INSTRUCTION MANUAL

FOR THE MODEL C

OPTICAL TESTER
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PRINCIPLES OF OPERATION

When a lens (or mirror) is illuminated through a grating, as in Figure 1, with the grating near the focal plane \( F \), then the eye, placed at \( P \) in the returning beam of light sees a number of dark lines which appear localized on the lens.

![Diagram](a)

Figure 1

In Figure 1, if the grating is behind the focal plane, then its image is an equal distance in front. Upon looking at the lens through the grating, all the rays passing through the grating image cannot reach the eye, as they are stopped by the opaque parts of the grating. As a result, a pattern of light and dark lines is seen.

If the lens is well corrected, the shadow lines or fringes are straight, parallel, and equidistant. The distance separating them increases as the grating is moved nearer to the focal plane, at which point they disappear completely. In the case of a poor lens or mirror the fringes have a complex form, varying according to the position of the grating. The pattern covers the entire lens (or mirror) when testing optics having focal lengths greater than 3 to 4 inches. For shorter focal lengths, the examination may be limited to proportionately smaller portions of the lens.
ASSEMBLY

The Model C Optical Tester, as shipped in its standard configuration, consists of the following parts:

1. A head unit to which can be mounted any of three gratings (50, 100 and 200 line pairs per inch Ronchi rulings) in metal mounts.
2. A lamp holder, which screws into the bottom of the head unit.
3. A 0.500 inch (12.7 mm) diameter precision stainless steel post, for hand-holding, mounting on an optical bench, or in a laboratory stand. This post screws into the bottom of the lamp holder.
4. Three #50 incandescent lamps, one installed plus two spares.
5. A universal power supply for providing power to the lamp from a 120 or 240 volt, 50-60 Hz outlet. Several output voltages are available to vary the intensity of the light. The lamp is rated for 1,000 hours at 7.5 volts. The lamp may be operated at 9 volts to produce a brighter light; however, the life of the lamp will be significantly shortened.
6. A first surface mirror and a lens, for demonstrating the use of the tester. The mirror is plate glass quality and the lens has visible distortion for demonstration purposes.
7. A padded carrying case.

The Optical Tester is shipped assembled, ready for immediate use, with the 50 line grating mounted in place. To interchange the gratings, it is only necessary to remove the two thumb nuts, and replace the grating mount with the one with the desired number of lines. Always install the grating mount so that the identifying number (line pairs per inch) on the mount is to the outside.
OPTICAL TESTING ARRANGEMENTS

The Optical Tester can be hand-held for a casual inspection of mirrors and lenses. However, for an accurate measurement of focal length or a critical analysis, it should be clamped in position, preferably with some mechanical adjustment for movement toward and away from the optical component being inspected. For this purpose, an adjustable laboratory stand of any kind can be used. Also good for this purpose is an inexpensive type of optical bench such as those used for instructional use. The particular optical arrangement depends on the type of lens or mirror being inspected, and the laboratory facilities available. A dark room is not necessary. The arrangements shown in Figure 1 can be arranged either vertically or horizontally.

Lenses:

With the Optical Tester are furnished a lens having a focal length of 7 to 9 inches and a first surface plane mirror 2" square. The lens and mirror are included to permit the user to familiarize himself with the method of using the Tester, and are not intended as optical test components.

To examine the lens, the arrangement shown in Figure 1(b) is used. The distance from the lens to the focal plane, F, should be approximately the focal length of the lens. Looking at the lens surface through the grating at the head of the Tester with the eye close to the grating holder, it will appear that the surface of the lens is illuminated. If the surface is not illuminated, it is because the grating is not on the optic axis or is not parallel to the lens surface. Moving the Tester around slightly will determine the proper position. Once this position is found, the Tester can be moved along the optic axis (taking care to keep it on the axis) to determine how the fringes crossing the illuminated surface increase or decrease in number on leaving or approaching the focal plane. The analysis of these fringes as pertaining to focal plane and aberrations is discussed in the sections entitled: Focal Length Determination and Aberrations.

A caution in the selection of the correct size of grating:

Use as coarse a grating as can be used to get the information desired. For instance, in examining the demonstration lens as above, the 50 lines per inch grating should be used. This grating will give the full information as to focal length, spherical aberration, and chromatic aberration for a lens of this quality. Using the finer gratings on this lens will result in a pattern far too complex for this component. The finer gratings, and especially the 200 lines per inch grating, should only be used in testing the highest quality optics. Likewise, for a more critical examination of quality optics, a better mirror or a silvered optical flat should be used. The mirror furnished has a surface accuracy of from 1/2 to 2 wavelengths of visible light.
Spherical Mirrors:
To test spherical mirrors, the apparatus is set up as in Figure 1(a). The Tester is located near the plane F. The distance from the mirror to the focal plane, F, in this case is the radius of curvature, or twice the focal length of the mirror. If this approximate value is not known, it can be determined by hand-holding the Tester in such a way that the mirror surface appears to be illuminated when viewed through the Tester grating. Then move the Tester toward or away from the mirror to the position of the least number of fringes in the pattern at which point the Tester is near the center of curvature of the mirror.

