Optical Specifications

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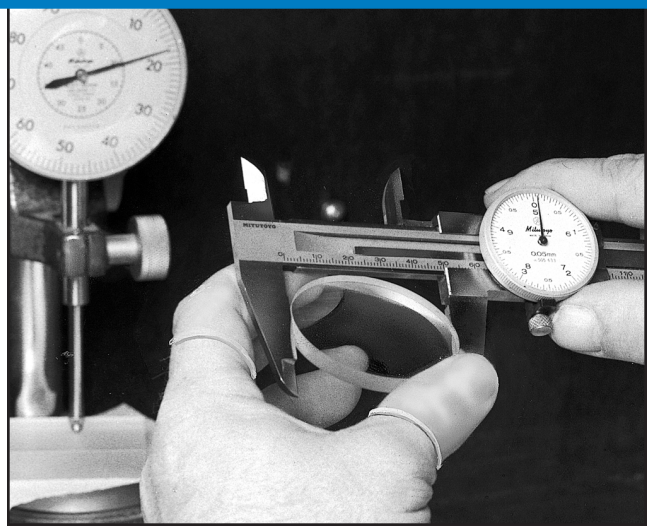

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Wavefront Distortion

Sometimes the best specification for an optical component is its effect on the emergent wavefront. This is particularly true for optical flats, collimation lenses, mirrors, and retroreflectors where the presumed effect of the element is to transmit or reflect the wavefront without changing its shape. Wavefront distortion is often characterized by the peak-to-valley deformation of the emergent wavefront from its intended shape. Specifications are normally quoted in fractions of a wavelength.

Consider a perfectly plane, monochromatic wavefront, incident at an angle normal to the face of a window. Deviation from perfect surface flatness, as well as inhomogeneity of the bulk material refractive index of the window, will cause a deformation of the transmitted wavefront away from the ideal plane wave. In a retroreflector, each of the faces plus the material will affect the emergent wavefront. Consequently, any reflecting or refracting element can be characterized by the distortions imparted to a perfect incident wavefront.

INTERFEROMETER MEASUREMENTS

CVI Melles Griot measures wavefront distortion with a laser interferometer. The wavefront from a helium neon laser (λ=632.8 nm) is expanded and then divided into a reference wavefront and test wavefronts by using a partially transmitting reference surface. The reference wavefront is reflected back to the interferometer, and the test wavefront is transmitted through the surfaces to the test element. The reference surface is a known flat or spherical surface whose surface error is on the order of $\lambda/20$.

When the test wavefront is reflected back to the interferometer, either from the surface being tested or from another $\lambda/20$ reference surface, the reference and test wavefronts recombine at the interferometer. Constructive and destructive interference occurs between the two wavefronts. A difference in the optical paths of the two wavefronts is caused by any error present in the test element and any tilt of one wavefront relative to the other. The fringe pattern is projected onto a viewing screen or camera system.

A slight tilt of the test wavefront to the reference wavefront produces a set of fringes whose parallelism and straightness depend on the element under test. The distance between successive fringes (usually measured from dark band to dark band) represents one wavelength difference in the optical path traveled by the two wavefronts. In surface and transmitted wavefront testing, the test wavefront travels through an error in the test piece twice. Therefore, one fringe spacing represents one-half wavelength of surface error or transmission error of the test element.

A determination of the convexity or concavity of the error in the test element can be made if the zero-order direction of the interference cavity (the space between the reference and test surfaces) is known. The zero-order direction is the direction of the center of tilt between the reference and test wavefronts.

Fringes that curve around the center of tilt (zero-order) are convex as a result of a high area on the test surface. Conversely, fringes that curve away from the center of tilt are concave as a result of a low area on the test surface.

By using a known tilt and zero-order direction, the amount and direction (convex or concave) of the error in the test element can be determined from the fringe pattern. Six fringes of tilt are introduced for typical examinations. CVI Melles Griot uses wavefront distortion measurements to characterize achromats, windows, filters, beamsplitters, prisms, and many other optical elements. This testing method is consistent with the way in which these components are normally used.

