror is mounted behind the lens in such a way that its center of curvature coincides with the focus of the lens. The mirror is adjusted to this position by means of a fine micrometer screw.

B. Fizeau Interferometer

An extremely useful and versatile interferometer is the Fizeau Interferometer. The interferometer has been used extensively for checking optical flats, wedges, front surface mirrors, and windows, to mention a few applications. Essentially, it comprises a monochromatic light source illuminating a pinhole situated at the focal point of a well-corrected objective, which acts as a collimator. The parallel light emerging from the collimator passes through a high quality reference flat which is permanently built into the instrument.

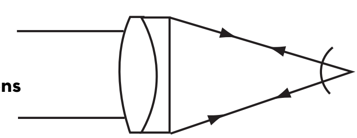
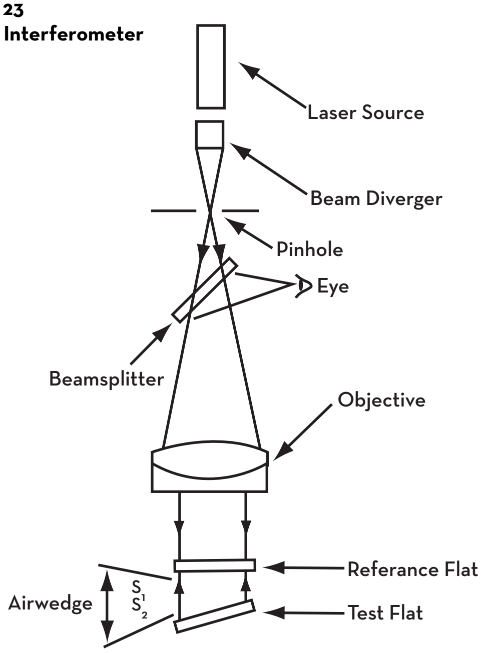


Figure 22b
Testing a Lens

In the arrangement shown in Fig. 23, fringes are formed by the air wedge introduced between S_1 and S_2. The base of the test flat is provided with adjusting screws to permit tip and tilt of the test flat, thereby enabling the operator to view the fringes from the test flat in transmission for the purpose of evaluating its wedge. The separation of the two S_1 and S_2 can be large and the risk of scratching surfaces during testing is minimized, as a result.

The fringes are viewed by means of a beamsplitter interposed in the position shown to form an image at the eye. A camera can be built into the instrument or added to the system later, facilitating the making of permanent records.

Figure 23
Fizeau Interferometer



6. Applications

Optical flats have been widely used in the optical industry as reference standards for plano surfaces in lens systems. In addition, they are widely used for testing front and rear surface mirrors, as well as for examining wedges and windows. The increased use of interferometers, particularly with laser sources, has created a large demand for high quality mirrors and beamsplitters. Accordingly, accurate calibrated reference flats are an invaluable asset.

In the manufacturing and metrology fields, many components are being specified in terms of light fringes. Using light fringe evaluations, for example, facilitates the examination of local flatness zones on smooth surface plates to within a few micro-inches using optical flats. Gage blocks, bearings, seals, and anvils are also tested using similar techniques. As a result, it is easier to produce these products to precise tolerances.

This form of flatness testing is very rapid also. The eye very quickly learns to interpret the various patterns that occur and, with a little practice, the procedure becomes a routine.

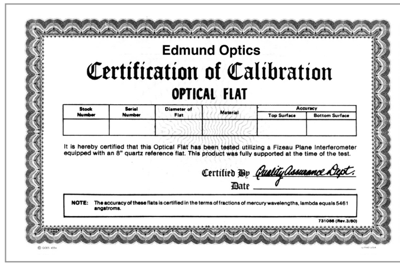
Testing flatness by optical means is quickly becoming more popular as new requirements exist and greater precision is demanded. Optical production techniques are now available for producing extremely high quality optical flats in large quantities. Thus, the effort continues to increase the accuracy of both the manufacture and the measurement of components.

Optical Testing

An optical flat is a precise flat-reflecting surface against which the flatness of another surface may be compared.

What an Optical Flat Shows

When an optical flat is placed on a surface to be tested (under monochromatic light), dark and light lines appear. These are called "interference bands" and are contour maps of the work surface. The amount of the bands' curves, with reference to the distance between them, indicates the amount of flatness error. Straight, parallel and evenly spaced bands mean the work surface is accurately flat.



Edmund Optics

Certification of Calibration

OPTICAL FLAT

Stock Number	Serial Number	Diameter of Flat	Material	Accuracy	
				Top Surface	Bottom Surface

It is hereby certified that this Optical Flat has been tested utilizing a Fizeau Plane Interferometer equipped with an 8" quartz reference flat. This product was fully supported at the time of the test.

Certified By Quality Assurance Dept.

Date

NOTE: The accuracy of these flats is certified in the terms of fractions of mercury wavelengths, lambda equals 5461 angstroms.