Parabolic Mirrors:
To test a parabolic mirror, the arrangement shown in Figure 2(a) should be used, where the distance of the focal plane, F, from the mirror is approximately the focal length. Here, as in the case of lenses, the choice of quality of the plane mirror M is governed by how critical the examination is to be. The plane mirror should have a 1" diameter hole through the center but if such a mirror is not available, the parabolic mirror can be tested in sections by using the arrangement in Figure 2(b). To test an off-axis parabolic mirror, the arrangement is that shown in Figure 2(c).
FOCAL LENGTH DETERMINATION

With the optics in proper alignment, parallel fringes will be seen when observing the lens or mirror surface through the grating at the head of the Optical Tester. The number of fringes decreases as the Tester approaches the focal plane F from either direction. The finer the grating, the more rapid is the decrease in fringes. Figure 3, page 6, shows the patterns obtained at the distances indicated inside and outside of the plane F for an 8 inch focal length spherical mirror with a 200 line per inch grating. On approaching F the fringes spread out rapidly and reveal the features which indicate the character of the optical surface. The interpretation of the pattern in terms of the optical surfaces is discussed in the next section.

To accurately determine the location of plane F, one can have the Tester mounted on a linear adjustment, so that it can be moved smoothly through F to select the pattern shown in Figure 3(d). When the tester is at this position, the side of the grating closest to the optics is either at the focal point or center of curvature, depending on which optical setup is being used (Figures 1 or 2).

When a more accurate determination of the plane F is desired, the Tester is moved away from F in the direction away from the optical surface until 3 to 10 fringes are visible across the surface. Then using the following relation, one can calculate the exact distance from the grating to the plane F. The derivation of this equation is given in Appendix I.

\[ x = \frac{nF}{2DN} \]

where:
- \( x \) = the distance from grating to focal plane
- \( n \) = number of fringes across the mirror or lens
- \( F \) = approximate focal length or radius of curvature
- \( D \) = diameter of mirror or lens
- \( N \) = number of lines per inch in grating

In the case of lenses having considerable chromatic aberration the fringes will vary in color across their width. This effect is somewhat disturbing in counting fringes, and can be eliminated by observing the pattern through a filter, such as a piece of colored cellophane or plastic. Also, when a lens has considerable spherical aberration (as in the demonstration lens) the fringe spacing varies across the lens. In this case no single focal plane exists for the lens, as the focal length is varying continually across the surface of the lens. The appearance of the pattern of such a lens when the Tester is at the focal plane of the central portion is shown in Figure 9, page 6. This photograph was taken through a Corning 5031 filter.
DETERMINING THE OPTICAL AXIS OF OFF-AXIS PARABOLIC MIRRORS

Often off-axis parabolic mirrors are received from the fabricator without markings indicating the side of the mirror which is toward the optical axis. Also, even with such markings, only the plane containing the axis is defined, and it is still necessary to locate the axis.

The position of the optical axis is easily determined by observing the pattern obtained with the Optical Tester. Only when the Tester is on the optical axis will the fringes be equally spaced and parallel to each other and to the lines in the grating when using an arrangement as in Figure 2(c).

The resulting patterns for the Tester in the correct and other positions with respect to the axis can be seen from the patterns pictures in Figure 4, page 6. Figure 4(a) shows the pattern obtained with the Tester on the optical axis of a 30° focal length parabolic mirror cut 7° off-axis. This position is illustrated in Figure 5, with the Tester at A and the edge of the parabolic mirror closest to the optical axis at A'. Figure 4(b) shows the pattern when the Tester, parabolic mirror, and plane mirror are still in the correct plane, but the grating is located outside the optical axis (B in Figure 5).

Moving the grating back to position A, and rotating the parabolic mirror 10° clockwise, the pattern shown in Figure 4(c) will be seen. In this case, the optical plane is rotated as shown dotted in Figure 5, and the grating is below the optic axis. If one continued to rotate the mirror to the 90° position, the optic axis would be as indicated by the dashed lines in Figure 5, and the pattern with the grating as A would appear as in Figure 4(d).
MIRROR ABERRATIONS

As indicated previously, when the grating approaches the focal plane, the fringes spread out rapidly and reveal the features which indicate the quality of the optics under test. When a lens or mirror is of good optical quality, the fringes remain straight and parallel as they spread out, while those of poor quality give distorted patterns.