INTERFEROGRAM INTERPRETATION

CVI Melles Griot tests lenses with a noncontact phase-measuring interferometer. The interferometer has a zoom feature to increase resolution of the optic under test. The interferometric cavity length is modulated, and a computerized data analysis program is used to interpret the interferogram. This computerized analysis increases the accuracy and repeatability of each measurement and eliminates subjective operator interpretation.

Laser interferometer

Centration

The mechanical axis and optical axis exactly coincide in a perfectly centered lens.

OPTICAL AND MECHANICAL AXES

For a simple lens, the optical axis is defined as a straight line that joins the centers of lens curvature. For a plano-convex or plano-concave lens, the optical axis is the line through the center of curvature and perpendicular to the plano surface.

The mechanical axis is determined by the way in which the lens will be mounted during use. There are typically two types of mounting configurations: edge mounting and surface mounting. With edge mounting, the mechanical axis is the centerline of the lens mechanical edge. Surface mounting uses one surface of the lens as the primary stability reference for the lens tip and then encompasses the lens diameter for centering. The mechanical axis for this type of mounting is a line perpendicular to the mounting surface and centered on the entrapment diameter.

Ideally, the optical and mechanical axes coincide. The tolerance on centration is the allowable amount of radial separation of these two axes, measured at the focal point of the lens. The centration angle is equal to the inverse tangent of the allowable radial separation divided by the focal length.

MEASURING CENTRATION ERROR

Centration error is measured by rotating the lens on its mechanical axis and observing the orbit of the focal point, as shown in figure 3.1. To determine the centration error, the radius of this orbit is divided by the lens focal length and then converted to an angle.

DOUBLETS AND TRIPLETS

It is more difficult to achieve a given centration specification for a doublet than it is for a singlet because each element must be individually centered to a tighter specification, and the two optical axes must be carefully aligned during the cementing process. Centration is even more complex for triplets because three optical axes must be aligned. The centration error of doublets and triplets is measured in the same manner as that of simple lenses. One method used to obtain precise centration in compound lenses is to align the elements optically and edge the combination.

CYLINDRICAL OPTICS

Cylindrical optics can be evaluated for centering error in a manner similar to that for simple lenses. The major difference is that cylindrical optics have mechanical and optical planes rather than axes. The mechanical plane is established by the expected mounting, which can be edge only or the surface-edge combination described above. The radial separation between the focal line and the established mechanical plane is the centering error and can be converted into an angular deviation in the same manner as for simple lenses. The centering error is measured by first noting the focal line displacement in one orientation, then rotating the lens 180 degrees and noting the new displacement. The centering error angle is the inverse tangent of the total separation divided by twice the focal length.

