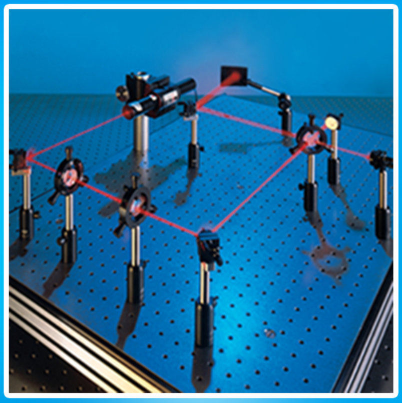
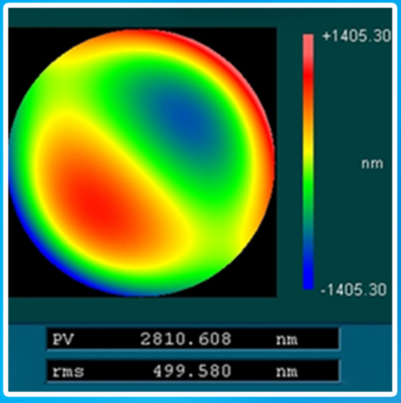
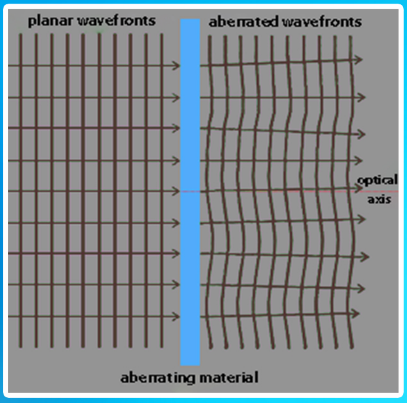
Metrology of Optical Systems







OP-TEC
National Center for Optics and Photonics Education

Precision Optics Series

Metrology of Optical Systems

PRECISION OPTICS SERIES

National Center for Optics and Photonics Education

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FORWARD

Precision optics is a critical U.S. industry from both an economic and security perspective, and precision optics technicians (POTs) are vital to the quality and future growth of this industry. These technicians produce, test, and handle optical components that are used in lasers and sophisticated electro-optical systems for defense, homeland security, aerospace, biomedical equipment, remote sensing, alternate energy production, and nanotechnology. Precision optics technicians also measure quality, add coatings and integrate optical components into electro-optical systems.

In 2009, the National Center for Optics and Photonics Education (OP-TEC) conducted a study of POT employers to project the demand for new precision optics technicians. The findings of this study showed that 6019 POT technicians were currently (2009) employed, and that the demand in five years would increase by 3100 additional precision optics technicians.

In 2012, OP-TEC updated and produced the second edition of the National Precision Optics Skill Standards for Technicians. The Standard provides the precision optics community and educators an updated listing of what technicians working in the precision optics industry should know and be able to do. It was developed from an extensive and comprehensive review process involving precision optics industry professionals and academic representatives, and has received endorsements from the American Precision Optics Manufacturers Association (APOMA), Colorado Photonics Industry Association, New Mexico Optics Industry Association, and the Rochester and Florida Photonics Clusters. This Standard has formed the basis for the design of OP-TEC's AAS degree POT curriculum. It also provides the "industry specifications" for developing these instructional materials.

Two of the courses in the curriculum are *Quality Assurance of Precision Optics (QAPO)* and *Interferometry and Metrology*. These courses can be infused into OP-TEC's Photonics Technician curriculum to prepare technicians to measure the quality of precision optics and integrate them into laser and other electro-optics systems. The full AAS degree POT curriculum is built on a manufacturing technology core, and prepares technicians who can not only perform the tasks described earlier, but also fabricate precision optics components.

OP-TEC, the National Center for Optics and Photonics Education, is a consortium of colleges and industry groups working to increase the supply of well-educated optics and photonics technicians by building and strengthening the capacity and quality of optics and photonics education in U.S. two-year colleges. By empowering community and technical colleges to meet the urgent need for new technicians and retraining workers in optics and photonics, OP-TEC plays a significant role in maintaining our country's economic competitiveness and military preparedness, and ensuring that highly rewarding jobs will be available for American citizens, including its veterans. OP-TEC is funded by the National Science Foundation to provide information about optics and photonics technology and technician careers, curricula and teaching materials, faculty professional development, and technical assistance to colleges and high schools. Twenty-nine colleges form the OP-TEC Photonics College Network.

Daniel Hull, PI
OP-TEC

PREFACE

The three instructional modules contained in this course are designed for use by students and instructors involved in the preparation of technicians in the area of precision optics fabrication and photonics. Educators can use this course is an AAS program in precision optics fabrication and as an elective in an AAS laser-electro-optics program. Corporate trainers can use it in programs designed to retrain or update the skills of engineering technicians who are already employed.

The National Center for Optics and Photonics Education, OP-TEC, developed this course under NSF ATE Grant number 1144377. Content specifications were determined from the 2nd Edition of The National Precision Optics Skill Standards for Technicians, available at www.op-tec.org.

Acknowledgements

The original manuscript of this course was authored by Brian Monacelli, Senior Research Scientist at the Optical Sciences Company (tOSC) and Photonics Instructor at Irvine Valley College and was edited by Gordon Snyder (OP-TEC).

GLOSSARY

The material presented in this course involves technical terms and measurement techniques that are often unique to the field of precision optics. To make certain users have the vocabulary needed to understand the concepts presented, a glossary of technical terms and scientific concepts is included at the end of this course. Terms in the glossary will be italicized throughout the course material.

CONTENTS

Module 1: Optical System Parameters and Performance Metrics

Module 2: Non-Interferometric Measurement of Optical Performance

Module 3: Using Interferometry to Measure Precision Optics

Optical System Parameters and Performance Metrics

Module 1

of

Metrology of Optical Systems

PRECISION OPTICS SERIES

National Center for Optics and Photonics Education

PREFACE TO MODULE 1

This is the first module in the *Metrology of Optical Systems* course. This course is designed for students seeking a basic understanding of the optical system measurement and testing techniques used to determine the overall quality of an optical system's performance. It presents a comprehensive review of measurement practices essential to ensuring the quality of optical systems. The course was designed to comply with the second edition of the *National Precision Optics Skill Standards for Technicians*.

Module 1, *Optical System Parameters and Performance Metrics*, addresses essential optical parameters of precision optical assemblies and systems. Topics include the definition and description of essential optical parameters, essential optical performance metrics, and the relationships between wavefront error, point-spread function, and modulation transfer function.

The material in this course includes technical terms and measurement techniques that are often unique to the field of precision optics. To make certain that students have the vocabulary necessary to understand the concepts presented, a glossary of technical terms and scientific concepts is included at the end of the course. We highly recommend that you review this glossary before moving forward in this module. Terms in the glossary are italicized throughout the course material.

CONTENTS OF MODULE 1

Introduction 1
Prerequisites 1
Objectives 2
Scenario 2
Basic Concepts 3
  Definition and Description of Essential Optical Parameters 3
    Effective Focal Length (EFL) and Back Focal Length (BFL) 3
    Clear Aperture (CA), Aperture Stop (AS), Exit Pupil, and Entrance Pupil 5
    Field of View (FOV) 9
    F-number (F/#), Numerical Aperture (NA), and Depth of Field (DOF) 9
  Definition and Description of Essential Optical Performance Metrics 13
    Wavefront Error (WFE) 13
    Specific Aberrations in the WFE Equations 17
    Point-Spread Function (PSF) 29
    Modulation Transfer Function (MTF) 34
    Relationship between Wavefront Error (WFE), Point-Spread Function (PSF), and Modulation Transfer Function (MTF) 38
Problem Exercises and Questions 40
Advanced Problem Exercises and Questions 43
Laboratories 44
References 48

Module 2-1
Optical System Parameters and Performance Metrics

INTRODUCTION

When learning how a technical system works, it is helpful to first know its purpose and some of its potential applications. Technical parameters describe the ability of a system to achieve its purpose—they quantify how well a system performs in operation. Optical systems can be used in diverse ways: some optical systems form images, some illuminate a specific region with a certain pattern of light, and others simply alter an optical property of a light source, perhaps its spectrum or polarization state. Understanding applications of a system can help to test the system by creating idealized operational situations. Evaluation of these technical parameters in such situations determines the quality of the system's performance.

The optical, mechanical, thermal, and electrical properties of precision optical components are discussed in the OP-TEC Quality Assurance of Precision Optics text. These properties are related to the composition and fabrication of the component. When components are assembled into systems, their properties combine to determine the parameters of the whole system. In optical systems this includes resolution, field of view, image quality, and output irradiance distribution, among other important parameters. The following module covers essential optical parameters of precision optical assemblies and systems.

PREREQUISITES

OP-TEC *Fundamentals of Light and Lasers*: Modules 1-1, 1-2, 1-4, 1-5

OP-TEC *Quality Assurance of Precision Optics*: Modules QAPO-1 and QAPO-2

Students should be able to calculate ratios and angles, apply scientific notation, perform dimensional analyses of units, and understand the use of geometric equations to describe conic sections (parabolas, ellipses, etc.) [high school algebra, geometry, college algebra]

Objectives

- Define and locate basic physical parameters of optical systems, such as clear aperture, aperture stop, physical diameter and thickness
- Comprehend imaging parameters such as field of view and depth of field
- Find the effective focal length of a compound lens system
- Understand the concepts of f-number, numerical aperture, entrance pupil, and exit pupil
- Represent the optical field through an optical system using optical path difference and various wavefront error representation methods
- Quantify the performance of an optical system knowing its wavefront aberration, Strehl ratio, or point-spread function
- Determine an optical system's resolving capabilities via its modulation transfer function or point-spread function
- Determine an optical system's wavefront aberration via its wavefront error or point-spread function
- Comprehend a number of metrics to specify and measure the resolution of an optical system.
- Relate to one another the optical performance metrics of wavefront error, point-spread function, and modulation transfer function

Scenario

A well-known camera manufacturer needs to measure the spatial response of its camera's pixels. To characterize pixel response, a tiny spot must be focused and scanned across the pixel. The size of this focused spot must be significantly smaller than the camera's pixels. Melanie learned how to assess a lens' ability to create an unaberrated, high-quality laser spot after studying this module and can now select an appropriate high-quality lens and align it without introducing aberrations to create a small, ideal spot to measure the camera's pixel response.

BASIC CONCEPTS

Definition and Description of Essential Optical Parameters

When learning about any technical system, it is vital to first know its purpose. Some optical systems are intended to form images, some are intended to illuminate a specific region with a certain pattern of light, and others are simply used to alter an optical property of a source, perhaps its spectrum or polarization state. Technical parameters describe the ability of a system to achieve its purpose. Evaluation of these technical parameters determines the quality of the system's performance.

The optical, mechanical, thermal, and electrical properties of precision optical components are covered in the OP-TEC Quality Assurance of Precision Optics text. These properties are related to the composition and fabrication of the component. When components are assembled into systems, their properties combine to determine the parameters of the whole system. The following section covers essential optical parameters of precision optical assemblies and systems.

Effective Focal Length (EFL) and Back Focal Length (BFL)

The focal length of an optical system is one of the most basic optical system parameters to assess. As covered in the OP-TEC Quality Assurance of Precision Optics text, individual elements (such as mirrors or lenses) each have their own focal length. For single spherical surfaces, the focal length is equal to half the radius. When two or more surfaces are integrated into a lens assembly or optical system, an effective focal length (EFL) results. To understand EFL, the concept of the *principal plane* is important: this is an imaginary single plane at which the refraction is considered to occur. That is, all light rays refracted through a lens (or reflected by a mirror) can be traced back to a single plane of refraction (or reflection), as shown in Figure 1-1.

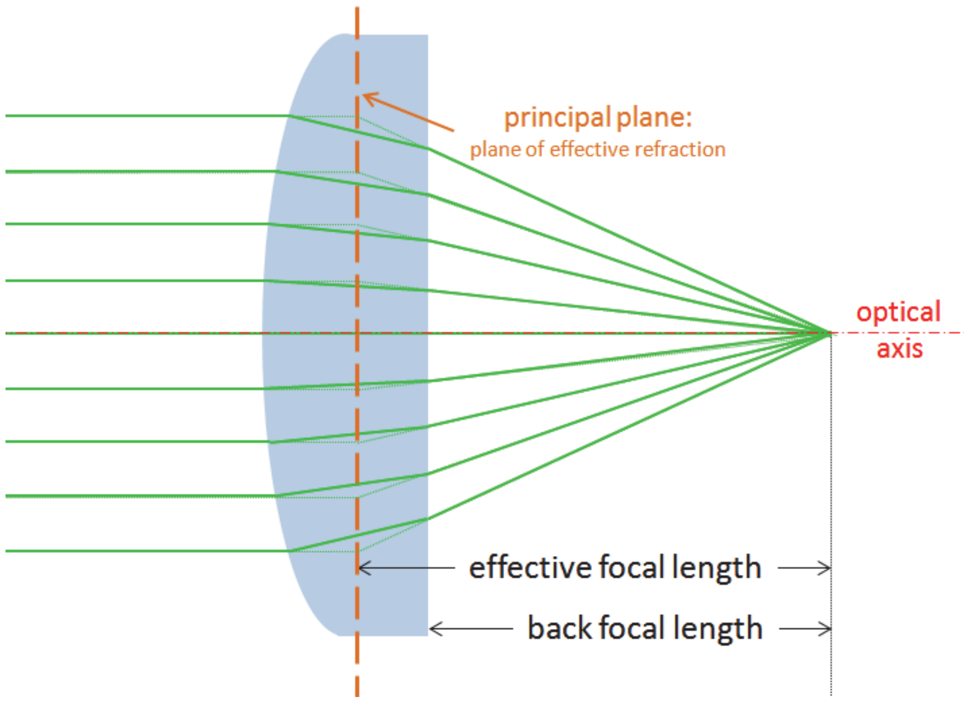


Figure 1-1 *The focal length is measured as the distance along the optical axis not from the back surface of the lens, but from the principal plane to the focal spot.*

The EFL is defined as the distance between the principal plane and the focal spot at which light from optical infinity converges to focus, or, in the case of a negative surface, the spot from which distant light appears to diverge. For thin lenses or mirrors, the principal plane runs through the center of the optic itself: the focal length is the distance from a thin optical element to its focal point. However, it is not necessary for the principal plane to run through the optics of an assembly—telephoto lenses and some telescopes, as shown in Figure 1-2, are good examples optical systems with principal planes displaced from the locations of the optics themselves. This allows the EFL of the system to be longer than the physical length of the system.

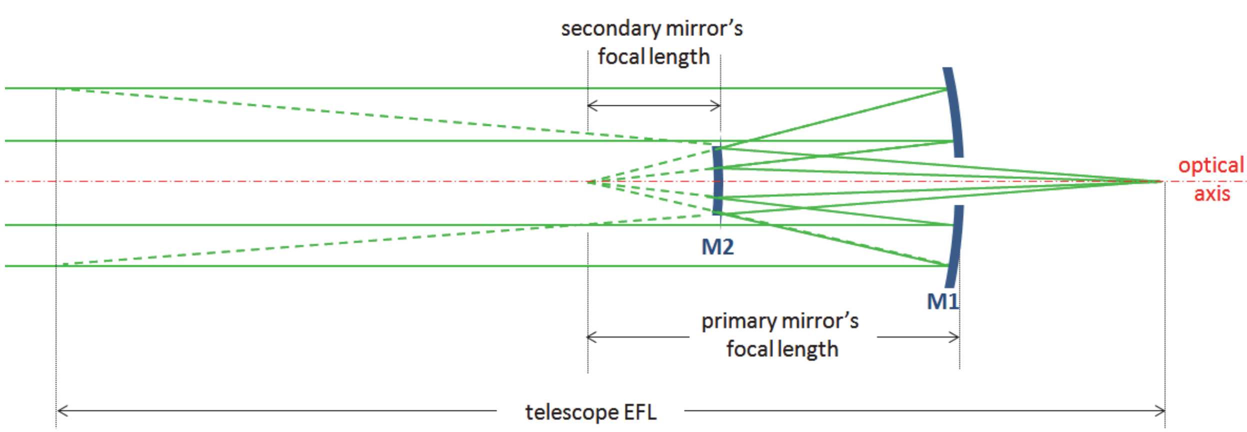


Figure 1-2 *A Cassegrain telescope creates a long effective focal length (EFL) in a short tube using two mirrors with focal lengths that are shorter than the composite EFL.*

The back focal length (BFL) is a more direct parameter to measure—it is simply the distance from the last (back) surface of the optical element to the focal point. The BFL is labeled in Figure 1-1, and in Figure 1-2, it is simply the distance from the secondary mirror (M2) to the focal point. In fact, BFL is important *because* it is a simpler parameter to measure. It is sometimes tedious to locate the principal plane of an optical assembly, but the last surface is usually straightforward to find.

Clear Aperture (CA), Aperture Stop (AS), Exit Pupil, and Entrance Pupil

To propagate through an optical system, light passes through a series of holes in each optic, referred to as "apertures." Apertures might be deliberately placed in the free space between optical components, or they may be formed by the physical extent of the lens glass or the coatings on the mirror substrates. Every optical element has its own clear aperture (CA), the diameter over which an optical element must meet its stringent manufacturing specifications. Outside the CA, manufacturers do not guarantee the element will meet specifications.

Figure 1-3 *The clear aperture is a diameter over which an optical element meets its design specifications. It is usually slightly smaller than the physical lens diameter.*

In every optical system, one aperture will limit the amount of light that makes it through the system. This limiting aperture is called the aperture stop (AS) or simply, the system pupil. (Though it can be confusing, the aperture stop may also be called the *clear aperture*.) The AS might not be the physically smallest aperture in the system, but it will be the optically smallest—that is, this aperture is the smallest as seen through the optics of the system itself. In many applications, the AS is adjustable, to limit the amount of light into the system. The pupil of your eye is its AS, and it will constrict under bright light conditions and dilate when it is dark.

Most cameras have an adjustable AS, often simply called the "aperture" or "f-stop" of the lens. It limits the amount of light that can reach the image (sensor) plane. In fact, the limiting aperture in an optical system may be the beam of light itself. For example, if a laser beam with a 3-mm diameter is directed through a lens with a 6-mm clear aperture, the aperture stop equals 3 millimeters because the entire 6-mm CA is not illuminated.

When considering optical systems that are designed to create images, often called imaging systems, it is important to be familiar with the concepts of object space and image space. Object space is the region in front of the optical system from which light comes, and image space is the region behind the optical system, where light ends, usually on a detector. An image can be real or virtual, depending on the location of image space with respect to the optical system. A good way to test whether an image is real or virtual is to assess whether it can be cast on a screen—only real images form on a screen. Virtual images will be located within the optical system itself (in a location where a screen cannot be placed).