The patterns received with mirrors are always colorless, because of the lack of chromatic aberration, but will give patterns describing the mirror surface. Figure 6, page 6, is the pattern of a 6 inch spherical mirror with an 8 inch focal length, photographed just outside the focal plane. It will be seen that there are three focal zones, indicated by the three sets of fringe spacing. In the inner zone, the fringes are spread further apart, thus indicating that the focus of this area is longer than the intermediate and outer zones. This can be demonstrated by moving the Tester gradually toward the mirror. On reaching the point where the fringes of the inner zone have disappeared, (the focal plane for this zone) it will be seen that the fringes in the other zones are still present, indicating that their focal plane is still further away. By continuing to move the Tester in, a point is reached where the fringes reappear in the inner zone but disappear in the outside zone, indicating its focal plane. Finally, by continuing to move the Tester in, the focal plane of the intermediate zone is reached. By measuring the distance which the Tester traveled in passing through these 3 zones, it was found that the maximum difference in the radius of curvature of the zones was about 0.120 inches.

A simpler method of determining the variation in radius of curvature over the surface of this mirror is to locate the Tester so that the fringes in the zone of least curvature (inner zone in this case) have disappeared. At this point, the grating is at the center of curvature of this zone. Then, by counting the fringes in the other zones and measuring the diameter of each zone, one can calculate the difference between their curvature and that of the central zone. The zone diameter is measured by placing a narrow ruler across the mirror surface while observing the pattern through the Tester. For example, in this case, when the Tester is at the position where the central zone fringes disappear, the number of fringes in the intermediate zone decrease to 7.

Then, as the zone diameter is 5 inches, the difference in the radius of curvature,

\[
x = \frac{nF}{2DN} = \frac{7 \times 16}{2 \times 5 \times 100} = 0.112
\]

Here D is the zone diameter, rather than the diameter of the mirror. This intermediate zone is parabolic in shape, as indicated by the narrower spacing of the fringes toward
the outside of the zone. The variation in the radius of curvature across this zone can be calculated by using the formula:

\[ x = \frac{F}{2mN} \]

where \( m \) is the distance between fringes (center to center)

The distance between the two inner fringes is 1.30 inches and the distance between the two outer fringes is 0.38 inches. Substituting these values in the above formula, one finds that the grating is displaced 0.062 inches from the center of curvature of the inner portion and 0.211 inches from the outer. The difference, 0.149, is the variation in radius of curvature across this intermediate zone.

An aberration found often in spherical mirrors is present in the 8" focal length mirror used to obtain the patterns shown in Figure 3. This mirror has a center zone two inches in diameter whose radius of curvature is 0.005 inches less than the rest of the mirror surface. This was determined from Figure 3(g), where the inner fringes are 1.34 inches apart and the outer fringes are 1.18 inches apart.

**LENS ABERRATIONS**

**Spherical Aberration:**

Spherical aberration causes a blurring of the image of a point object placed anywhere along the optic axis. Since many of the lenses in optical instruments are used to focus parallel incident rays, such as a point object at a great distance, it is usual for comparison purposes to compute spherical aberration for parallel incident light.

![Figure 7](image)

Figure 7(a) illustrates this special case, showing the focal points for parallel rays passing through various portions of the lens. The ray A comes to a focus at A', B at B', and C at C'. The distance from A' to C' is the measure of spherical aberration for this lens. In using the Tester, parallel incident rays are focused by the lens under test, but as the rays transverse the lens twice, the distance A' to C' is doubled, so therefore all measurements of spherical aberration in lenses with the Tester must be divided by 2 to abide by convention. The series of drawings (Figures 8(a), (b), and (c)) shows the affect on the patterns when moving the Tester along the optic axis through the points A', B', and C' of Figure 7(a).
Spherical aberration is identified by the manner in which the fringe spacing decreases to the outside of the lens when the Tester is at the focal plane of the center of the lens (Figure 7(a)). This can be seen in Figure 9, page 6, which is a picture of the pattern of a simple lens, taken through a Corning 5031 filter to eliminate the effect of chromatic aberration.

Observing the pattern in the focal plane of the center of a lens, the amount of spherical aberration can be calculated by using the formula on page 10. By measuring the distance between fringes, the difference in focal length between each zone and the center zone can be determined. One can then plot a graph of this difference in focal length versus the radius of the various zones. This measure of spherical aberration is shown in Figure 7(b) for the lens pattern pictures in Figure 9.