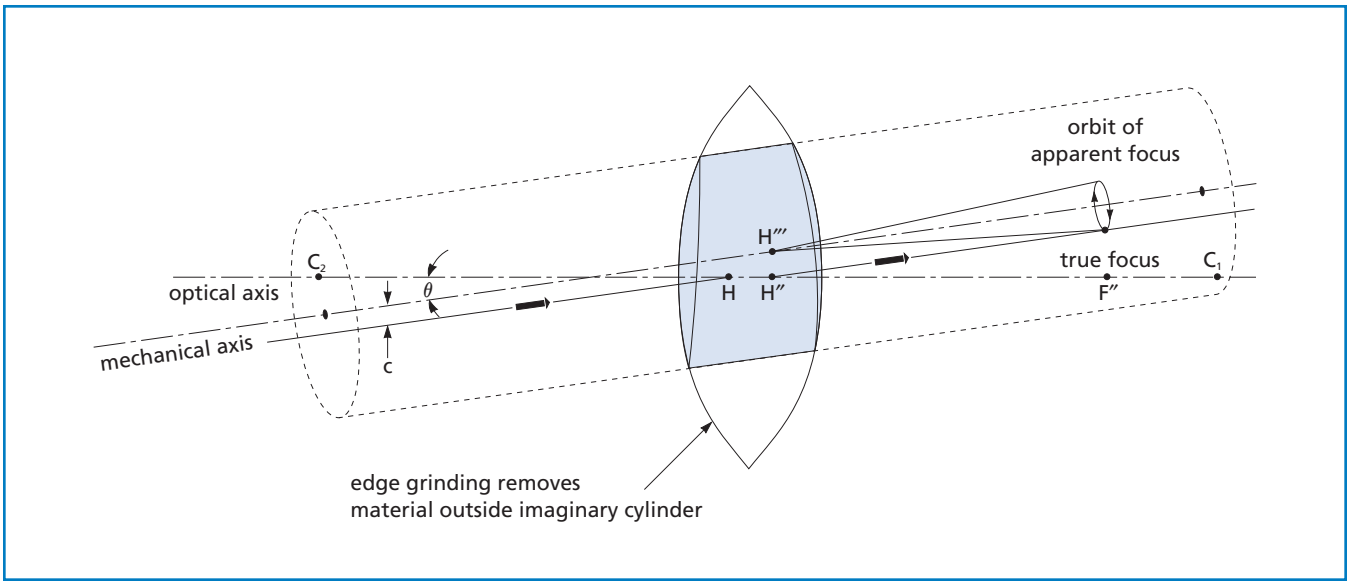

Figure 3.1 **Centration and orbit of apparent focus**

Modulation Transfer Function

The modulation transfer function (MTF), a quantitative measure of image quality, is far superior to any classic resolution criteria. MTF describes the ability of a lens or system to transfer object contrast to the image. MTF plots can be associated with the subsystems that make up a complete electro-optical or photographic system. MTF data can be used to determine the feasibility of overall system expectations.

Bar-chart resolution testing of lens systems is deceptive because almost 20 percent of the energy arriving at a lens system from a bar chart is modulated at the third harmonic and higher frequencies. Consider instead a sine-wave chart in the form of a positive transparency in which transmittance varies in one dimension. Assume that the transparency is viewed against a uniformly illuminated background. The maximum and minimum transmittances are T_{max} and T_{min}, respectively. A lens system under test forms a real image of the sine-wave chart, and the spatial frequency (u) of the image is measured in cycles per millimeter. Corresponding to the transmittances T_{max} and T_{min} are the image irradiances I_{max} and I_{min}. By analogy with Michelson's definition of visibility of interference fringes, the contrast or modulation of the chart and image are defined, respectively, as

$$M_c = \frac{T_{max} - T_{min}}{T_{max} + T_{min}} \tag{3.1}$$

and

$$M_i = \frac{I_{max} - I_{min}}{I_{max} + I_{min}} \tag{3.2}$$

where M_c is the modulation of the chart and M_i is the modulation of the image.

The modulation transfer function (MTF) of the optical system at spatial frequency u is then defined to be

$$\mathrm{MTF} = \mathrm{MTF}(u) = M_i / M_c. \tag{3.3}$$

The graph of MTF versus u is a modulation transfer function curve and is defined only for lenses or systems with positive focal length that form real images.

It is often convenient to plot the magnitude of MTF(u) versus u. Changes in MTF curves are easily seen by graphical comparison. For example, for lenses, the MTF curves change with field angle positions and conjugate ratios. In a system with astigmatism or coma, different MTF curves are obtained that correspond to various azimuths in the image plane through a single image point. For cylindrical lenses, only one azimuth is meaningful. MTF curves can be either polychromatic or monochromatic. Polychromatic curves show the effect of any chromatic aberration that may be present. For a well-corrected achromatic system, polychromatic MTF can be computed by weighted averaging of monochromatic MTFs at a single image surface. MTF can also be measured by a variety of commercially available instruments. Most instruments measure polychromatic MTF directly.