The image of the AS through an optical system in the direction from object space into image space is the *exit pupil* of the optical system. That is, the exit pupil is the image of the AS that is seen from the perspective of image space. Conversely, the image of the AS through the optical system in the direction from image space into object space is the *entrance pupil* of the optical system. Similarly, the entrance pupil is the image of the AS that is seen from the perspective of object space. Examples of the locations and sizes of these pupils are conveyed in Figure 1-4 of a multielement lens system. For a single thin lens or mirror, the AS, entrance pupil, and exit pupil are co-located on the lens itself with identical size—the CA of the thin optical element equals the AS of the optical system it forms.

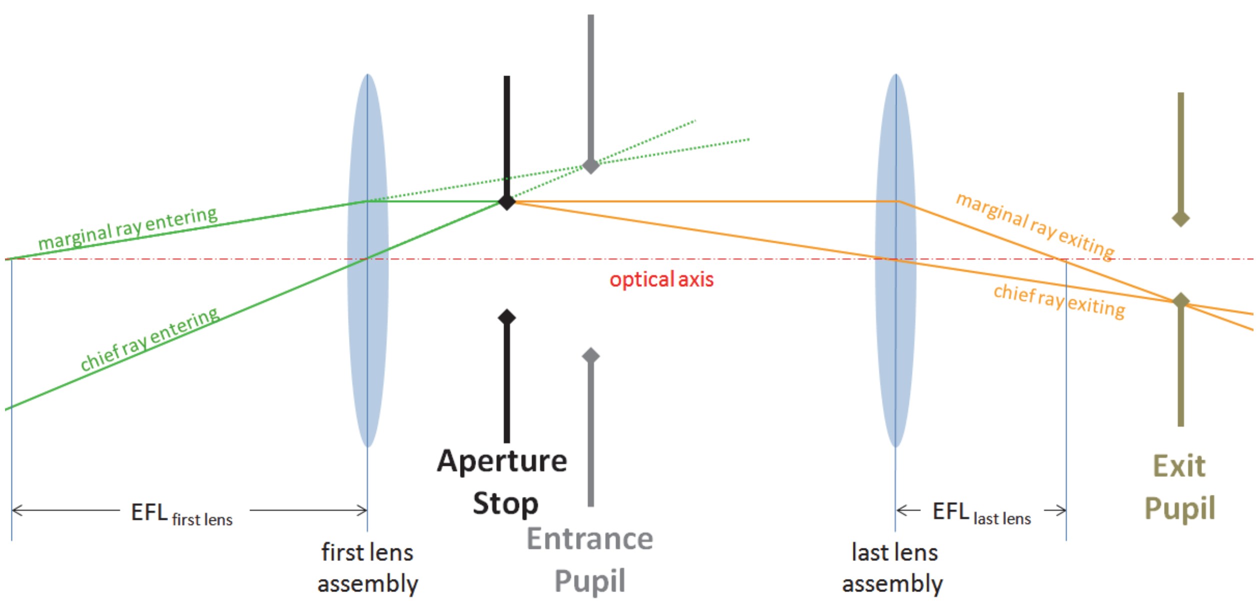


Figure 1-4 *The entrance and exit pupil location and size are determined by imaging the aperture stop.*

For a lens system with an internal aperture stop, the entrance pupil must be located by imaging the aperture stop (AS) into object space, and the exit pupil (ExP) must be located by imaging the AS into image space. In the case of Figure 1-4, the exit pupil is slightly smaller than the AS. It is real, and located just beyond the last lens assembly. The entrance pupil is larger than the aperture stop, virtual, and located within the lens system. Note how the dashed lines need to be projected back into the system to find the location and size of the virtual entrance pupil.

These concepts are important parameters because optical assemblies are most efficiently linked to one another by matching, along the optical axis, the exit pupil of the first system to the entrance pupil of the next. This is readily seen by considering the optical system of your eye when you use an instrument with an eyepiece, such as a microscope or a telescope. A well-designed scope has its exit pupil sized to match appropriately a human's pupil diameter (about 3 to 4 millimeters in bright light, and up to 8 mm in low light), and a high-quality scope's exit pupil should be located 15 to 20 millimeters from the user's cornea during use. (This so-called *eye relief* distance may be much farther away for those who wear glasses or are using the scope for a firearm sight.) Your eye's entrance pupil is located slightly in front of your eye—it is the image of your eye's aperture stop (again, the eye's pupil), through the cornea. By placing the exit pupil of the scope slightly beyond the glass of the eyepiece lens, a human eye can comfortably view through the scope without strain, physical contact with the glass, or loss of light.

The concept of losing light is known as *vignetting*. Simply put, this effect is due to viewing through an optical system without matching the entrance pupil of the viewing system to the exit pupil of the imaging system. Matching must be achieved in size and location or vignetting will occur. In addition, an image may vignette if the clear apertures of the internal optical components are improperly sized. Figure 1-5 shows what it looks like when there is a mismatch between the exit pupil of one optical system (a binocular) and the entrance pupil of the next optical system (the camera used to take this picture). Successive images of this figure are taken as the two optical systems are moved closer together, thereby moving their pupils closer together until they are nearly matched.

Figure 1-5 *Successive images of this figure are taken as two optical systems, a binocular and a camera (the camera used to take these pictures) are moved closer together. In the first three images, a mismatch exists between the size and location of the exit pupil of the binoculars and the entrance pupil of the camera used to take the picture. The mismatch exists due to incorrect separation of the two optical systems along the optical axis. Therefore, the mismatch is improved by moving the systems (and their pupils) closer together until they overlap and nearly all light through the binocular enters the camera's aperture.*

Field of View (FOV)

The lateral size of an object may determine the range of angles over which light must be accepted by the optical system—bigger objects require larger angles to enter an optical system than smaller objects at the same distance. Conversely, a system may be limited by the size of the available detector to be used in the image plane (e.g., a camera's detector, the human retina, etc.). The maximum of this range of angles accepted by the optical system is called the field of view (FOV). The concept of the FOV is shown in the Figure 1-6. The field of view is simply the range of angles that enter an optical system. In Figure 1-6, the exit pupil is located *at* the simplified optical system.

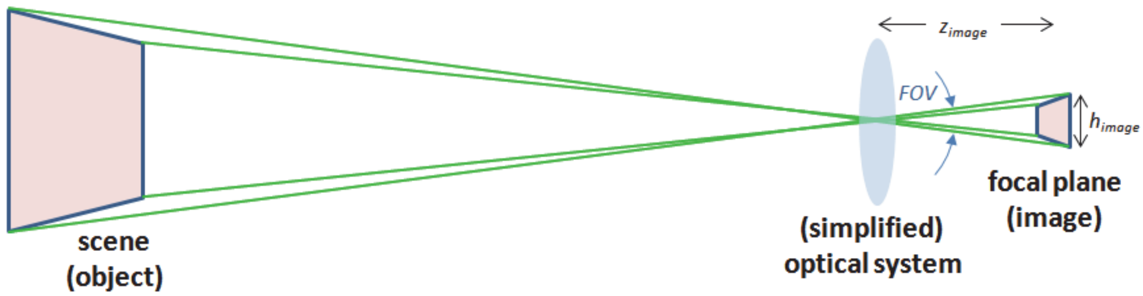


Figure 1-6 *The FOV is proportional to the physical extent of the focal plane (image)*

The FOV can be calculated using trigonometry as angle defined by the lateral image size, h_{image} and the exit pupil-to-image plane distance, z_{image}. For example, if the image plane is 35-mm in size and the distance from the exit pupil to that plane is 50 mm, then the optical system's full FOV equals 673 mrad (38.6°).

$$FOV = 2\tan^{-1}\left(\frac{h_{image}/2}{z_{image}}\right)$$

The FOV is often a confusing parameter because it is poorly specified. Optical systems are symmetric, so the half FOV is often given. Objects are usually imaged onto a rectangular plane, so the FOV may be specified in terms of the diagonal of the detector (image) plane. If any confusion about this parameter arises, it is essential to ask further questions and make additional measurements.

F-number (F/#), Numerical Aperture (NA), and Depth of Field (DOF)

Another common optical system parameter, the *f-number* (or sometimes the "*f-ratio", "f-stop", or relative aperture*), is defined by the ratio of the effective focal length (EFL) to the clear aperture (CA).

$$F/\# = \frac{EFL}{CA}$$

The f-number is written as F/#, where the "#" is replaced by the ratio. For instance, if the EFL equals 100 mm and the CA equals 20 mm, the system would be described as F/5. Another term that is often associated with the f-number is the numerical aperture (NA) of the optical system. This is related to the f-number by the following equation, which is an approximation that is valid for common optical systems.

$$F/\# \cong \frac{1}{2\,NA}$$

The parameter *NA* is defined as the sine of the input or output angle, depending on whether the *NA* is in object (input) or image (output) space. *NA* is a parameter typically used with optical fiber, microscopy, and lithography systems since it is a measure of the light-collecting ability of an optical system; higher NAs means more light can be collected.

$$NA = \sin\theta_{output}$$

The output angle that defines the *NA* and the parameters that define the F/# (EFL and CA) are shown for two F/5 optical systems in Figure 1-7.

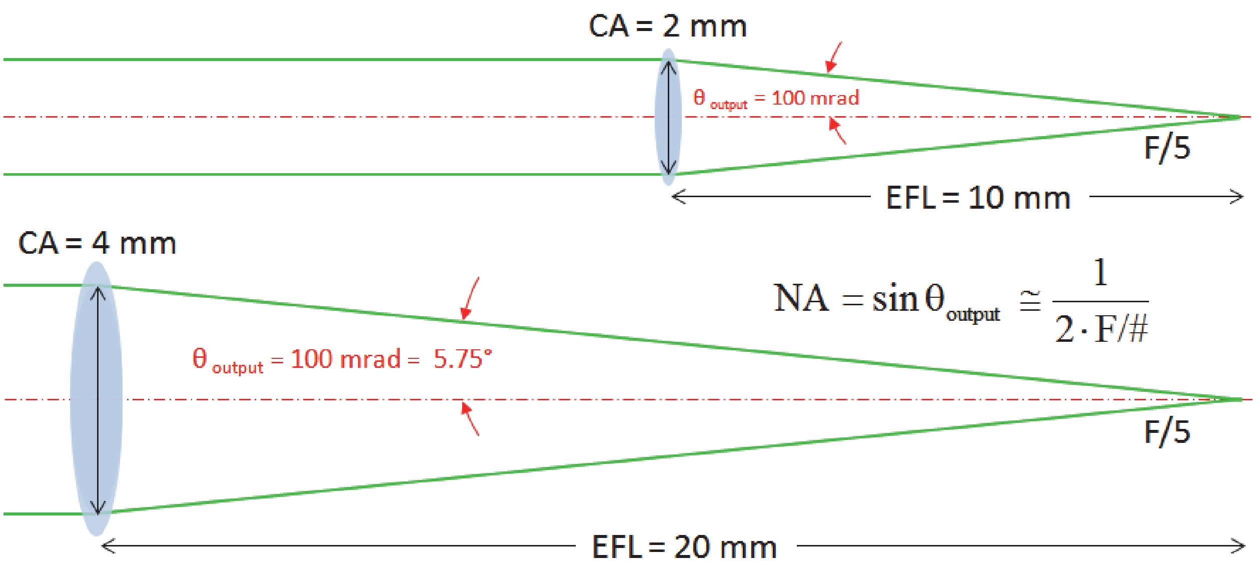


Figure 1-7 *Two F/5 optical systems with different defining parameters are shown. For an F/5 system,* θ_{output} *equals 100 milliradians or 5.75°.*

The EFL and f-number are not just defining technical parameters of an optical assembly, but they are used to name and label the assembly. Most photographic lenses are simply called out by their EFL and minimum f-number, or in the case of zoom lenses, by the range of EFLs the lens assembly allows. (Note that the minimum f-number indicates the maximum CA.) A lens with a focal length range from 28 to 200 millimeters and a clear aperture that can be adjusted down to 10 millimeters may simply be called a "2.8 28-200," whereas a photographic lens with a fixed focal length is called "prime," indicating that the lens is not a zoom lens (and is typically very high quality as a result of the optical designer carefully refining performance for that one EFL). A single focal-length lens with an EFL equal to 60 millimeters and a minimum f-number of 1.3 may be called a "1.3 60-mm prime."

The concept of the focal "spot" is interesting because its exact position along the optical axis can be difficult to precisely locate. In fact, there is a range of positions along the optical axis where the size of the focal spot is approximately the same. This range is known as the *depth of focus* (DOF), and it can be approximated by the following equation.

$$DOF \cong \pm 2 \cdot \lambda \cdot (F/\#)^2$$

Though traditional ray optics diagrams show focal spots as the intersection of two lines (rays of light), the actual focal region is a caustic (literally meaning "hot zone") in which the light is condensed. This creates a region over which the light is focused, depending on the wavelength and the f-number of the optical system. Figure 1-8 shows this effect.

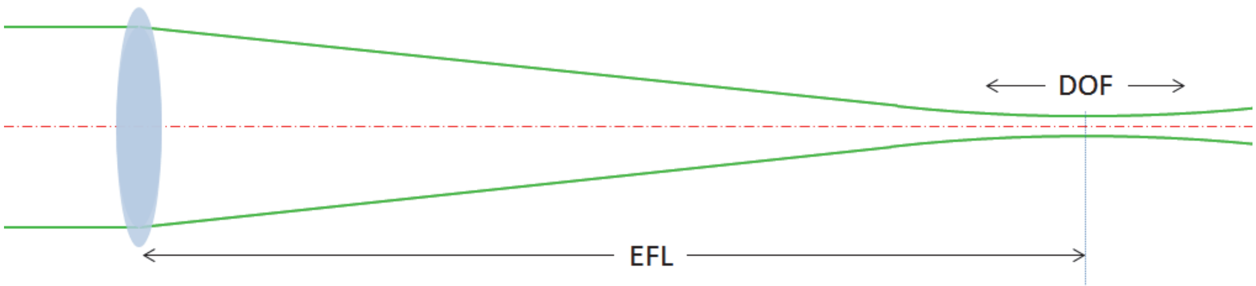


Figure 1-8 *Light is in focus over a focal region known as the depth of focus (DOF). Faster (lower) f-numbers and shorter wavelengths create smaller depths of focus.*

In fact, because the focal spot size is effectively constant over a range of image distances, the image will stay in focus over that same range. This means that optical systems with longer wavelengths and higher f-numbers will create images that are in focus over a greater range of object distances. Figure 1-9 illustrate the depths of field associated with various f-numbers of the camera that took the images.

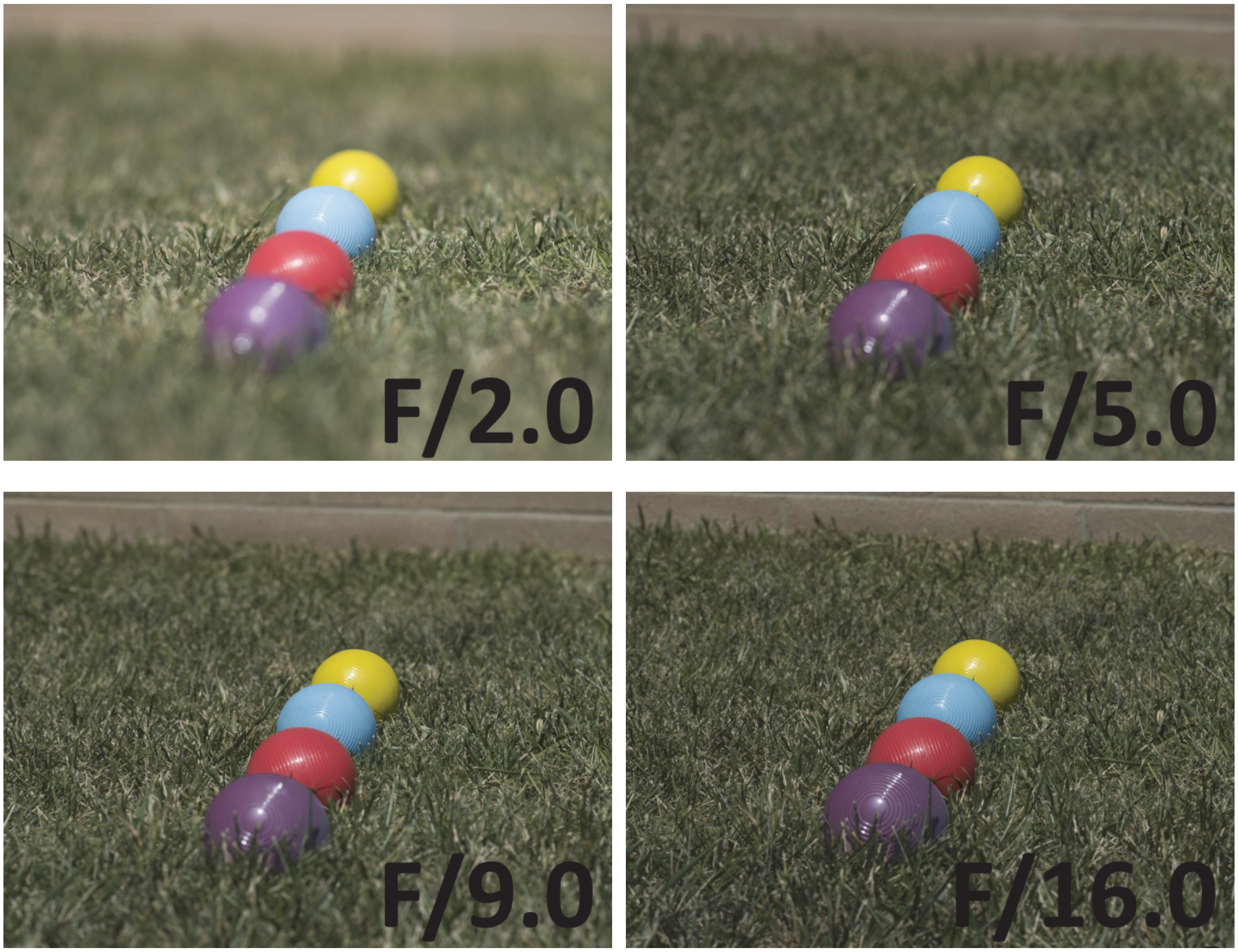


Figure 1-9 *The principal of depth of field (DOF) is illustrated by these four images. When the camera's aperture is stopped down (reduced in diameter), the value of the F/# increases and the DOF increases. The grooves in the blue ball are evident in the image shot at F/2.0, but the other balls' grooves are out of focus. When the aperture is stopped down to F/5.0, the red ball's grooves become apparent. Further stopping down the aperture to F/9.0 makes the red grooves sharply focused and shows some detail in the purple ball's grooves, but only at F/16.0 are all balls in focus. The DOF dependence on the F/# is also seen by observing fact that a deeper patch of grass is in focus for higher f-numbers.*

Definition and Description of Essential Optical Performance Metrics

The previous section highlighted performance parameters that could be either measured or calculated directly. The following discussion will highlight more complicated performance metrics that are used to assess the quality of an optical system.