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Applications

Optical flats are versatile devices for measuring surface flatness of polished areas by determining variations between work surfaces and the surface of the optical flat. They also facilitate the testing of prisms, filters, and optical windows and are ideal for inspecting wear and accuracy in gage blocks.

Fizeau Interferometer

Our Fizeau Interferometer was built by the late Dr. David Rank for Edmund Optics, to inspect for flatness error in optical flats.

Available in Both Quartz and Zerodur®

We use clear optical fused quartz, which has very low thermal expansion (much lower than Pyrex®) and a great abrasion resistance. In addition, some flats are crafted from Zerodur®. Developed by Schott Research Labs, this glass ceramic has thermal expansion approaching zero, a fifth of the expansion of fused quartz.

Precision Optical Flats

All single surface flats are certified by a Fizeau Interferometer to guarantee stated accuracies. The second surface is pitch polished for better viewing of interference patterns. All edges are beveled. Each flat comes with its own durable box for permanent protection.

Precision Optical Flat Mirrors

These mirrors are aluminized and then overcoated with silicon monoxide for protection. Exceptionally good for laser applications and holography, as well as in telescopes, siderostats, coelostats, optical path folding, and as reflectors for autocollimating photographic lenses, telescope lenses and mirrors.

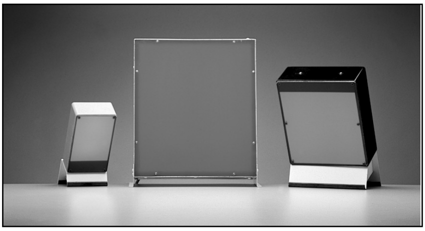
Quality

These mirrors are of the same quality as our precision optical flats, with the same certification and guarantees.

Coatings:

Protected Aluminum: 88% reflection across visible spectrum
Enhanced Aluminum: 95% reflection across visible spectrum
Protected Gold: 94% reflection in near infrared (97% in far infrared)

Edmund Optics® Green Monochromatic Lamps



Light source for testing the flatness of polished optical surfaces. Very effective for viewing Brewster's Fringes and Newton's Rings. Each lamp contains two fluorescent bulbs without coating, except the smallest, which has one u-shaped bulb. Each window is composed of two plastic sheets, one diffusing white and one transparent green to pass only the green line, 5461Å, of the mercury spectrum present. Green filter displays sharply-defined interference rings. Visibility is several times greater than helium-type lights and the green light helps eliminate eye fatigue. The unit is tilted forward at 120° angle of diffusion, allowing uniform illumination over the surface. Lamps are provided with a grounded 3-prong cord and tilting base (approximately 30° tilt forward) which may be suspended with a chain. Available in three window sizes: 3½" x 5", 7" x 7", 10½ x 11¾".

⅒ Optical Flats				Optical Flat Mirror		
Dia.	Thickness	Material	Uncoated Number	Protected Alum. Number	Enhanced Alum. Number	Protected Gold Number
1"	½"	Quartz	01-913	01-919	32-101	32-107
1"	½"	Zerodur®	32-195	32-196	32-197	32-198
2"	½"	Quartz	01-914	01-920	32-102	32-108
2"	½"	Zerodur®	32-199	32-200	32-201	32-202
3"	¾"	Quartz	01-915	01-921	32-103	32-109
3"	¾"	Zerodur®	31-391	31-396	32-113	32-117
4"	¾"	Quartz	01-611	01-615	32-105	32-110
4"	¾"	Zerodur®	31-392	31-397	32-114	32-118
6"	1"	Quartz	01-612	01-616	32-104	32-111
6"	1"	Zerodur®	31-393	31-398	32-115	32-119
8"	1½"	Quartz	31-390	31-395	32-106	32-112
8"	1½"	Zerodur®	31-394	31-399	32-116	32-120

1⁄20 Optical Flats				Optical Flat Mirror		
Dia.	Thickness	Material	Uncoated Number	Protected Alum. Number	Enhanced Alum. Number	Protected Gold Number
1"	½"	Quartz	32-632	32-633	32-634	32-635
1"	½"	Zerodur®	32-656	32-657	32-658	32-659
2"	½"	Quartz	32-636	32-637	32-638	32-639
2"	½"	Zerodur®	32-660	32-661	32-662	32-663
3"	¾"	Quartz	32-640	32-641	32-642	32-643
3"	¾"	Zerodur®	32-664	32-665	32-666	32-667
4"	¾"	Quartz	32-644	32-645	32-646	32-647
4"	¾"	Zerodur®	32-668	32-669	32-670	32-671
6"	1"	Quartz	32-648	32-649	32-650	32-671
6"	1"	Zerodur®	32-672	32-673	32-674	32-675
8"	1½"	Quartz	32-652	32-653	32-654	32-655
8"	1½"	Zerodur®	32-676	32-677	32-678	32-679