PERFECT CIRCULAR LENS

The monochromatic, diffraction-limited MTF (or MDMTF) of a circular aperture (perfect aberration-free spherical lens) at an arbitrary conjugate ratio is given by the formula

$$\mathrm{MDMTF}(x) = \frac{2}{\pi}\left[\arccos(x) - x\sqrt{1-x^2}\right] \tag{3.4}$$

where the arc cosine function is in radians and x is the normalized spatial frequency defined by

$$x = \frac{u}{u_{ic}} \tag{3.5}$$

where u is the absolute spatial frequency and u_{ic} is the incoherent diffraction cutoff spatial frequency. There are several formulas for u_{ic} including

$$\begin{aligned} u_{ic} &= \frac{1.22}{r_d} \\ &= \frac{n''D\sqrt{1-\left(\frac{1.22\lambda}{n''D}\right)^2}}{\lambda s''} \\ &= \frac{2n''\sin(u'')\sqrt{1-\left(\frac{1.22\lambda}{n''D}\right)^2}}{\lambda} \\ &= \frac{2n''\sin(u'')}{\lambda} \\ &= \frac{n''D}{\lambda s''} \end{aligned} \tag{3.6}$$

where r_d is the linear spot radius in the case of pure diffraction (Airy disc radius), D is the diameter of the lens clear aperture (or of a stop in near-contact), λ is the wavelength, s is the secondary conjugate distance, u'' is the largest angle between any ray and the optical axis at the secondary conjugate point, the product $n''\sin(u'')$ is by definition the image space numerical aperture, and n'' is the image space refractive index. It is essential that D, λ, and s'' have consistent units (usually millimeters, in which case u and u_{ic} will be in cycles per millimeter). The relationship

$$\sin(u'') = \frac{D}{2s''} \tag{3.7}$$

implies that the secondary principal surface is a sphere centered upon the secondary conjugate point. This means that the lens is completely free of spherical aberration and coma, and, in the special case of infinite conjugate ratio ($s'' = f''$),

$$u_{ic} = n''\frac{D}{\lambda f}. \tag{3.8}$$

PERFECT RECTANGULAR LENS

The MDMTF of a rectangular aperture (perfect aberration-free cylindrical lens) at arbitrary conjugate ratio is given by the formula

$$\mathrm{MDMTF}(x) = (1 - x) \tag{3.9}$$

where x is again the normalized spatial frequency u/u_{ic}, where, in the present cylindrical case,

$$u_{ic} = \frac{1}{r_d} \tag{3.10}$$

and r_d is one-half the full width of the central stripe of the diffraction pattern measured from first maximum to first minimum. This formula differs by a factor of 1.22 from the corresponding formula in the circular aperture case. The following applies to both circular and rectangular apertures:

$$u_{ic} = \frac{2n'' \sin(u'')}{\lambda} \tag{3.11}$$

The remaining three expressions for u_{ic} in the circular aperture case can be applied to the present rectangular aperture case provided that two substitutions are made. Everywhere the constant 1.22 formerly appeared, it must be replaced by 1.00. Also, the aperture diameter D must now be replaced by the aperture width w. The relationship $\sin(u'') = w/2s''$ means that the secondary principal surface is a circular cylinder centered upon the secondary conjugate line. In the special case of infinite conjugate ratio, the incoherent cutoff frequency for cylindrical lenses is

$$u_{ic} = n'' \frac{w}{\lambda f} \tag{3.12}$$

IDEAL PERFORMANCE AND REAL LENSES

In an ideal lens, the x-intercept and the MDMTF-intercept are at unity (1.0). MDMTF(x) for the rectangular case is a straight line between these intercepts. For the circular case, MDMTF(x) is a curve that dips slightly below the straight line. These curves are shown in figure 3.2. Maximum contrast (unity) is apparent when spatial frequencies are low (i.e., for large features). Poor contrast is apparent when spatial frequencies are high (i.e., small features). All examples are limited at high frequencies by diffraction effects. A normalized spatial frequency of unity corresponds to the diffraction limit.

All real cylindrical, monochromatic MTF curves fall on or below the straight MDMTF(x) line. Similarly, all real spherical and monochromatic MTF curves fall on or below the circular MDMTF(x) curve. Thus the two ideal MDMTF(x) curves represent the perfect (ideal) optical performance. Optical element or system quality is measured by how closely the real MTF curve approaches the corresponding ideal MDMTF(x) curve (see figure 3.3).