Wavefront Error (WFE)

It is common to represent a beam of light as a surface of energy known as a *wavefront.* A wavefront can be envisioned as a sheet of energy that moves through space with the light—it is not necessarily flat or curved, but has contours. It is bent by the imperfections and features of the surfaces it encounters. Every wavefront represents one point of equal phase of the light wave's oscillations as it moves through space, at a separation of one wavelength, as shown in Figure 1-10 and the left side of Figure 1-12. The wave in Figure 1-10 is shown for reference—each dot corresponds to one wavefront. An ideal, collimated plane wave will be represented by a series of perfect planes that are separated by the wavelength of the light, as shown in Figure 1-11.

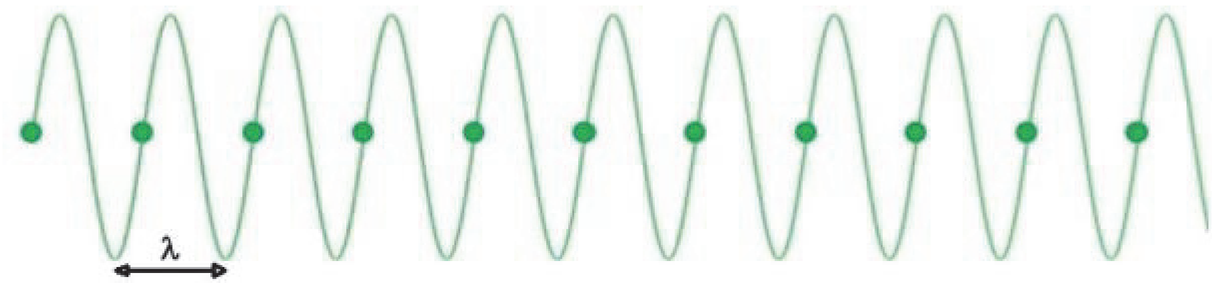


Figure 1-10 *Each dot along this wave represents a point of equal phase*

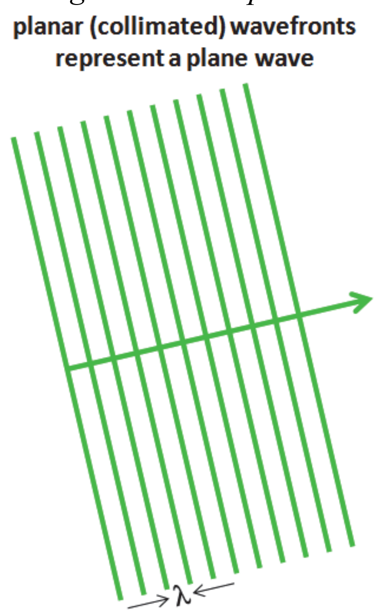


Figure 1-11 *The concept of the plane wave is shown here, along with the propagation vector of the light.*

An ideal spherical wave is represented by perfect, concentric spheres that are separated by the wavelength of the light. Figures 1-12 and 1-13 show wavefronts when an ideally collimated wavefront is imaged through a lens to a focus, or when an ideal point source is collimated by a lens.

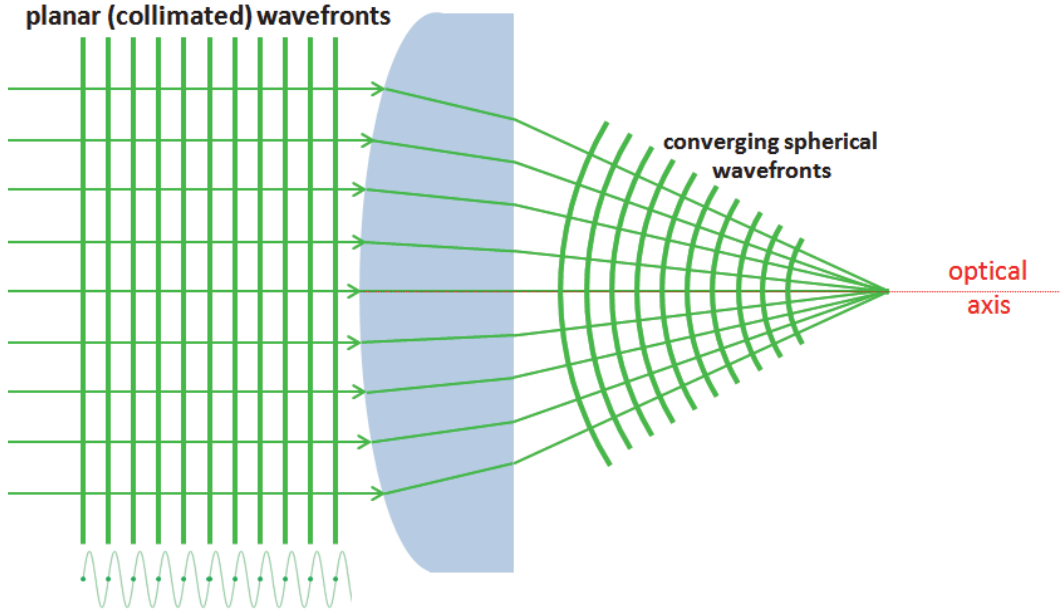


Figure 1-12 *This figure represents an ideal, collimated plane wavefront moving through a converging (focusing) lens.*

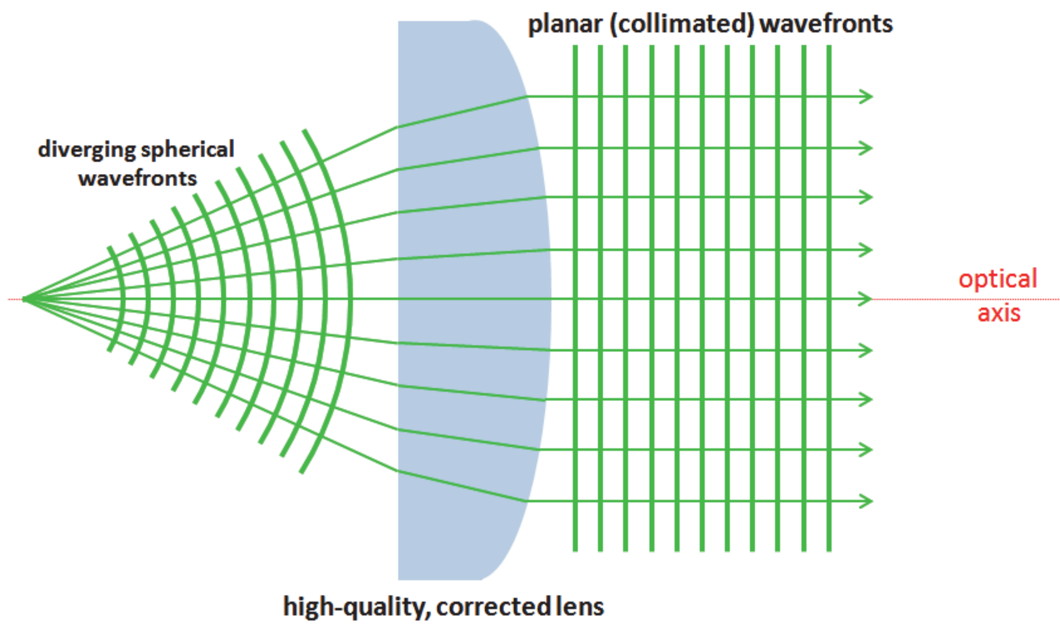


Figure 1-13 *The opposite scenario to Figure 1.12 is shown here, the collimation of a point source to an ideal, flat, collimated wavefront.*

Ideal wavefronts are great when it comes to instruction and learning, but they are not realistic in practice. Whenever a wavefront of light interacts with an optical surface, it not only undergoes large changes to its shape due to the prominent, macroscopic curvature of the optical surface, as shown in Figures 1-12 and 1-13, but the surface also slightly changes the wavefront's quality due to small imperfections in the surface itself. Any changes to the shape of a wavefront are known as *aberrations*. An imperfect surface will impart aberrations across an optical wavefront, making the wavefront *aberrated*. An aberrating material diminishes the quality of the wavefront by causing each part of the wavefront to move in a slightly different direction. Even a simple, thin material can aberrate, as shown in Figure 1-14.

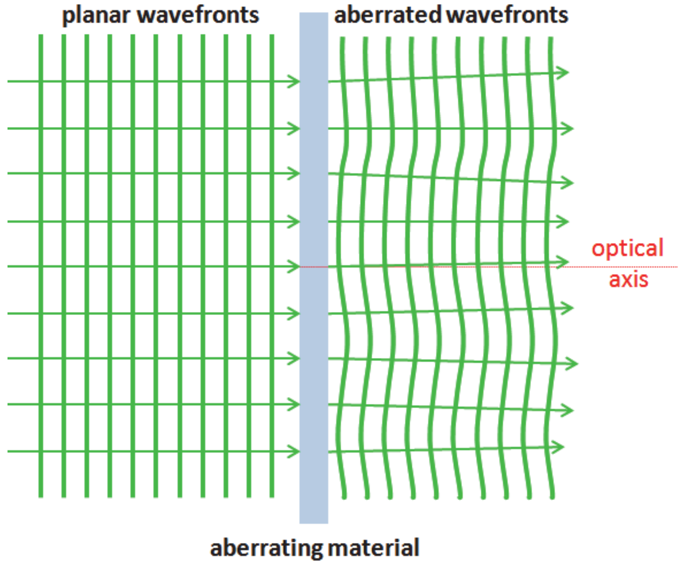


Figure 1-14

Nearly all optical elements aberrate optical wavefronts to some degree. Some optics are designed to remove or cancel aberrations induced by previous aberrating elements. Figure 1-15 shows a lens that is aberrating a diverging spherical wave.

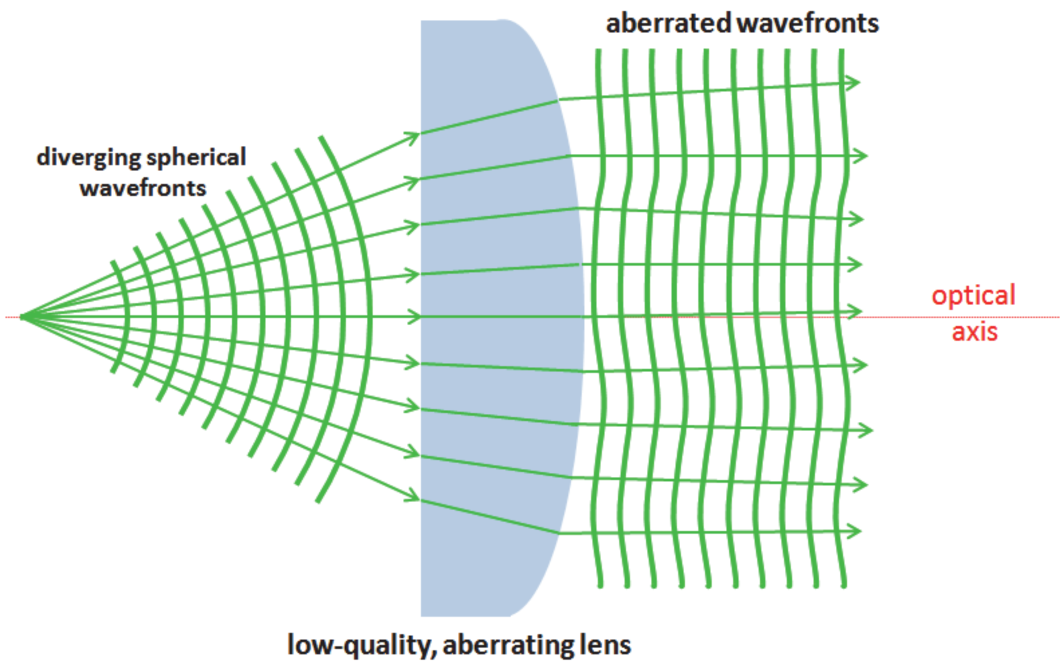


Figure 1-15

Aberrations are deviations from an ideal wavefront, causing errors are collectively referred to as the *wavefront error* (WFE). It is important to understand that WFE is an optical path difference (OPD). An *optical* path is defined by taking the physical path of the light multiplied by the refractive index of the material through which it travels. An OPD compares two wavefronts by taking their difference, usually comparing an ideal wavefront to a real wavefront in a measurement setup. The OPD between two wavefronts is defined in the following equation.

$$\boldsymbol{OPD = n_2 d_2 - n_1 d_1}$$

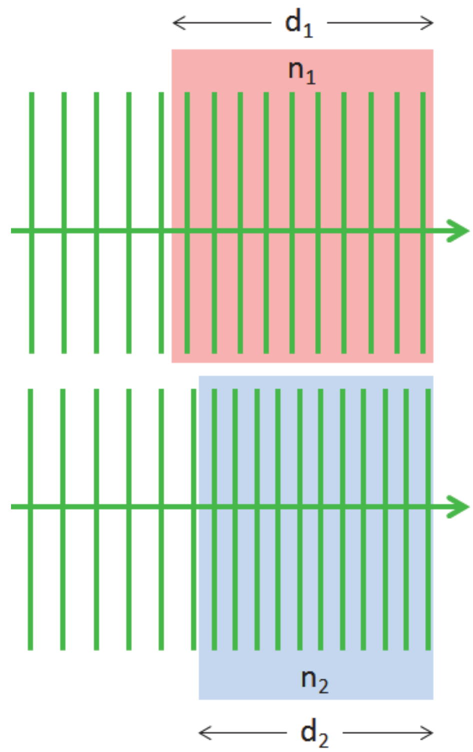


Figure 1-16 *The two rays shown take different physical paths, d_1 and d_2, through different optical materials, n_1 and n_2, resulting in an optical path difference. Even if d_1 was equal to d_2, the refractive index difference still gives the rays an OPD.*

A related parameter describes the phase shift, $\Delta\varphi$, that the light goes through as a function of the OPD. This is shown graphically in Figure 1-17.

$$\Delta\phi = \frac{2\pi}{\lambda}\,\mathrm{OPD} = \frac{2\pi}{\lambda}(n_2 d_2 - n_1 d_1) \qquad (1\text{-}1)$$

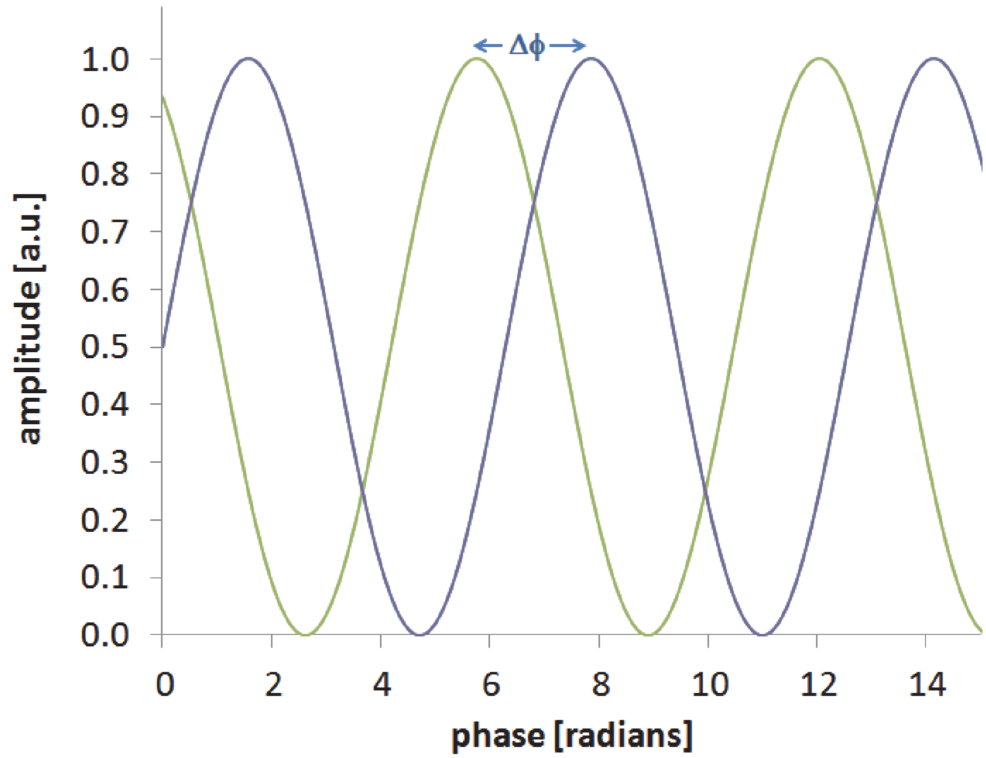


Figure 1-17 *The change in phase between the two waves shown here is indicated by the parameter $\Delta\varphi$. In this example, $\Delta\varphi$ equals about 2 radians.*

The OPD only represents what is happening over a small region of the wavefront, while the WFE is the representation of all errors in the entire three-dimensional wavefront. WFE is presented in a few different ways throughout the remainder of this section because different mathematical WFE representations are used in practice. Each term, each part of the equation, taken individually, gives a relatively simple trigonometric expression that is instructive for each particular type of aberration.

Specific Aberrations in the WFE Equations

WFE equations or wavefront aberration equations are based on the rays of light that are launched through the optical system. As shown in Figure 1-18, the variables of WFE equations are the object height, h, radial magnitude in the aperture stop, ρ, and angle within the aperture stop, ψ. The light rays start at the object, so the object height variable, h, is located in the object plane of the optical system. This variable corresponds to the field angles through the system, so that the maximum size of h defines the field of view of the optical system. It is a normalized value in mathematical WFE representations—that is, it is divided by the actual maximum object height so that its maximum value is 1. If $h = 0$, the object is said to be *on-axis*, if $h \neq 0$, the object is said to be *off-axis*.

The radial magnitude of the light ray's position in the aperture stop, ρ, is also normalized to the maximum physical size of the aperture stop. The light ray's angle in the aperture stop, ψ, is defined from the positive y-axis clockwise as in Figure 1-18. Both ρ and ψ are needed to learn the coordinate of the light ray within the optical system's aperture stop.