Figure 10 is a sketch of a pattern received from a lens partially corrected for spherical aberration.

Coma:
Coma is the aberration resulting when off-axis rays pass through an uncorrected lens. It is detected and measured with the Optical Tester in the same manner as spherical aberration, except that the lens is rotated slightly, so that the rays from the Tester transverse the lens at an angle of 2 to 5 degrees with the optic axis. This produces a pattern with an appearance such as sketched in Figure 11.
Chromatic Aberration:
A single lens forms a series of images, one for each color of light present in the beam, because of the change in refractive index with color. This is illustrated in Figure 12 for a point source of white light at infinity.

The presence of chromatic aberration in the demonstration lens is indicated by the color separation in the fringes. This aberration can be measured in the same manner as spherical aberration, by setting the Optical Tester in the focal plane of green light (indicated by a green spot in the center of the lens) and measuring the distance out to the red fringe. Then, by using the formula on page 8, one can calculate the distance to the focal plane of red light, which is a measure of longitudinal chromaticism between these two colors. In a lens uncorrected for spherical aberrations, this measurement is difficult to make, because the red fringe is partially covered by succeeding fringes.
Model E Distortion Test Set-up

To Align Suggested Set-up for MIL-SPEC

Place the mirror mount and the 235 mm focal length, achromatic lens approximately in position. Keep the mirror as close as possible to the lens but still have room for the specimen. The lens must face towards the tester with the face that produces minimal aberration. The other face will show considerable spherical aberration in the tester. Trying the lens both ways without a sample in place will allow the proper face to be determined. Place your eye about 200 mm (8 inches) from the 235 mm focal length lens and sight through to the mirror mount. Adjust the mirror so that the reflected image (a circle outline) is centered in the lens diameter. The mirror should just about fill the lens.

Place the lens tester on the rail about 200 mm (8 inches) from the lens. Adjust the tester vertically so that the maximum amount of illuminated area is showing. The image might not completely fill the lens especially along the bottom.

Move the tester away from the lens. The illuminated area should completely fill the lens and the tester. Vertical lines should be seen. The lines will become spaced farther apart as the grating in the tester passes through the focal point of the lens.

Move the tester to the position specified in the MIL-SPEC. Place the specimen between the mirror and the lens. Distortions in the specimen should now be observed.
BIBLIOGRAPHY


APPENDIX I

Determining the focal plane of a perfect lens

Consider the case where L is a perfect lens backed by a mirror as in Figure 1(b).

![Figure 13](image)

If the grating T (Figure 13) is the distance x behind the focal plane, then its image T' is formed a distance x ahead of the focus. The optic axis passes through the grating at the center of a transparent strip.

The point A on the grating, on the axis of the lens, acts as a luminous source whose image A' is also on the axis and in the plane T'.

The cone of rays having A' as the vertex and the lens as the base passes through the grating within a circle of radius r. Then by geometry:

\[
\frac{r}{2x} = \frac{R}{(F-x)} \quad \text{or} \quad r = \frac{2xR}{F-x}
\]

But, when the grating is near the focal plane, x is small compared to F, and the above relation can be written:

\[
r = \frac{2xR}{F} \quad \text{or} \quad x = \frac{rF}{2R}
\]

But, the radius in inches of the circle of radius r is n/2N, where n is the number of dark fringes in the circle (or as observed across the face of the lens) and N is the
number of lines per inch in the grating. Also, 2R is equal to the aperture D of the lens. Substituting into the above equation, one gets:

\[ x = \frac{nF}{2DN} \tag{1} \]

Also, the number of fringes observed per inch, p, across the lens is equal to n/D, or the distance between fringes, m, is equal to D/n. So equation 1 can be written:

\[ x = \frac{pF}{2N} \tag{2} \]

and

\[ x = \frac{F}{2mN} \tag{3} \]

**APPENDIX II**

**Pattern Photography**

Photographic records of test patterns can be obtained either by use of a camera or by using a lens (such as the demonstration lens) in a darkroom.

Holding the Optical Tester with a laboratory stand or in any other stable manner, adjust the Tester to give the pattern to be photographed. Then mount the camera with its lens close and centered in the grating opening and focus on the closest optical surface being tested.

All the patterns pictured in this manual were photographed in a darkroom using a 4", f/0.1, simple lens. The lens is put in the eye position shown in Figure 1. The lens can have a focal length of from 2" to 8", depending on the focal length of the optics being tested and the size pattern desired. A ground glass is moved back and forth to find the plane of best focus on the pattern, and then replaced with a photographic plate, such as Process or Lantern Slide plates. Because of the long exposures involved (1/2 to 2 minutes), the light switch on the Tester can be used to control the time of exposure.