MTF is an extremely sensitive measure of image degradation. To illustrate this, consider a lens having a quarter wavelength of spherical aberration. This aberration, barely discernible by eye, would reduce the MTF by as much as 0.2 at the midpoint of the spatial frequency range.

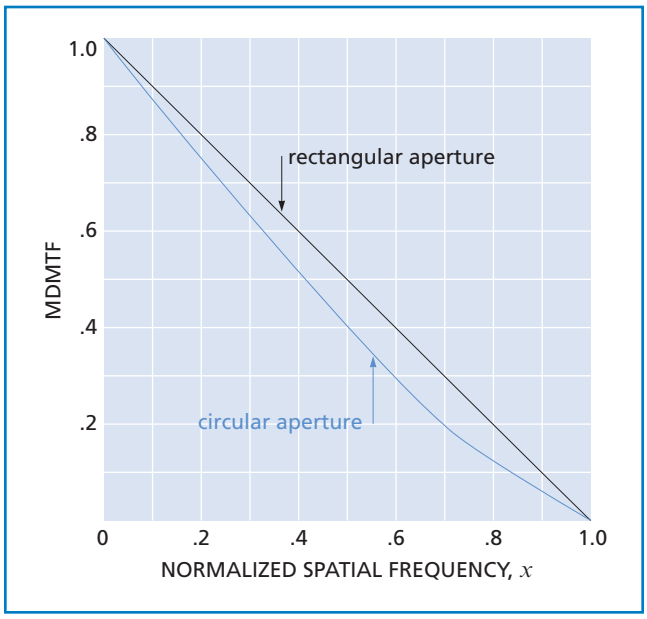

Figure 3.2 **MDMTF as a function of normalized spatial frequency**

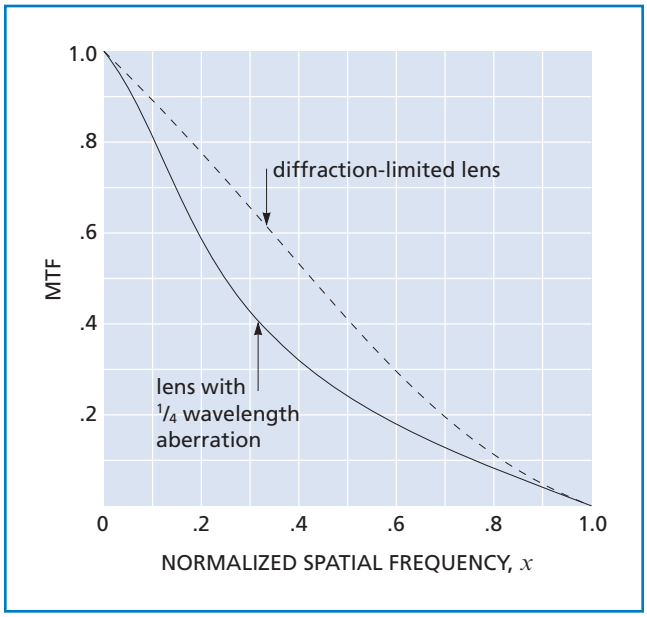

Figure 3.3 **MTF as a function of normalized spatial frequency**

Cosmetic Surface Quality — U.S. Military Specifications

Cosmetic surface quality describes the level of defects that can be visually noted on the surface of an optical component. Specifically, it defines state of polish, freedom from scratches and digs, and edge treatment of components. These factors are important, not only because they affect the appearance of the component, but also because they scatter light, which adversely affects performance. Scattering can be particularly important in laser applications because of the intensity of the incident illumination. Unwanted diffraction patterns caused by scratches can lead to degraded system performance, and scattering of high-energy laser radiation can cause component damage. Overspecifying cosmetic surface quality, on the other hand, can be costly. CVI Melles Griot components are tested at appropriate levels of cosmetic surface quality according to their intended application.