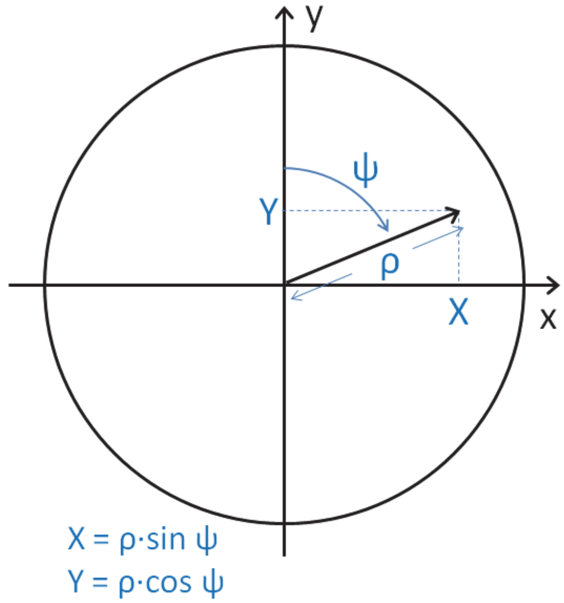


Figure 1-18 *Cooridinates aberration function*

Using just these three variables, mathematicians were able to construct complicated polynomial equations that represent an aberrated wavefront of light energy—the wavefront error. This equation represents the OPD between the measured wavefront and an ideal reference sphere. (That is, an ideal, unaberrated sphere with a similar radius.) Each term of the polynomial defines a different type of aberration, and the name of each aberration describes the aberration.

$$\boldsymbol{WFE\ (h, \rho, \psi) = defocus + tilt + spherical\ aberration + coma}$$
$$\boldsymbol{+astigmatism + field\ curvature + distortion + higher\ order\ terms} \ldots$$
$$\boldsymbol{WFE\ (h, \rho, \psi) = W_{020}\rho^2 + W_{111}h\rho\cos\psi + W_{040}\rho^4 + W_{131}h\rho^3\cos\psi}$$
$$\boldsymbol{+W_{222}h^2\rho^2\cos^2\psi + W_{220}h^2\rho^2 + W_{311}h^3\rho\cos\psi + higher\text{-}order\ terms} \ldots$$

That is,

- *Defocus* corresponds to the term $\boldsymbol{W_{020}\rho^2}$
- *Tilt* corresponds to the term $\boldsymbol{W_{111}h\rho\cos\psi}$
- *Spherical aberration* corresponds to the term $\boldsymbol{W_{040}\rho^4}$
- *Coma* corresponds to the term $\boldsymbol{W_{131}h\rho^3\cos\psi}$
- *Astigmatism* corresponds to the term $\boldsymbol{W_{222}h^2\rho^2\cos^2\psi}$
- *Field Curvature* corresponds to the term $\boldsymbol{W_{220}h^2\rho^2}$
- *Distortion* corresponds to the term $\boldsymbol{W_{311}h^3\rho\cos\psi}$

The details of each aberration will be covered in detail in OP-TEC's Metrology of Optical Systems Module 2-3, so only a brief description is offered here. These basic aberrations are referred to as the first-order (tilt and focus) and third-order aberrations. First-order aberrations can always be removed from an optical system by alignment, while higher-order aberrations are a natural part of the optical system's components. In some systems, higher-order aberrations can be removed by alignment, but all higher-order aberrations can only be reduced in magnitude by compensating them with an equal and opposite aberration in another part of the optical system.

Defocus (sometimes called focus error) represents a wavefront that is aberrated because it is measured before or after the beam comes to focus. The image plane can be translated along the optical axis to remove this aberration, but it is often used to balance other aberrations. *Tilt* represents a measured wavefront tilt about the vertical axis (usually the y-axis) or tip about the horizontal axis (x-axis) with respect to the optical axis. This aberration is used to emphasize the magnitude of other aberrations during alignment, but it can be removed simply, by tilting or tipping the image plane.

Spherical aberration occurs because the lens has a spherical shape, which is not the exact shape of the wavefront. Rays that enter the aperture stop at different radial distances from the optical axis, ρ, and converge to different points along the optical axis. Rays of light near the optical axis are called paraxial rays. They typically come to focus farther along the optical axis than rays that enter the aperture far from the optical axis, as shown in Figure 1-19.

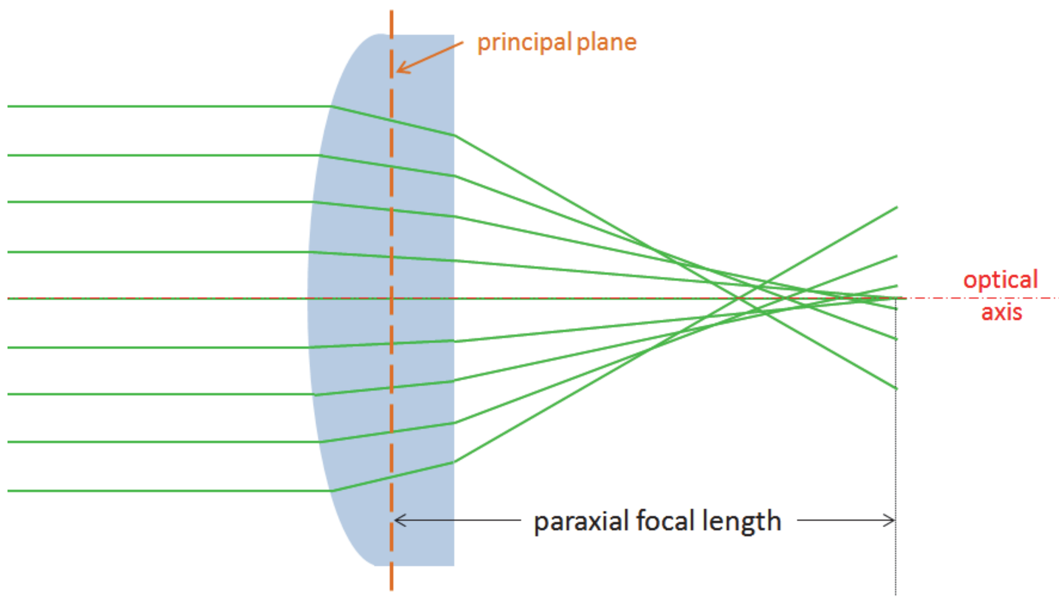


Figure 1-19 *A lens with spherical aberration is shown. The lens itself is the aperture stop, so that rays farther from the optical axis are more aberrated with respect to the paraxial rays, those near the optical axis.*

Coma, shown in Figure 1-20, occurs because rays from object heights, *h,* enter the aperture stop at different radial distances from the optical axis, ρ, and converge to different points in the image plane. Coma results in a focus spot that looks like a comet (as shown later in Figure 1-35 which is how it was named.

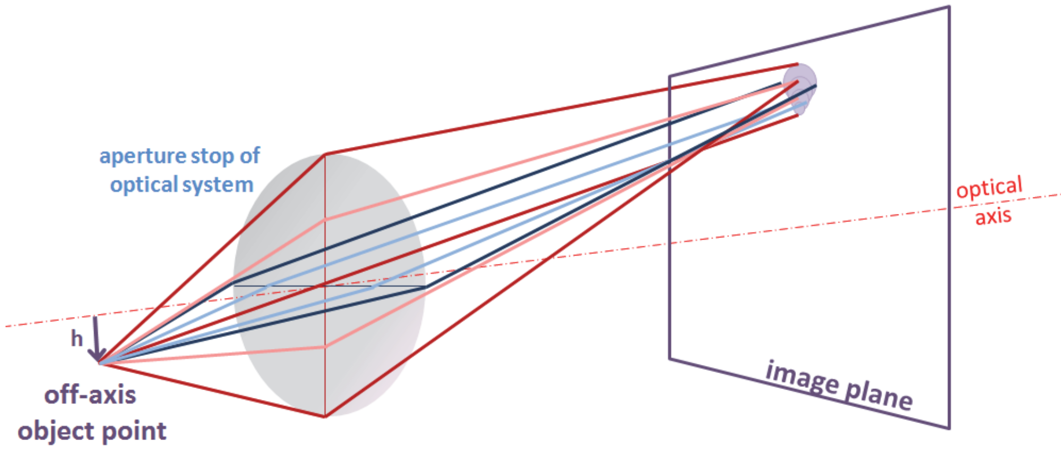


Figure 1-20 *A lens with coma is shown. Rays of different colors represent light in perpendicular planes. The lens itself is the aperture stop, so that rays entering the system at larger distances from the optical axis are more aberrated.*

Astigmatism is considered in two perpendicular planes: rays from the object enter the aperture stop (1) in a plane that includes the optical axis and the object, say, at ψ = 0° (or 180°), the so-called *tangential rays*, and (2) in a plane that is perpendicular to this plane, say, at ψ = 90° (or 270°), the so-called *saggital rays*. Tangential and saggital rays converge to different points along the light's path from the object to the image, resulting in line focuses at each extreme (as shown later in Figures 1-38 and 1-39. This results in a medial point where the rays between tangential and saggital, say, at ψ = ±45°, converge. This medial point is known as the *circle of least confusion*.

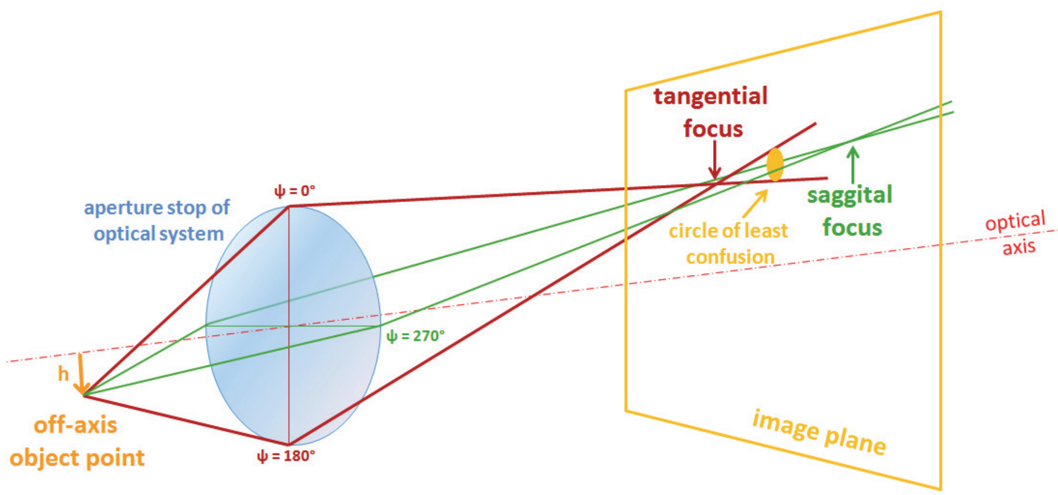


Figure 1-21 *An optical system with astigmatism is shown as an aperture stop. Rays of different colors represent light in different, perpendicular planes. The saggital (green) and tangential (red) line focuses of the off-axis point on the object are evident on either side of the circle of least confusion.*

Field curvature occurs when rays along linear object heights, *h*, (which corresponds to larger field angles) are imaged to a curved surface, rather than a planar image. This is sometimes called Petzval field curvature.

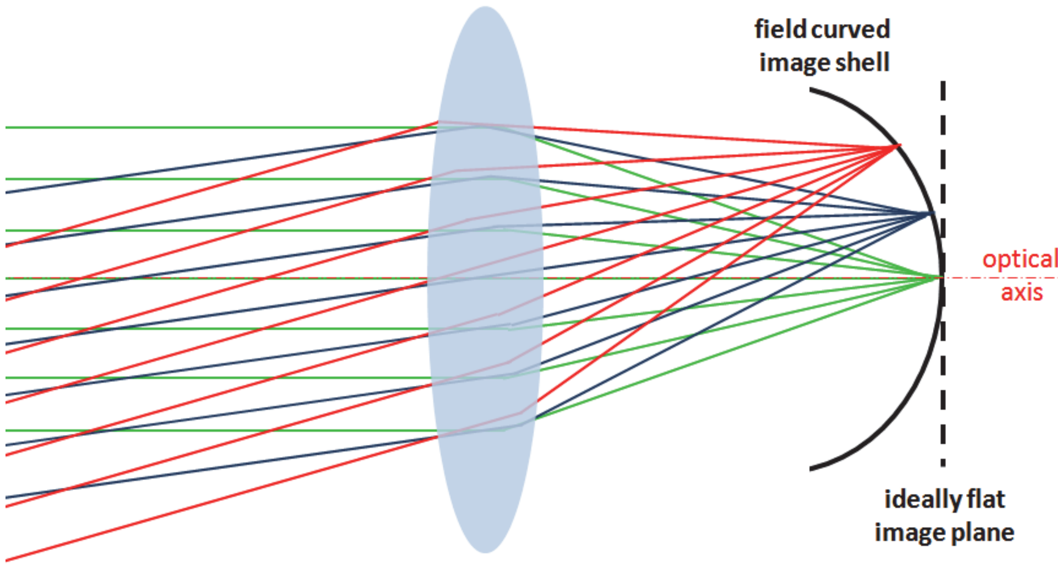
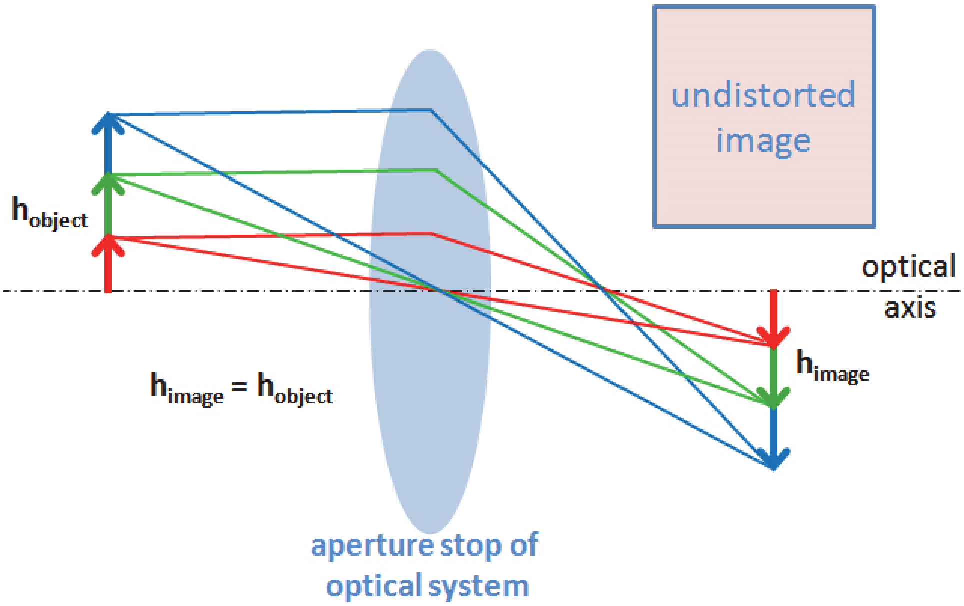


Figure 1-22 *An optical system with field curvature is shown. Different colors represent different field angles in this figure. The curved image plane is evident—larger object heights (that is, larger field angles) are imaged closer to the aperture stop than on-axis object heights.*

Distortion relates how magnification changes as a function of object height, *h*. Distortion results in magnification changes as a function of distance from the optical axis in the image plane. Images with *barrel distortion* produce larger images (higher magnification) than an ideal system in the image plane, while images with *pincushion distortion* produce smaller images (lower magnification) than an ideal system in the image plane.


undistorted
image
h_{object}
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axis
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$h_{image} = h_{object}$
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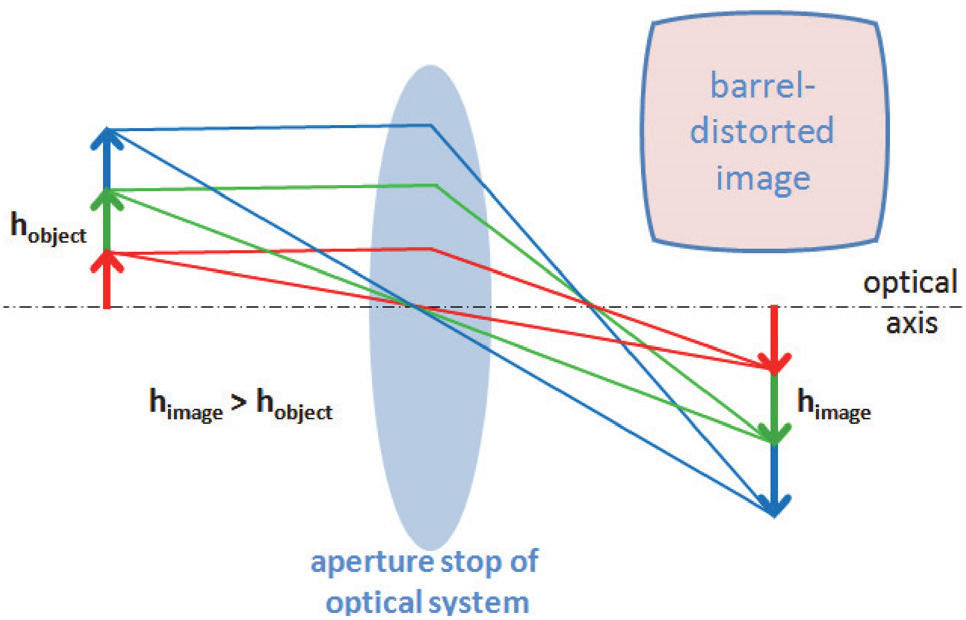
optical system


barrel-
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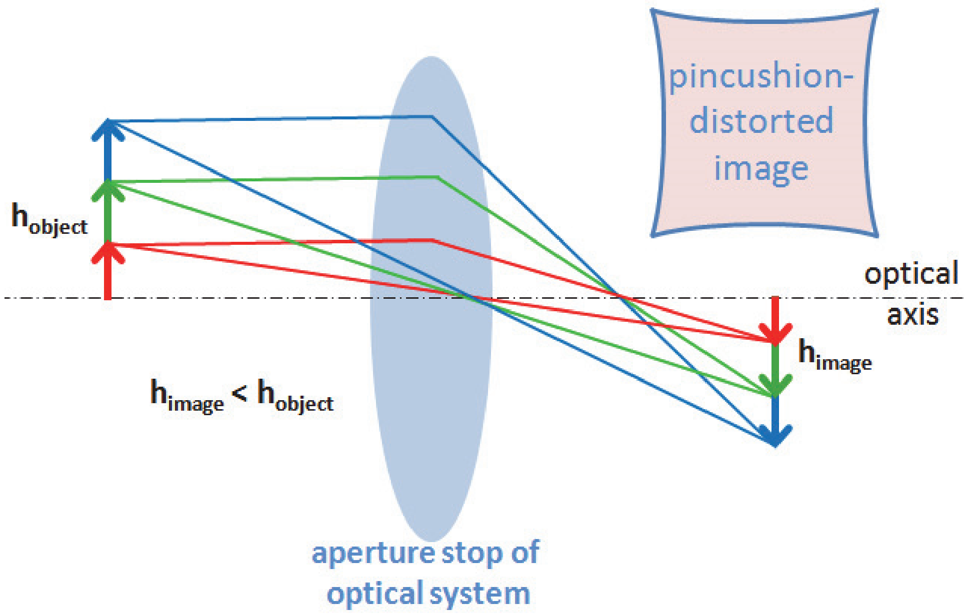


Figure 1-23 *Optical systems with zero distortion, barrel distortion, and pincushion distortion are shown. In this figure, distortion is exaggerated at about 16%. That is, image heights are equal to the object heights in the undistorted optical system, but they are 16% larger in the barrel-distorted image, and 16% smaller in the pincushion-distorted image.*

These are known as the third-order aberrations. Higher-order aberrations certainly exist, and although they will not be written in detail in this text, they certainly will be observed in the laboratory, so they are worth mentioning here. Note that the subscripts on the third-order WFE coefficients W indicate the powers to which h, ρ, and ψ are raised. E.g., defocus is W_{020} because it is associated with $h^0\rho^2(\cos\psi)^0 = 1\cdot\rho^2\cdot 1 = \rho^2$. If an aberration is higher-order, the values of these subscripts will be represented mathematically by larger numbers. For instance, fifth-order spherical aberration is represented by W_{060} and trefoil by W_{333}. It is also important to note that there is a constant "aberration" called *piston* that basically represents a uniform aberration of the entire wavefront, analogous to a DC offset in electronics. Piston is usually neglected in practice since it is not part of the wavefront's structure.