The most common and widely accepted convention for specifying surface quality is the U.S. Military Surface Quality Specification, MIL-PRF-13830B. The surface quality of all CVI Melles Griot optics is tested in accordance with this specification. In Europe, an alternative specification, the DIN (Deutsche Industrie Norm) specification, DIN 3140, Sheet 7, is used. CVI Melles Griot can also work to ISO-10110 requirements.

SPECIFICATION STANDARDS

As stated above, all optics in this catalog are referenced to MIL-PRF-13830B standards. These standards include scratches, digs, grayness, edge chips, and cemented interfaces. It is important to note that inspection of polished optical surfaces for scratches is accomplished by visual comparison to scratch standards. Thus, it is not the actual width of the scratch that is ascertained, but the appearance of the scratch as compared to these standards. A part is rejected if any scratches exceed the maximum size allowed. Digs, on the other hand, specified by actual defect size, can be measured quantitatively.

Because of the subjective nature of this examination, it is critical to use trained inspectors who operate under standardized conditions in order to achieve consistent results. CVI Melles Griot optics are compared by experienced quality assurance personnel using scratch and dig standards according to U.S. military drawing C7641866 Rev L. Additionally, our inspection areas are equipped with lighting that meets the specific requirements of MIL-PRF-13830B.

The scratch-and-dig designation for a component or assembly is specified by two numbers. The first defines allowable maximum scratch visibility, and the second refers to allowable maximum dig diameter, separated by a hyphen; for example,

80-50 represents a commonly acceptable cosmetic standard.
60-40 represents an acceptable standard for most low power scientific research applications.
40-20 represents an acceptable standard for low to moderate power laser or imaging applications that tolerate low light scatter.
20-10 represents a minimum standard for laser mirrors or extra-cavity optics used in moderate power laser and imaging applications.
10-5 represents a precise standard for very demanding high power laser applications.

SCRATCHES

A scratch is defined as any marking or tearing of a polished optical surface. The numeric designations for scratches are not related in any way to the width of a scratch, as the appearance of a scratch can depend upon the shape of the scratch, or how it scatters the light, as well as the component material and the presence of any coatings. Therefore, a scratch on the test optic that appears equivalent to the 80 standard scratch is not necessarily 8 μm wide.

The combined length of the largest scratches on each surface cannot exceed one-quarter of the diameter of the element. If maximum visibility scratches are present (e.g., several 60 scratches on a 60-40 lens), the sum of the products of the scratch numbers times the ratio of their length to the diameter of the element cannot exceed half the maximum scratch number. Even with some maximum visibility scratches present, MIL-PRF-13830B still allows many combinations of smaller scratch sizes and lengths on the polished surface.

Scratch-and-dig inspection

DIGS

A dig is a pit or small crater on the polished optical surface. Digs are defined by their diameters, which are the actual sizes of the digs in hundredths of a millimeter. The diameter of an irregularly shaped dig is $\frac{1}{2}(L + W)$, where L and W are, respectively, the length and width of the dig:

50 dig = 0.5 mm in diameter
40 dig = 0.4 mm in diameter
30 dig = 0.3 mm in diameter
20 dig = 0.2 mm in diameter
10 dig = 0.1 mm in diameter

The permissible number of maximum-size digs shall be one per each 20 mm of diameter (or fraction thereof) on any single surface. The sum of the diameters of all digs, as estimated by the inspector, shall not exceed twice the diameter of the maximum size specified per any 20-mm diameter. Digs less than 2.5 μm are ignored.

EDGE CHIPS

Lens edge chips are allowed only outside the clear aperture of the lens. The clear aperture is 90 percent of the lens diameter unless otherwise specified. Chips smaller than 0.5 mm are ignored, and those larger than 0.5 mm are ground so that there is no shine to the chip. The sum of the widths of chips larger than 0.5 mm cannot exceed 30 percent of the lens perimeter.