Though this polynomial equation is a complete representation, there is an alternative representation of WFE parameters, given by the Zernike (read "zer-nik-ee") representation. This representation is important because each of its terms independently represent the aberrations within the commonly circular optical pupil. (Mathematically, it is said that the Zernike aberration terms are orthogonal.) Therefore, it is most often used when measuring optical aberrations because Zernike terms are of the same form as the terms observed during measurements. As such, Zernike terms are the usually parameters used to describe the WFE when working with metrology systems such as interferometers.

The variables of the Zernike equation are similar, but slightly different from those shown above because they do not include the object height, h. Again, this equation represents the OPD between the measured wavefront and an ideal reference sphere. They represent the wavefront aberration in the pupil. The radial coordinate in the aperture stop, ρ, is the same, but the angle within the aperture stop is θ (this is different from ψ!), defined from the positive x-axis counterclockwise, as in Figure 1-24. Conversions between the standard wavefront error terms (previous page) and the Zernike terms exist, but they are seldom required when making optical measurements.

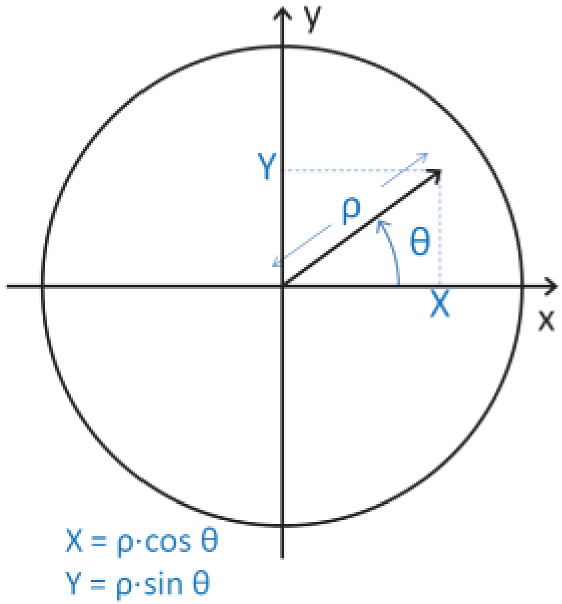


Figure 1-24 *Zernike Coordinates*

$$\boldsymbol{WFE_{Zernike}\,(\rho,\theta) = 1 + \rho\cos\theta + \rho\sin\theta + (2\rho^2 - 1) + \rho^2\cos 2\theta + \rho^2\sin 2\theta}$$
$$\boldsymbol{+(3\rho^2 - 2)\rho\cos\theta + (3\rho^2 - 2)\rho\sin\theta + (6\rho^4 - 6\rho^2 + 1) + higher\text{-}order\ terms} \ldots$$

In the Zernike representation,

- Z_0 ≡ *Piston* corresponds to the term $\mathbf{1}$ (That is, piston is just a uniform shift of the entire wavefront.)
- Z_1 ≡ *X-tilt* (tilt about the x-axis, also may be called "tip") corresponds to the term $\boldsymbol{\rho \cos \theta}$
- Z_2 ≡ *Y-tilt* (tilt about the y-axis) corresponds to the term $\boldsymbol{\rho \sin \theta}$
- Z_3 ≡ *Defocus* corresponds to the term $\mathbf{2}\boldsymbol{\rho}^{\mathbf{2}} - \mathbf{1}$
- Z_4 ≡ *X-astigmatism or 0-90° astigmatism* corresponds to the term $\boldsymbol{\rho}^{\mathbf{2}} \boldsymbol{\cos 2\theta}$
- Z_5 ≡ *Y-astigmatism* corresponds to the term $\boldsymbol{\rho}^{\mathbf{2}} \boldsymbol{\sin 2\theta}$
- Z_6 ≡ *X-coma* corresponds to the term $(\mathbf{3}\boldsymbol{\rho}^{\mathbf{2}} - \mathbf{2})\boldsymbol{\rho \cos \theta}$
- Z_7 ≡ *Y-coma* corresponds to the term $(\mathbf{3}\boldsymbol{\rho}^{\mathbf{2}} - \mathbf{2})\boldsymbol{\rho \sin \theta}$
- Z_8 ≡ *Spherical aberration* corresponds to the term $\mathbf{6}\boldsymbol{\rho}^{\mathbf{4}} - \mathbf{6}\boldsymbol{\rho}^{\mathbf{2}} + \mathbf{1}$

Note that there are additional functional forms of the Zernike polynomial. This is just a common representation. The user should read the manual of any interferometer or similar wavefront-measuring instrument to ensure that the terms are as expected.

Another WFE representation with which a technician should be familiar are the Seidel coefficients, which detail five aberrations, spherical aberration, coma, astigmatism, field curvature, and distortion. Though they do not represent a wavefront as completely as Zernike terms, it is worth understanding that, particularly when higher-order aberrations are negligible, there exists yet another set of coefficients that an interferometer may output.

Understanding the details of these polynomials is not as important as recognizing each type of aberration when viewing a 3D surface plot of the WFE called a *WFE map* or an *aberration map*. This is the primary data product output by a system that measures WFE, such as an interferometer or wavefront sensor.

Representative WFE maps and their corresponding interferograms are shown for third-order aberrations in Figures 1-25 through 1-29. These WFE plots are computed using Zygo's MetroPro software package with a one-micrometer magnitude for each aberration type independently, in order to isolate each Zernike term. In real optical systems, higher-order aberrations (represented via higher-order Zernike terms) exist and impart more complex spatial detail on a wavefront. In some optical designs, aberrations are deliberately introduced to balance or emphasize other aberrations. This will be discussed in OP-TEC's Metrology of Optical Systems Module 2-3.

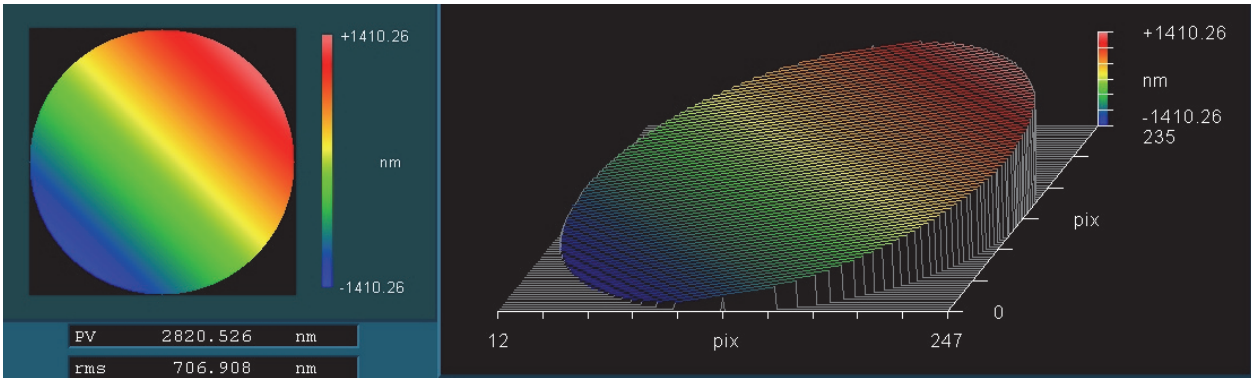


Figure 1-25 *One micrometer of x- and y-tilt are shown here, resulting in an ideally flat wavefront that is tilted at 45°.*

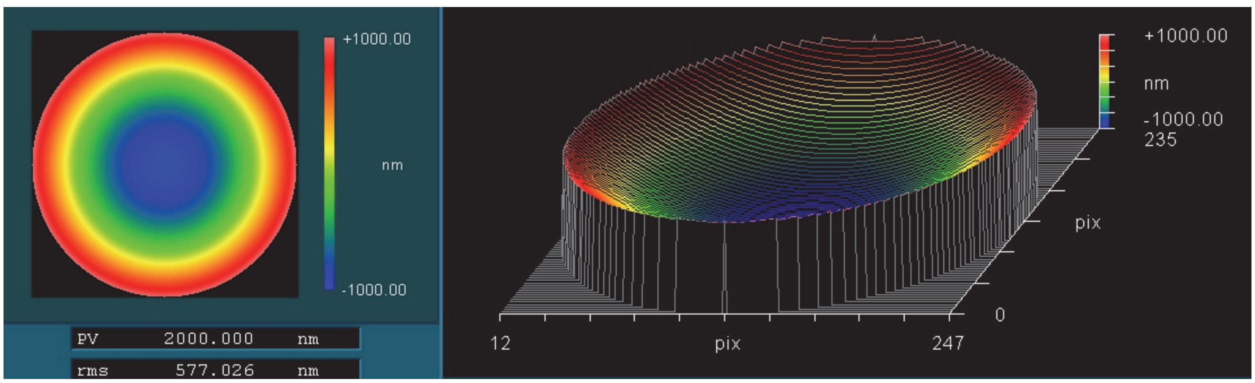


Figure 1-26 *One micrometer of focus is shown here, resulting in a wavefront that is defocused by a total of 2 μm.*

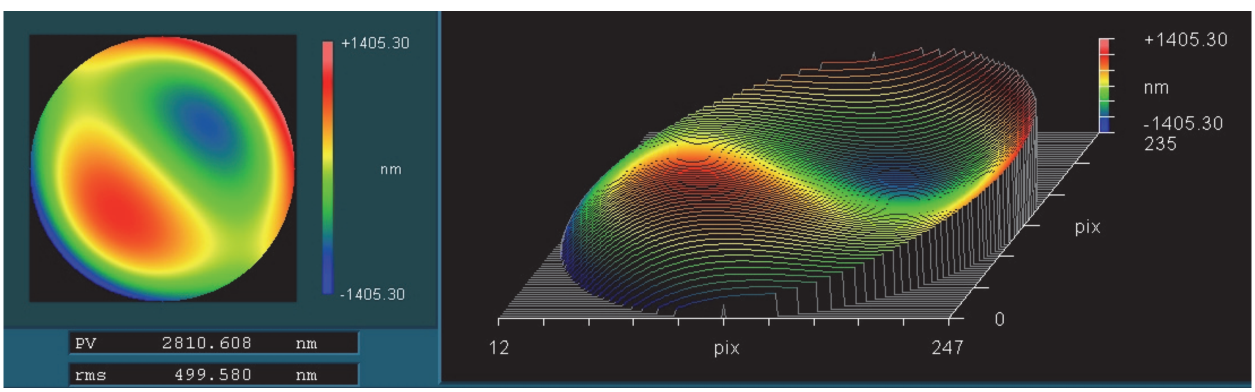


Figure 1-27 *One micrometer of x- and y-coma gives the asymmetric wavefront map shown here.*

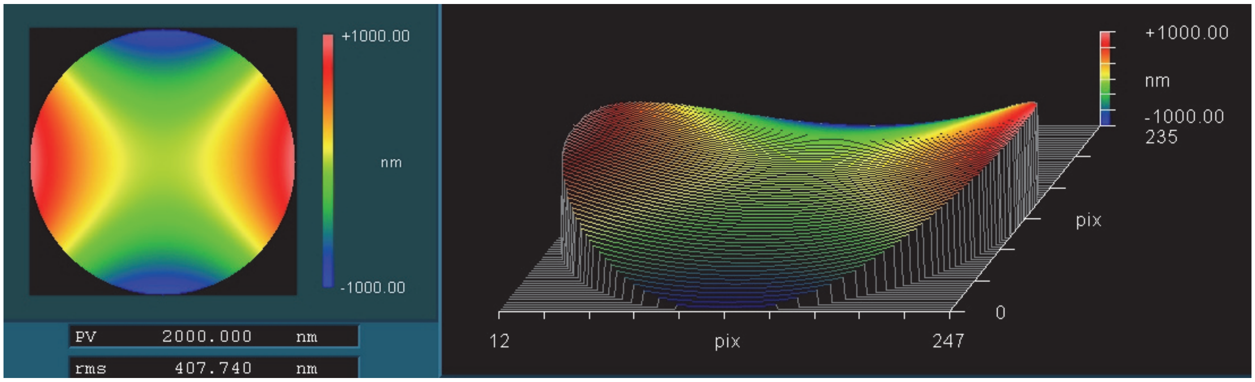


Figure 1-28 *One micrometer of x-astigmatism gives the asymmetric saddle-shaped wavefront map shown here.*

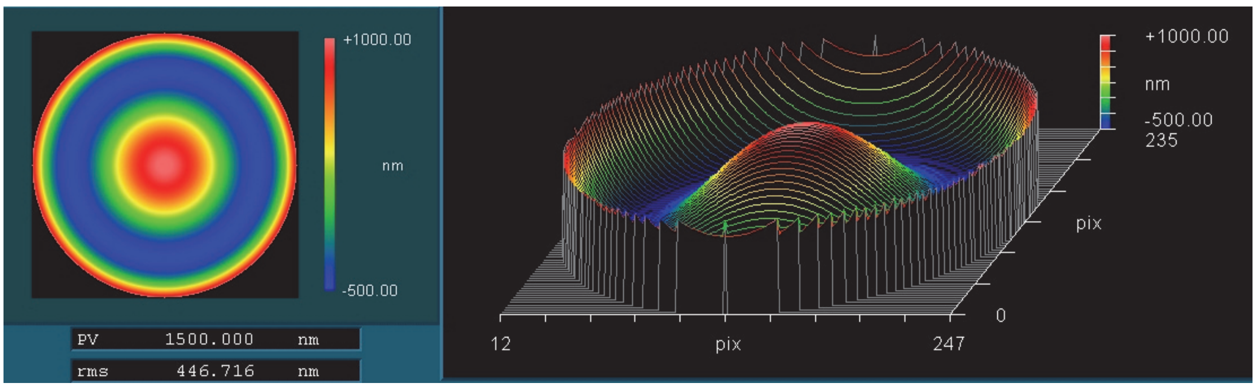


Figure 1-29 *One micrometer of spherical aberration gives the symmetric, sombrero-shaped wavefront map shown here.*

The WFE map for a system that has been aberrated by more than just the basic aberrations is shown in Figure 1-30. The aberrated wavefront was synthesized by adding a lot of low- and high-order Zernike terms together, but is it not uncommon to view a WFE map like this when first aligning an optical system. (In fact, you might be fortunate if the systems wavefront was already this good!)

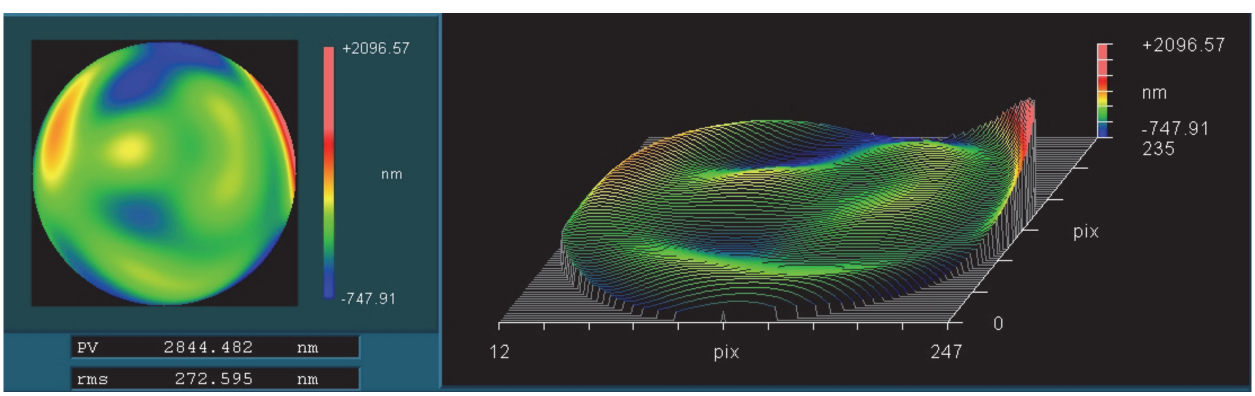


Figure 1-30 *The WFE map is shown for an aberrated optical system.*

Aberrations also influence each wavelength of an optical wavefront differently, leading to so-called *chromatic aberrations*. That is, different WFEs often exist for each wavelength present in the optical system, leading to an error for each color relative to the others. Chromatic aberrations are caused by dispersion in the glass used in the optical system, so they do not exist in all-reflective optical systems. Since each color sees a different refractive index, it will be aberrated in a slightly different way.

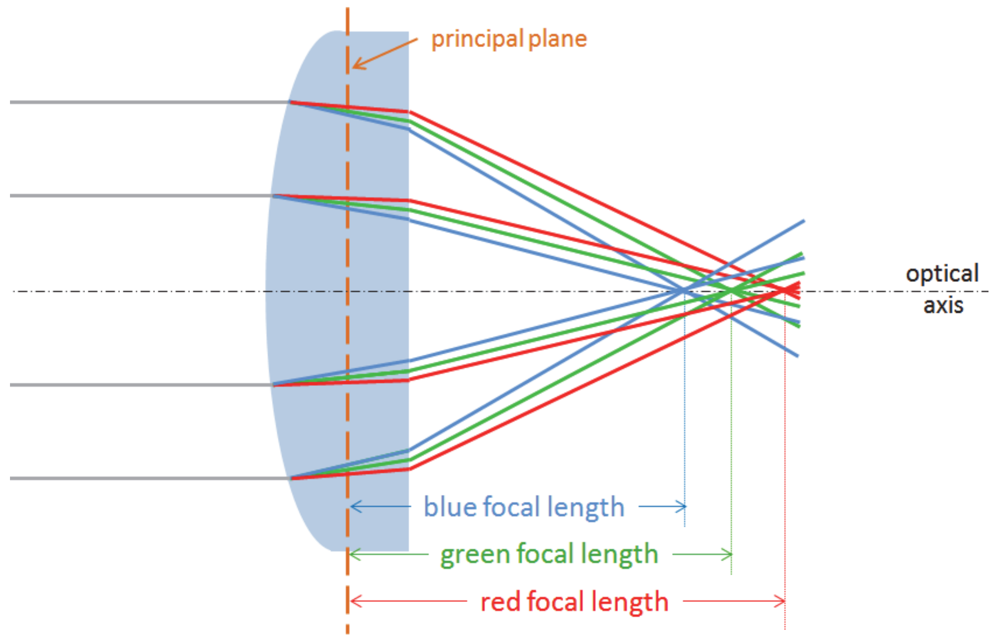


Figure 1-31 *A lens with chromatic aberration is shown. Rays of different colors represent light of those colors. Note the separation of red, green, and blue wavelengths along the optical axis and laterally as a result. This is a typical representation of chromatic aberration in the visible portion of the spectrum, but chromatic aberrations exist for all spectral regions and must be compensated over the optical system's operational spectrum.*

All aberrations of the optical wavefront require correction through careful optical design and alignment. The optical designer is responsible for minimizing aberrations in the optical system design so that there are few design-residual aberrations, and the technician or engineer performing the optical integration and alignment is responsible for understanding any aberrations induced by bonding, mounting, alignment, and environment effects. A measured 3D WFE map can often be broken down into aberrations that are design residual, due to improper assembly or imperfect alignment, and those manufactured in the optical elements themselves.

This optical system performance metric is covered first because it represents the shape of the light's entire full-aperture wavefront after it traverses an optical system. The WFE map is a powerful metric by which to quantify the performance of an optical system, so the various techniques by which to measure the WFE of an optical system will be covered in detail in OP-TEC's Metrology of Optical Systems Module 2-3.

Point-Spread Function (PSF)

The focal spot of an optical system is the image of an object (the source) that is located at optical infinity. If that input source is a single, ideal point of light, the distribution of energy at the image plane, the focal spot is the *point-spread function* (PSF) of the optical system. (Literally, the spatial *function* of how an ideal *point* of light is *spread* by the optical system.) PSF is directly related to the optical quality and performance of the system, and, ultimately, the wavefront errors induced on the light as it traverses the optical system. It is equivalent to the impulse response that is commonly used to qualify the performance of electrical systems.

An ideal system is called *diffraction limited*, meaning that the optical system performs perfectly, only limited by the effects of diffraction through its apertures. If an optical system is diffraction limited, its optics no longer need to be improved by fabrication or alignment. The ideal, *diffraction-limited* spot shown in the PSF of Figure 1-32 is known as the *Airy disk*. A system is diffraction limited if its wavefront error function, W, is approximately equal to zero.

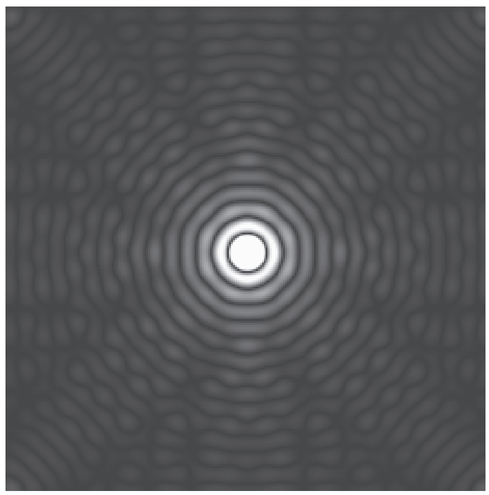


Figure 1-32 *The point-spread function of an ideal, diffraction-limited optical system.*

The energy distribution of the Airy disk is the basis of the spot equation because its first zero (the inner black ring) occurs with a diameter equal to the following calculation (which has distance units, such as micrometers or millimeters):

$$(central)\ spot\ diameter \cong 2.44\ \cdot \lambda \cdot\ F/\# \qquad (1\text{-}2)$$

The physical extent (size) of the spot formed by an optical system is only a function of the wavelength of the light through the optical system and the system's "speed" or f-number. It is important to recognize that because *F/#* equals the focal length divided by the clear aperture diameter; larger apertures lead to smaller spot diameters. For example, if this system was operating with 650-nm light at F/12, the spot size equals about 19 µm. Reduce or "stop down" the aperture by a factor of two to F/24 and the spot size doubles to 38 µm. It is also useful to consider another representation of this formula, which represents the angular size of the image as:

$$angular\ size \cong 2.44\ \cdot \lambda/CA \qquad (1\text{-}3)$$

This dimensionless quantity often defines the angular resolution of an optical system, as will be discussed later in this section.

Whether the image is represented by physical or angular size, such perfect performance may be achieved in practice when directing single-mode lasers through well-corrected optics, or using adaptive optics systems to correct the wavefront aberrations. Most optical systems contain some aberrations in their elements, so they do not produce perfect images. Figure 1-33 shows the PSF of a highly aberrated system; in fact, it is the PSF for the system of Figure 1-30.

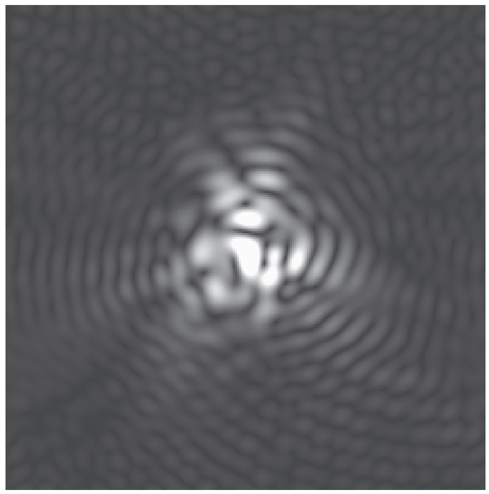


Figure 1-33 *The PSF is shown for an aberrated optical system.*

Examples of the PSF that would result from individual, isolated aberrations are shown for low-order Zernike terms in Figures 1-34 through 1-37. (A PSF for the aberration tilt is not shown because a tilted wavefront simply decenters the diffraction-limited PSF.) All PSF plots have the same scale as the diffraction-limited case, which depends on the wavelength and the speed (F/#) of the optical system. Notice how the spot size increases considerably when the wavefront is aberrated.

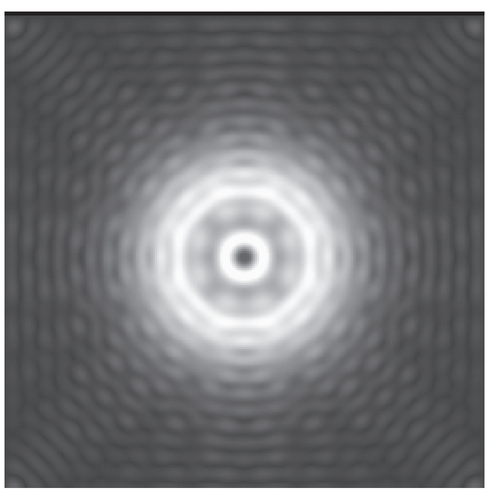


Figure 1-34

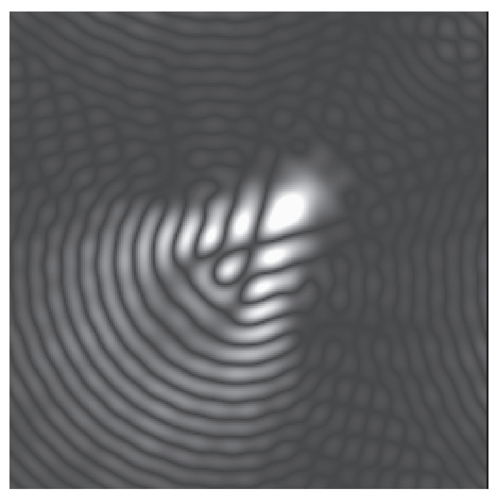


Figure 1-35

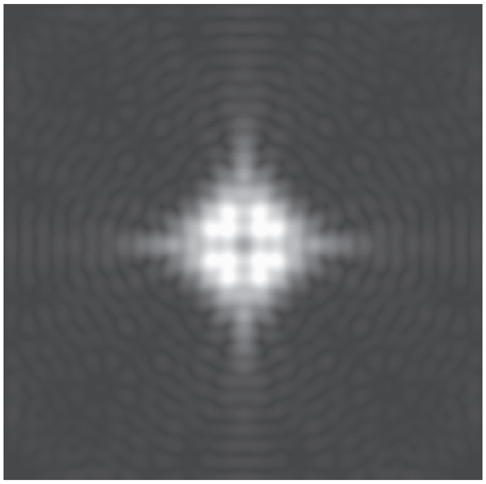


Figure 1-36

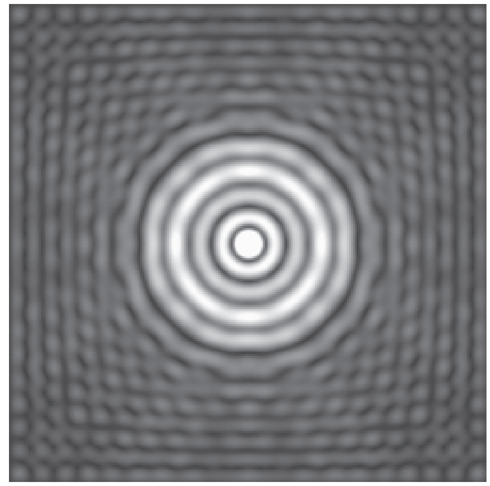


Figure 1-37

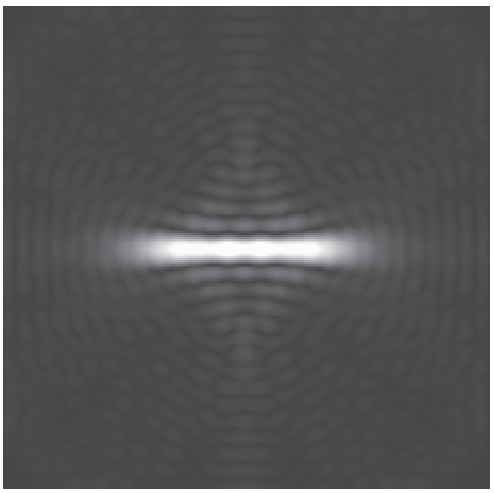


Figure 1-38

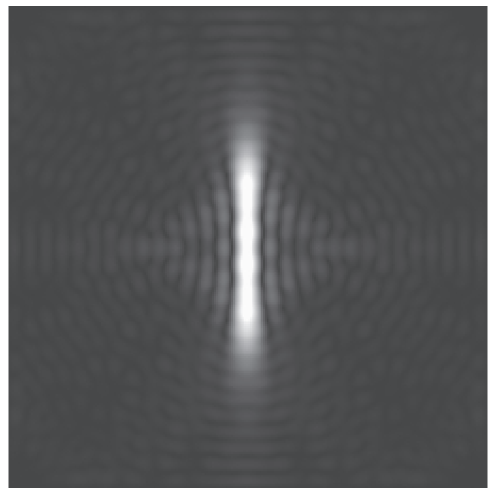


Figure 1-39

PSF is a great physical metric of optical system performance because it is the spot actually seen when an ideal point of light traverses the optical system under test. This is often called the "star test" because a good object to use is a bright star. In fact, if you look at a distant star through one of your own optical systems—your eyes—you will see the PSF of that eye as a blurred spot on your retina. As will be discussed in OP-TEC's Metrology of Optical Systems Module 2-3, wavefront sensors actually use a two-dimensional array of PSFs to sample the wavefront and create a WFE map of an optical system.

PSFs are used to define an important optical system parameter, the Strehl ratio, because it indicates the image quality in the presence of aberrations. This is the ratio of the measured on-axis irradiance (the on-axis value of the PSF) to the on-axis irradiance of a diffraction-limited system with an identical *F/#* and wavelength range, as shown in Equation 1.4, in which r is the radial coordinate starting at the center (on-axis) of the PSF. Examining this ratio shows that higher Strehl ratios correspond to optical system performance that approaches diffraction-limited performance. A Strehl ratio greater than 0.8 is accepted to determine a high-quality optical system. (Note that this is sometimes given as a percentage, e.g., Strehl ratio = 80%.)

$$\text{Strehl} \equiv \frac{PSF_{measured}\ (r = 0)}{PSF_{diffraction-limited,}\ (r = 0)} \qquad (1\text{-}4)$$

Lower-than-unity Strehl ratios effectively spread the energy of a PSF from the diffraction-limited irradiance distribution of the PSF to its side lobes, as can be seen by comparing the diffraction-limited PSF in Figure 1-31 to the defocused PSF in Figure 1-34. Figure 1-40 compares the PSF with Strehl ratios of 0.4, 0.8, and the ideal case of 1.0.

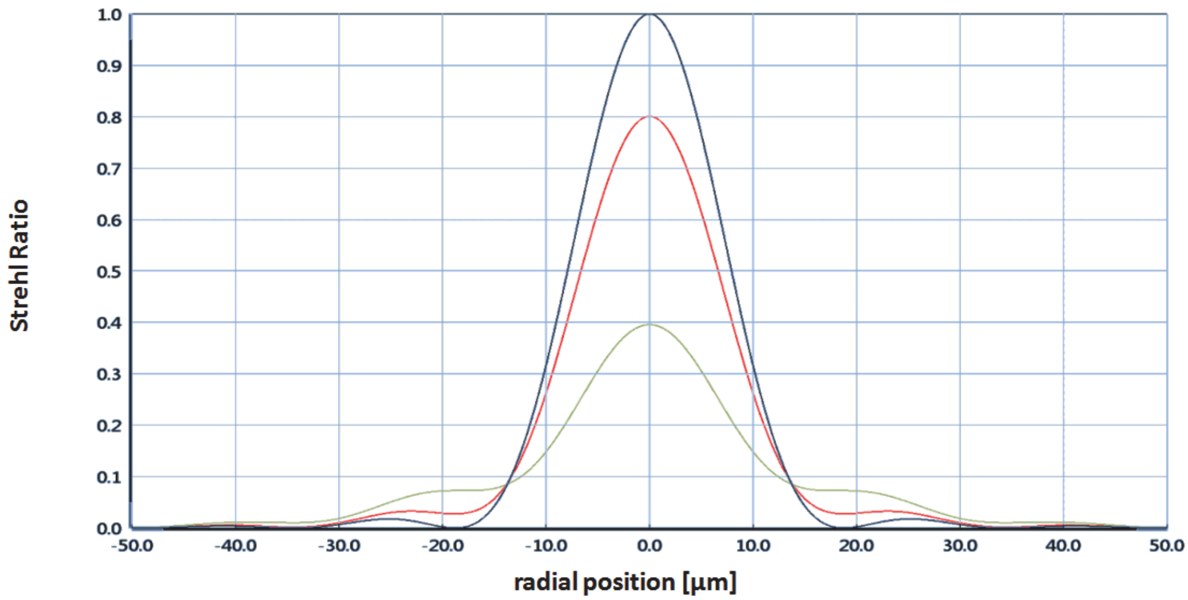


Figure 1-40 *Strehl ratios of 0.4 (green), 0.8 (red), and 1.0 (blue) are shown here. Ratios lower than unity were achieved to create this figure by defocusing the optical system.*

The Strehl ratio is also related to the WFE equation. Specifically, the statistics of the WFE are frequently used to approximate the Strehl, as shown in Equation 1-5.

$$\text{Strehl} = \left|\left\langle e^{\left(i\frac{2\pi}{\lambda}WFE\right)}\right\rangle\right|^2 \approx e^{-\left(\frac{2\pi}{\lambda}\sigma\right)^2} \approx 1 - \left(\frac{2\pi}{\lambda}\sigma\right)^2 \qquad (1\text{-}5)$$

The parameter σ represents the root-mean-square (RMS) error of the wavefront phase, Δφ, as in Equation [phase shift], remembering that WFE is an OPD. The units of the RMS error, σ, are distance units, such as meters (the same units as the wavelength specified).

PSFs are also important because they provide a way to define the resolution of an optical system. When two point objects are imaged through an optical system, their minimum resolvable separation provides a measure of this resolution. There are quite a few metrics used to define resolution, but the most common is the Rayleigh criterion. Using this criteria, two adjacent objects are imaged. If the minimum of one object's PSF (its image) is located at the maximum of the other object's PSF, then the objects are said to be resolved via the Rayleigh criterion. That is, when two objects' PSFs are aligned equal to or greater than this separation, then the two objects are said to be resolved. This can be applied using either the physical image size (as in Equation 1-2) or the angular image size (as in Equation 1-3). It is illustrated graphically in Figure 1-41, which shows a cross section through the center of two ideal PSFs (as in Figure 1-31). The two diffraction-limited PSFs shown are offset until the maximum of one PSF is aligned to the minimum of the other (the Rayleigh criterion), at a physical separation of $1.22 \cdot \lambda \cdot F/\#$ or an angular separation of $1.22 \cdot \lambda / CA$ (or $1.22 \cdot \lambda / D$, since the variable "D" is sometimes used for clear aperture). A stricter criterion drops the coefficient 1.22, so that an optical designer may talk about the number of "lambda over Ds" that the system can resolve. Once this separation is achieved, the objects are said to be resolved.

Though the resolution of an optical system may be specified, the next section will detail an optical performance parameter that provides more complete information than a resolution specification alone.