Prism edge chips outside the clear aperture are allowed. If the prism leg dimension is 25.4 mm or less, chips may extend inward 1.0 mm from the edge. If the leg dimension is larger than 25.4 mm, chips may extend inward 2.0 mm from the edge. Chips smaller than 0.5 mm are ignored, and those larger than 0.5 mm must be stoned or ground, leaving no shine to the chip. The sum of the widths of chips larger than 0.5 mm cannot exceed 30 percent of the length of the edge on which they occur.

CEMENTED INTERFACES

Because a cemented interface is considered a lens surface, specified surface quality standards apply. Edge separation at a cemented interface cannot extend into the element more than half the distance to the element clear aperture up to a maximum of 1.0 mm. The sum of edge separations deeper than 0.5 mm cannot exceed 10 percent of the element perimeter.

BEVELS

Although bevels are not specified in MIL-PRF-13830B, our standard shop practice specifies that element edges are beveled to a face width of 0.25 to 0.5 mm at an angle of 45° ± 15°. Edges meeting at angles of 135° or larger are not beveled.

COATING DEFECTS

Defects caused by an optical element coating, such as scratches, voids, pinholes, dust, or stains, are considered with the scratch-and-dig specification for that element. Coating defects are allowed if their size is within the stated scratch-and-dig tolerance. Coating defects are counted separately from substrate defects.

Clean-room assembly

Surface Accuracy

When attempting to specify how closely an optical surface conforms to its intended shape, a measure of surface accuracy is needed. Surface accuracy can be determined by interferometry techniques. Traditional techniques involve comparing the actual surface to a test plate gauge. In this approach, surface accuracy is measured by counting the number of rings or fringes and examining the regularity of the fringe. The accuracy of the fit between the lens and the test gauge (as shown in figure 3.4) is described by the number of fringes seen when the gauge is in contact with the lens. Test plates are made flat or spherical to within small fractions of a fringe. The accuracy of a test plate is only as good as the means used to measure its radii. Extreme care must be used when placing a test plate in contact with the actual surface to prevent damage to the surface.

Modern techniques for measuring surface accuracy utilize phase-measuring interferometry with advanced computer data analysis software. Removing operator subjectivity has made this approach considerably more accurate and repeatable. A zoom function can increase the resolution across the entire surface or a specific region to enhance the accuracy of the measurement.

SURFACE FLATNESS

Surface flatness is simply surface accuracy with respect to a plane reference surface. It is used extensively in mirror and optical-flat specifications.

POWER AND IRREGULARITY

During manufacture, a precision component is frequently compared with a test plate that has an accurate polished surface that is the inverse of the surface under test. When the two surfaces are brought together and viewed in nearly monochromatic light, Newton's rings (interference fringes caused by the near-surface contact) appear. The number of rings indicates the difference in radius between the surfaces. This is known as power or sometimes as figure. It is measured in rings that are equivalent to half wavelengths.

Beyond their number, the rings may exhibit distortion that indicates nonuniform shape differences. The distortion may be local to one small area, or it may be in the form of noncircular fringes over the whole aperture. All such nonuniformities are known collectively as irregularity.

Surface inspection

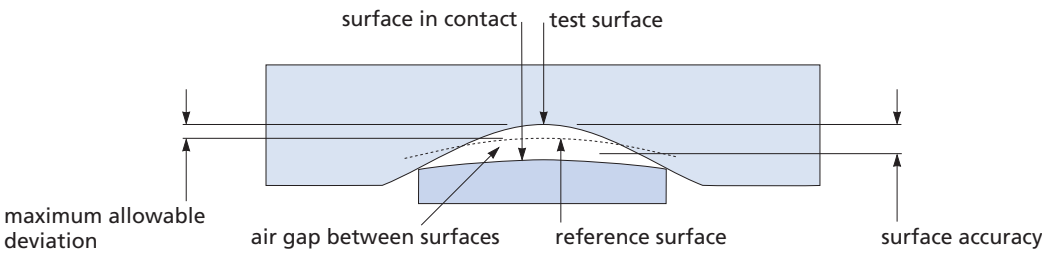

Figure 3.4. **Surface accuracy**