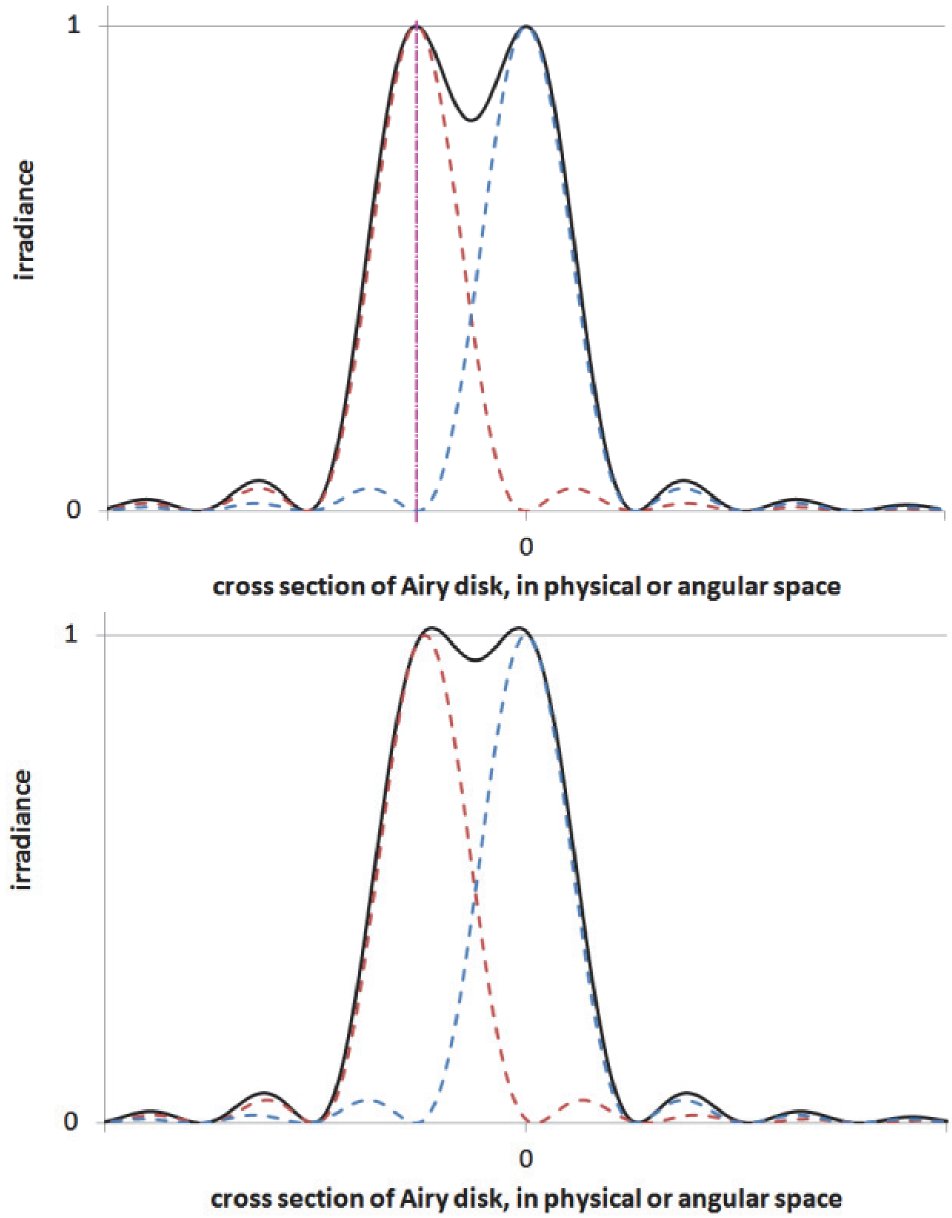


Figure 1-41 *The first figure shows the PSF cross-section of two resolved spots, with the vertical line indicating where the minimum of one spot exactly overlaps the maximum of the other spot—this is the criterion for resolution. The second plot shows two spots that are too close and therefore unresolved.*

Modulation Transfer Function (MTF)

An incoherent optical imaging system is expected to make high-resolution, high-contrast images of the objects in a scene. To describe this ability of an optical system, one of the three following synonymous terms are used: *modulation*, *contrast,* or *visibility*. This concept defines a ratio of the difference between the most radiant signal and the least radiant signal in an image to the sum of those signals, as in Equation 1-6. This is really a ratio of the alternating component to the direct offset component, or the AC function divided by the DC offset, in electronics terms. This was written using units of irradiance, although units of power or intensity or any other radiometric unit are also acceptable. Optical systems are usually designed to obtain high-contrast images with many gray levels between the whitest whites and the blackest blacks, as illustrated by Figure 1-42 for an image of black and white sinusoidal bands with 50% contrast and 100% contrast.

$$modulation = \frac{(E_{max} - E_{min})}{(E_{max} + E_{min})} = \frac{AC}{DC} \quad (1\text{-}6)$$

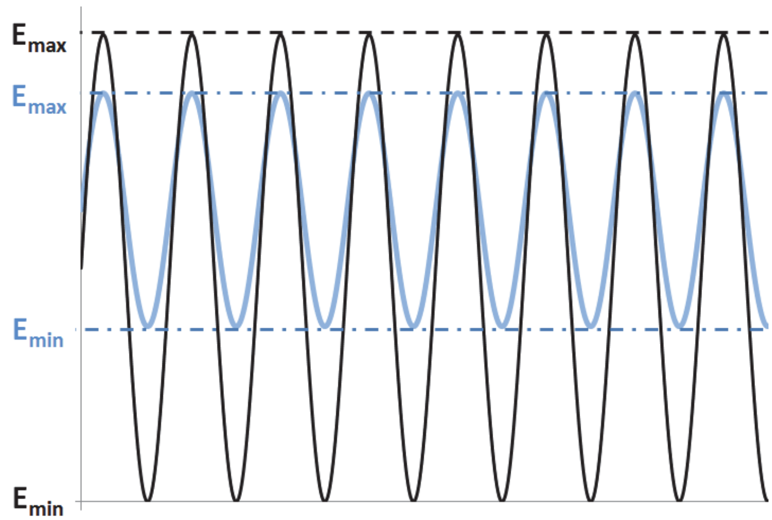


Figure 1-42 *This plots irradiance as the modulation (or contrast or visibility) of features in a sinusoidal image. Crests represent points of maximum irradiance, and troughs are minima in irradiance. The darker curve shows 100% contrast, and the lighter curve is lower, about 50% contrast, wherein both the blackest blacks and the whitest whites appear gray.*

The measure of an optical system's ability to form resolved, high-contrast images within a scene is called its *modulation transfer function* (MTF), which is a ratio of the modulation achieved in image space to the actual modulation of the object. (When applied to the human vision systems, the MTF may be known as the contrast transfer function (CTF).) The MTF shows how the contrast of spatial features (the *modulations*) are *transferred* from the object scene to the image plane, analogous to output-to-input transfer functions commonly used in electronics and other technical fields. The sources considered when assessing an optical system's MTF must be incoherent to avoid interference effects in the imaging plane.

$$\mathrm{MTF}(\xi) = \frac{modulation_{\text{image}}(\xi)}{modulation_{\text{object}}} \quad (1\text{-}7)$$

The MTF of an optical system ranges from zero to one, where an MTF of one indicates perfect transfer of the object to the image. MTF is given as a plot of modulation (contrast) versus spatial frequency, ξ—it represents the contrast obtained for different spatial frequencies of the image, in units of modulation cycles per distance (e.g., [cycles/mm]). Spatial frequency is analogous to position, as temporal frequency (in units of inverse seconds or Hertz) is analogous to time.

MTF curves start at 100% modulation transfer for spatial frequencies of very low contrast (i.e., a uniform background), and decrease as the object's spatial frequencies, ξ, increase. As might be expected, high-resolution objects are more challenging to image with high contrast through an optical system. *MTF provides complete information about an optical system's ability to resolve objects of different spatial frequencies.*

An example of MTF curves for two different field angles (angles of incidence) are shown in Figure 1-43, along with the diffraction-limited MTF. This MTF curve is calculated and plotted using the optical design software ZEMAX. The diffraction-limited MTF is the solid black curve—this is as good as an optical system can perform, in the ideal, diffraction-limited case for a given wavelength and f-number. The middle, red curve shows the on-axis (0°-incidence) field point, and the lower, green curve is the (rather large) off-axis field point at an angle of 2.865° (50 mrad).

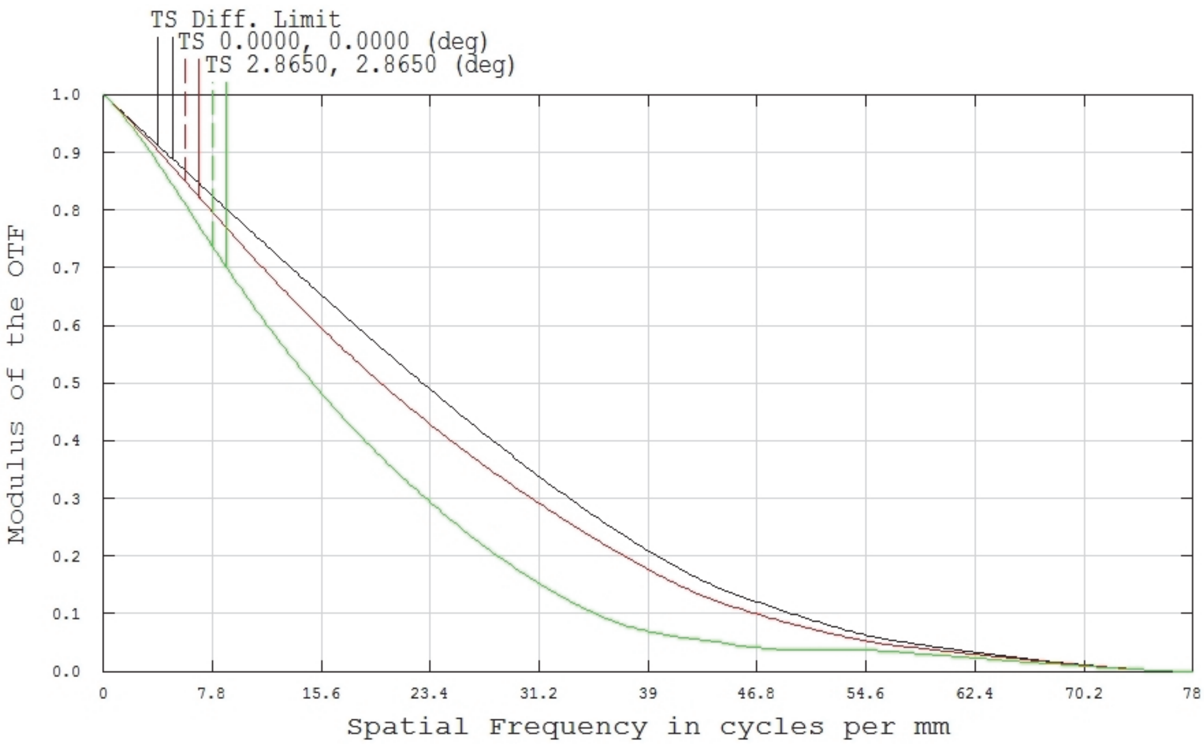


Figure 1-43 *An example of an MTF curve, with the ideal, diffraction-limited performance shown as a solid black curve, an on-axis field curve shown in red, and an off-axis field shown as in green.*

Strictly speaking, the MTF is the magnitude (the modulus) of the optical transfer function (OTF). The remaining part of the OTF, called the phase-transfer function (PTF), conveys the phases with which different spatial frequency, ξ, components combine at the image plane. Particularly because phase information is available via the OTF, small amounts of aberration appear more prominently in an OTF, MTF, or PTF curves than in a PSF, as seen by comparing the MTF curve of Figure 1-43 to the MTF curve of Figure 1-44, in which the image plane has been defocused by 2 millimeters.

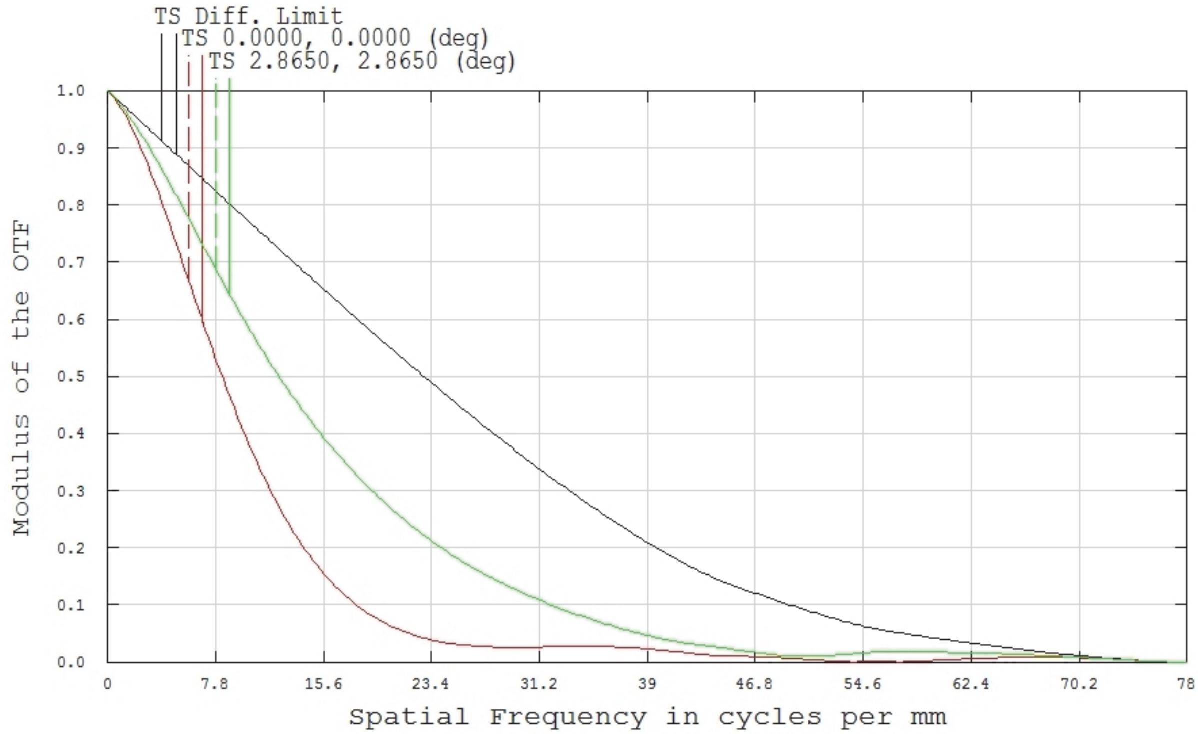


Figure 1-44 *The same plot as shown previously, but defocused by 2 mm.*

It should be apparent that the MTF curve ends or cuts off at a specific spatial frequency. This *cutoff frequency* is an important parameter that can be calculated based on optical system parameters λ and F/#. It should be known that the spatial frequency axis of an MTF curve is sometimes normalized to this cutoff frequency so that the values along that axis range from zero to one, plotting spatial frequencies as a ratio to this cutoff frequency.

$$\xi_{\text{cutoff}} = \frac{1}{\lambda \cdot \text{F/\#}} = \frac{CA}{\lambda \cdot \text{EFL}} \approx \frac{2 \cdot NA}{\lambda} \qquad (1\text{-}8)$$

Spatial frequencies are important parameters when considering the sampling interval required by an image-plane detector, such as pixels in a camera. The sampling interval required to sample a particular spatial frequency within an image plane is given by the Nyquist criterion, shown in Equation 1-9. That is, the detector elements in an optical system should be separated by a distance of x_{sample} in order to adequately sample spatial frequency, ξ.

$$x_{\text{sample}} = \frac{1}{2\,\xi} \qquad (1\text{-}9)$$

“Adequate” sampling means that the image’s spatial frequencies will be sampled without *aliasing*. Aliasing can be envisioned by considering the two spatial frequencies represented by sine waves in Figure 1-45. If an image with these two spatial frequencies is sampled by detector elements located at the **X**-marks shown, then the lower-frequency sine wave (red) cannot be discerned from the higher-frequency sine wave (blue). These two frequencies are said to be aliased. To avoid aliasing, the finest sampling interval required in an optical system must be the reciprocal of twice the cutoff spatial frequency, ξ_{cutoff}. In the case of the spatial frequencies shown in Figure 1-45, sampling should occur twice per cycle of the blue sine wave. If aliasing is present in an image, images of objects with high spatial frequencies will appear to have low spatial frequencies. This is the phenomenon that makes low-frequency Moiré patterns appear when two higher-frequency patterns are overlapped.

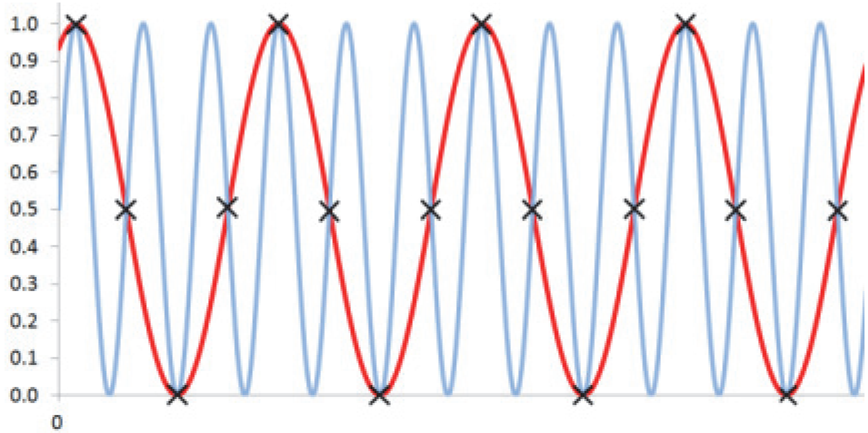


Figure 1-45 *The* ***X****-marks show a sampling frequency that is appropriate to reconstruct the lower-frequency sine wave (red), but not the higher-frequency sine wave (blue). These two spatial frequencies are aliases.*

MTF has a key advantage as a quality metric in that it can measure directly the imaging performance of an optical system using the complete incoherent spectrum of light required in operation. The MTF allows the optical designer the option to specify explicitly the desired optical system resolution in a design drawing. If the optical designer is concerned about particular ranges of spatial frequencies that might be present in an object scene, then, rather than specifying the entire MTF or OTF, the parameter *mid-spatial frequency* (MSF) *error* (sometimes abbreviated "MSE" or "MSFE") may be explicitly called out on the design drawing of an optical element or system. A MSF error specification states the allowed modulation value within a region of the MTF curve, so it is specified over a range of spatial frequencies, as in the following example.

MID-SPATIAL FREQUENCY ERROR:
MODULATION TRANSFER FUNCTION (MTF) SHALL BE GREATER THAN 40% FOR SPATIAL FREQUENCIES BETWEEN 50 AND 150 CYCLES PER MILLIMETER

MSF error may also be included within the scan resolution/scan length portion of the surface texture specification of an ISO 10110 drawing, per part ISO10110-8. This is considered an error because it is a deviation from the diffraction-limited performance of an optical system. Note how the MTF shown in Figure 1-43 is significantly lower than the diffraction-limited curve for mid-spatial frequencies, particularly for the off-axis field points, and in Figure 1-44 for an aberrated (defocused) system. MSF error is an important parameter to specify. The diffraction-limited MTF curve and the cutoff frequency, ξ_{cutoff}, will be different for every optical system, since they depend on the wavelength region, focal length, and clear aperture of the optical system, as described above. Whether or not the system performance is diffraction limited, the diffraction-limited MTF curve is usually plotted along with the measured MTF curve for reference.

If two or more optical systems are independent, well-corrected, and operate with incoherent light, the combined MTF of these optical systems often can be estimated by simply multiplying the MTFs of each individual system on a spatial frequency-by-spatial frequency basis. Care must be taken to ensure that the systems are operating using incoherent light, and that each system can operate independently without significant aberrations. If the second optical system is intended to correct the aberrations of the first, this approach cannot be applied.

Relationship between Wavefront Error (WFE), Point-Spread Function (PSF), and Modulation Transfer Function (MTF)

The WFE, PSF, and MTF all represent the quality of an optical wavefront after it passes through an optical system, thereby quantifying the system's performance. Though these metrics are defined by differently, they can be related mathematically. Detailed treatment of these mathematics is beyond the scope of this text, but it has been demonstrated that the Strehl ratio can be calculated from PSFs, or by using the variance of the WFE equation. Many optical metrology software packages compute one parameter from another. For example, interferometer software can compute the MTF and PSF from a measurement of the wavefront error. Similarly, MTF-measuring instruments can calculate the measured PSF. It is important to recognize that only one performance metric is measured by the interferometer or MTF-measuring instrument itself, and the other metrics reported are merely calculations.

PROBLEM EXERCISES AND QUESTIONS

1. The principal plane of a optical system can be found by connecting two lines:

    (1) the line defined by collimated input light and

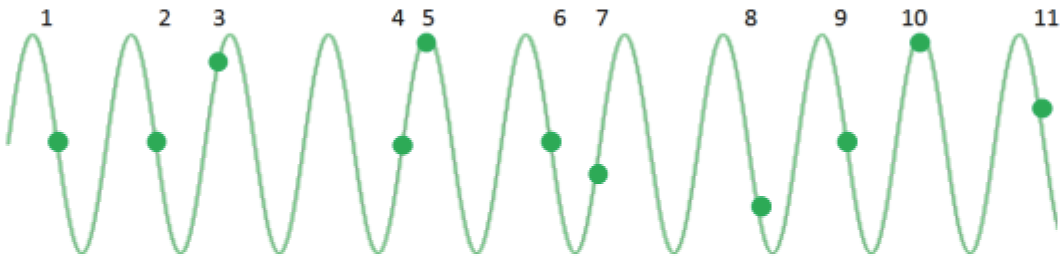
    (2) a line between the focal point and the point from which light exits the optical system.

    A beam of collimated input light hits a 50 mm diameter optical system 20 mm above the optical axis and exits the final surface of the optical system 14 mm above the optical axis, coming to focus on the optical axis at a location 70 mm from the final surface. Find the location of the principal plane relative to the final surface.

    This problem can be solved arithmetically or even graphically. Experimentally, this problem may be solved using a small-diameter laser beam.

2. 100 mm – 70 mm = 30 mm between final surface and principal plane
3. Geometrically, by similar triangles:
4. $\frac{14\text{ mm}}{70\text{ mm}} = \frac{20\text{ mm}}{\text{X}} \therefore \text{X} = 100\text{ mm}$
5. X – 70 mm = 100 mm – 70 mm = 30 mm between final surface and principal plane
6. The effective focal length of an optical system is 300 mm. However, the total length of the optical system from the first surface to the final surface is only 100 mm. Use a sketch to explain how this is possible.
7. Draw a two-lens system to scale, as in Figure 1-4.
8. Draw a two-lens system to scale, as in Figure1-4, but replace the last lens assembly with a negative lens of equal but opposite effective focal length.
9. Light comes to focus on a focal plane array (FPA), a camera's detector surface. The FPA is located at a focal length of 63 mm from the exit pupil of the optical system. The diagonal size of the FPA is 35 mm, with an aspect ratio of 4:3. What are the horizontal and vertical fields of view for this system?
10. The effective focal length of an optical system is 300 mm. The limiting aperture of this system has a 45 mm diameter. What is the *F/#* of this system?
11. A 3 mm diameter laser beam is incident on a microscope objective with a working distance of 10 mm, a clear aperture of 7.5 mm, and an NA of 0.25. What is the effective *F/#* of this optical system?
12. When imaging through an optical system, it is determined that the image stays in focus over a 150 μm range of image plane locations. This system is filtered to use only green light at 543.1 nm. What is the approximate *F/#* for this system?
13. What is the approximate depth of field for an 85 mm camera lens with its aperture set to a 15.2 mm diameter in daylight?

14. Of the 11 points shown, what set of points can be used to represent an optical wavefront?



15. What are the units of OPD? What parameters are required to calculate OPD? What other parameter is needed to convert OPD to a phase?

16. What are imperfections to an optical wavefront called? What are some causes of these imperfections?

17. Which two aberrations can be eliminated by simply manipulating the image plane orientation? How would each of these aberrations be removed?

18. Name and describe the five third-order aberrations.

    Which aberration keeps the wavefront flat?

    Which aberration makes a bowl-shaped wavefront?

    Which aberration yields a sombrero-shaped wavefront?

    Which aberration yields a saddle-shaped wavefront?

19. Which third-order aberration varies most strongly with field of view (object height, *h*)?

    Which third-order aberration varies most strongly with pupil coordinate, ρ?

    Which third-order aberration varies most strongly with pupil angle, ψ?

20. Research and sketch or photograph what actual images distorted by barrel and pincushion distortion look like.

21. The pixels to many silicon cameras are 7.4 µm in size. Assuming your lenses are diffraction-limited, shoot a photo of a distant star at F/22 and determine how many pixels the image of the distant star subtends.

22. One reason that more data can be stored on a BluRay Disc (BD) versus a digital versatile disc (DVD) or a compact disc (CD) is that the wavelength used to read and write BDs is smaller than the wavelength used for DVDs or CDs. (The wavelength used for DVDs is smaller than the wavelength used for CDs.)

    Research the wavelengths used by each of the optical storage media types (CD, DVD, BD), and calculate the spot diameter produced when each of these lasers is focused through F/1 optics onto the optical medium.

    Determine the data storage density factor you would expect when going from CD to DVD and from DVD to BD for just one groove around a disc. (You might also research and report other techniques that are used to fit even more information onto the higher-capacity discs.)

    :

23. Sketch a realistic MTF curve that complies with the resolution specification called out in section “Modulation Transfer Function,” and highlight the frequency range of interest.

24. What is the contrast of a scene if the most radiant portion has an irradiance of 150 W/mm^2 and the portion of least irradiance measures 37.5 W/mm^2?

ADVANCED PROBLEM EXERCISES AND QUESTIONS

25. At the on-axis field point, an optical system is measured to have aberrations containing only the spherical aberration term (w_{400}). All other aberration terms were measured to be negligible. The engineer performing the alignment can usually control tilt and defocus. Explain how the introduction of tilt (w_{111}) and defocus (w_{200}) will (or will not) help minimize the RMS wavefront error (WFE). If these first-order aberrations can compensate for the spherical aberration present, show how.

26. At an off-axis field point, an optical system is measured to have aberrations containing only the astigmatism term (w_{222}). All other aberration terms were measured to be negligible. The engineer performing the alignment can usually control tilt and defocus. Explain how the introduction of tilt (w_{111}) and defocus (w_{200}) will (or will not) help to minimize the RMS WFE. If these first-order aberrations can compensate the astigmatism present, show how.

27. Two 500 mW sources interfere to illuminate a 1 cm^2 area. What background irradiance, in units of W/m^2, yields a fringe visibility of exactly 0.8?

28. What is the maximum wavelength that will fit the first lobe of an Airy disk into a standard multimode optical fiber core if its numerical aperture is 0.2?

29. What is the depth of field of a pinhole camera?

LABORATORIES

Laboratory 1-A

Pupils Match Pupils

Theory

When aligning one optical system to another, you will achieve optimal throughput if you align the exit pupil of the first system to the entrance pupil of the second. To learn where an entrance or exit pupil is located, the optical system's aperture stop must be imaged through the system into object or image space, respectively. It is a critical technical skill of a photonics technician to be able to locate the pupils of any optical system.

Equipment

- 2 to 4 positive lenses with focal lengths between 25 and 200 mm, all with diameters ≥25 mm
- 1 iris diaphragm with a diameter less than 25 mm
- 1 white light source (LED or incandescent light)

Procedure

The physical extent (the diameter) of a single lens alone is its own aperture stop, entrance pupil, and exit pupil. This lab uses an iris to insert a specific aperture stop and entrance pupil before a lens.

1. Position the iris between the light source and the first lens, separated from the lens by 2 or 3 times the lens's focal length—the iris becomes the entrance pupil for the first lens. Measure the diameter and distance of the entrance pupil from the first lens.
2. Determine the location of the exit pupil of the lens by imaging the iris through the lens. An image should be formed on the side of the lens opposite the iris and light source. This is the exit pupil of the system. Measure the diameter and distance of the exit pupil from the first lens.
3. Position a second lens after the exit pupil of the first lens. This creates a simple two-lens relay system. Find an image of the source after the second lens. Observe and record how the size of the exit pupil relative to the lens either causes light to be lost (vignetted), if the second lens is smaller than the exit pupil, or how it allows stray light to enter the system, if the second lens is larger than the exit pupil of the first lens.
4. Experiment by replacing the second lens with larger or smaller lenses of different focal lengths. Record the vignetting or stray light effects in each two-lens relay system.

Laboratory 1-B
Can We Resolve This?

Theory

An optical system's ability to resolve closely spaced objects is a critical performance metric. In fact, one of the basic examinations of the human optical systems, the eyes, is a resolution test in which a person is asked which letters can be resolved.

Equipment

- 2 positive lenses, one with a focal length that is more than 2.5 times the other (nominally with focal lengths of 50 mm and 150 mm)
- 1 white light source (LED or incandescent light) and 1 resolution target (USAF1951 bar target)
- 1 pair of point sources (small LEDs) or illuminated pinhole apertures
- 1 human vision resolution chart
- 1 caliper

Procedure

1. Begin by testing the resolution of your own eyes by observing the human vision resolution chart. Calculate the angular resolution of your own eyes by measuring the size of the spacing in the smallest letters that you can visually resolve and dividing that by the distance between the chart and your eye. (I.e., if you are looking at a capital letter E, measure the distance between the lines in the E and divide that by the distance between the chart and your eye.)
2. In bright light conditions, the clear aperture of your eye is approximately 2 to 3 mm in diameter. (Be VERY CAREFUL if you attempt to measure this.) Calculate the angular size of the spot formed on your eye for a medial wavelength of visible light (say, 550 nm for ambient lighting). Discuss how this compares to the resolution measured in part 1.
3. Next, set up a simple two-lens Keplerian telescope by separating the two lenses by the sum of their focal lengths. Locate the telescope at least one meter from the source. (If you have one available, locate the USAF1951 resolution target directly in front of the source.)
4. Find the image of the resolution target and observe its quality. Document which spatial features are resolved, paying careful attention to which closely spaced features within the resolution target are not resolved. Measure the separation of the unresolved target features with a caliper.
5. Measure the clear aperture of this two-lens telescope after you determine which lens is the aperture stop (i.e., which is the limiting aperture). Using a medial wavelength of the source's output, calculate the angular size of the spot formed by the telescope.

6. If you are using a pair of point sources, change their separation until you can no longer resolve two distinct points in the image plane. Once you have done this, use a caliper to measure the separation of the sources.

Laboratory 1-C
Display Contrast

Theory

The optical display industry prides itself on the contrast of its displays, even though typical ambient home lighting conditions spoil the blackest blacks created by the display, just by the reflection of ambient light off the display. Measurements of display contrast are not standardized in the industry, but they can be taken in a variety of ways in the lab.

Equipment

1 optical display with controllable contrast, such as a CRT, LCD, or LED monitor, connected to a computer with an application that allows drawing of figures with specified color values (such as Microsoft PowerPoint).

1 optical power meter connected to a optical detector (e.g., a silicon photodiode)

Procedure

1. Create a half-white and half-black display using the drawing application. Ensure that the white fields portion has RGB (red, green, blue) values of 255, 255, 255 (for an 8-bit display). Ensure that the black portion has RGB values of 0, 0, 0.
2. Turn the display “contrast” and “brightness” settings to maximum, and hold the optical detector against the monitor. Measure the power recorded in both the white and the black regions.
3. Create a plot of measured power in each region as a function of the contrast settings, taking data for at least ten different intervals from the maximum to the minimum values of the contrast setting.
4. Turn the brightness setting to one-half its maximum value, and repeat the collection of a set of ten contrast-setting measurements.
5. Turn the brightness setting to zero, and repeat the collection of a set of ten contrast-setting measurements.
6. Plot the measured optical power data as a function of the contrast setting for each brightness setting. (Three curves can be displayed on one plot, one for each brightness setting.)
7. Comment on the range of modulations achievable by the display.
8. Repeat your measurements for other available displays, if desired.

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Non-Interferometric Measurement of Optical Performance

Module 2

of

Metrology of Optical Systems

PRECISION OPTICS SERIES

National Center for Optics and Photonics Education

PREFACE TO MODULE 2

This is the second module in the *Metrology of Optical Systems* course. This course is designed for students seeking a basic understanding of the optical system measurement and testing techniques used to determine the overall quality of an optical system's performance. It presents a comprehensive review of measurement practices essential to ensuring the quality of optical systems. The course was designed to comply with the second edition of the *National Precision Optics Skill Standards for Technicians*.

Module 2, *Non-Interferometric Measurement of Optical Performance*, addresses the optical parameters that describe the performance of an optical system. The module focuses on non-interferometric techniques, including the tools and optical setups used to perform non-interferometric tests. Topics include metrology sources and targets, effective focal length and back focal length measurement, point spread function and line spread function measurement, wavefront error measurement, modulation transfer function measurement, and optical system integration with detectors.

The material in this course includes technical terms and measurement techniques that are often unique to the field of precision optics. To make certain that students have the vocabulary necessary to understand the concepts presented, a glossary of technical terms and scientific concepts is included at the end of the course. We highly recommend that you review this glossary before moving forward in this module. Terms in the glossary are italicized throughout the course material.

CONTENTS OF MODULE 2

Introduction 1
Prerequisites 1
Objectives 2
Scenario 2
Basic Concepts 3
Introduction to the Tools and Techniques Used to Measure Optical System Parameters 3
Metrology Sources 4
Metrology Targets 7
Effective Focal Length (EFL) and Back Focal Length (BFL) Measurement 9
Autocollimation Techniques 9
Ronchi-Ruling Techniques 12
The Nodal Slide 13
The Focimeter 16
Magnification Techniques 17
Reciprocal Magnification Technique 18
Traveling Microscope Techniques 19
Point-Spread Function (PSF) and Line-Spread Function (LSF) Measurement 20
Beam Profiling via Knife Edge: The Foucault Test 20
Beam Profiling via Camera Sensor 23
Wavefront Error (WFE) Measurement 24
Wavefront Sensor (WFS) Techniques 24
Surface-Contact Techniques 27
Modulation Transfer Function (MTF) Measurement 29
Optical Setups for MTF Measurement 30
Data products of MTF Measurements 31
The Final Performance Metric of Optical Systems: Integration with Detectors in Application33
Laboratories 35
Problem Exercises and Questions 41
Advanced Problem Exercises 43
References 44

Module 2-2
Non-Interferometric Measurement of Optical Performance

INTRODUCTION

Parameters that describe the performance of an optical system may each be measured by a variety of techniques. In fact, per the discussion at the end of *Metrology of Optical Systems* Module 2-1, the results of many measurement techniques may be mathematically transformed into another optical system parameter. The key to making a high-quality optical measurement is understanding of the measurement equipment. A variety of instruments may be used to assess optical performance. The most common and versatile instrument for this purpose is, arguably, the interferometer—the many uses of this sensitive, multipurpose instrument deserve a dedicated, detailed description, so interferometry is covered in *Metrology of Optical Systems* Module 2-3. This module focuses on non-interferometric techniques, including the tools and optical setups used to perform these non-interferometric tests.

PREREQUISITES

OP-TEC *Fundamentals of Light and Lasers*: modules 1-1, 1-2, 1-4, 1-5

OP-TEC *Quality Assurance of Precision Optics*: Modules QAPO-1, QAPO-2, MOS-1

Students should be able to calculate ratios and angles, apply scientific notation, perform dimensional analyses of units, understand use of geometric equations to describe conic sections (parabolas, ellipses, etc.) (high school algebra, geometry, college algebra)

Objectives

- Conduct optical metrology measurements and inspections for in-process work and final distribution
- Coordinate with quality assurance to ensure compliance to design specifications and documentation requirements
- Participate in the development of inspection plans that use the appropriate metrology for all measured specifications
- Test finished components by appropriate means including test place or interferometric techniques to ensure compliance with design specifications
- Use autocollimators to measure angular error, pyramid error, beam deviation, and dimensional deviations for both in-process and finished products
- Use collimator or interferometer to measure focal length and on-axis aberrations
- Measure surface roughness using white light interferometry or other optical means
- Measure the processed surfaces or components using appropriate equipment (e.g., profilometer, optical comparator, coordinate measuring device, micrometer, or drop gage)
- Determine and select using written instructions and specifications, appropriate packaging for protecting, storing and shipping optics
- Document final inspection results according to instructions, procedures, and/or specifications to close-out job jacket or equivalent
- Maintain NIST certified calibration standards and samples, be able to calibrate all-optical instruments per proper procedures and maintain a calibration log
- Use statistical process control guidelines for sampling finished components

Scenario

Just after Marion bought an expensive, new, brand-name photographic lens for his digital single-lens reflex (DSLR) camera, he found a cheap, old, generic lens with the exact same focal length specifications at a local garage sale. Now he wants to test both lenses to quantitatively compare their performance, and to learn if the new lens was worth its higher cost. He enrolled at a local community college that offers course 2 of the OP-TEC Precision Optical Technology (POT) sequence, in which he learns about the modulation transfer function (MTF) of a lens. He learns that an MTF test will provide a useful, quantitative measurement of his lenses, so he can assess how much optical performance he bought when he paid for the expensive lens. Using this technique, he will learn how well different objects are resolved by each lens. In fact, after these MTF measurements are complete, he will better understand how to use the lenses because he will understand their physical limitations.

Basic Concepts

Introduction to the Tools and Techniques Used to Measure Optical System Parameters

Throughout this text, the term "optical system" is used. Optical systems include everything from single lenses or mirrors to complex multi-component optical assemblies that contain both lenses and mirrors (so-called catadioptric systems) in addition other beam-directing and beam-shaping elements like diffraction gratings or prisms. For simplicity, a single positive lens at a simple wavelength is used in the examples, but in practice, it can be replaced by a more complex optical system with application-specific modifications to the test equipment. For example, when testing a spectrometer optical system that includes a grating, multiple output angles and wavelengths may need to be considered.

As a starting point, it is helpful to recognize that many parameters of optical systems are simple physical dimensions, such as lengths, thicknesses, diameters, and angles. These parameters can be measured by standard shop tools like precision vernier calipers or height/depth gauges, or they may be determined using calibrated references such as gauge blocks (shown in the figure).

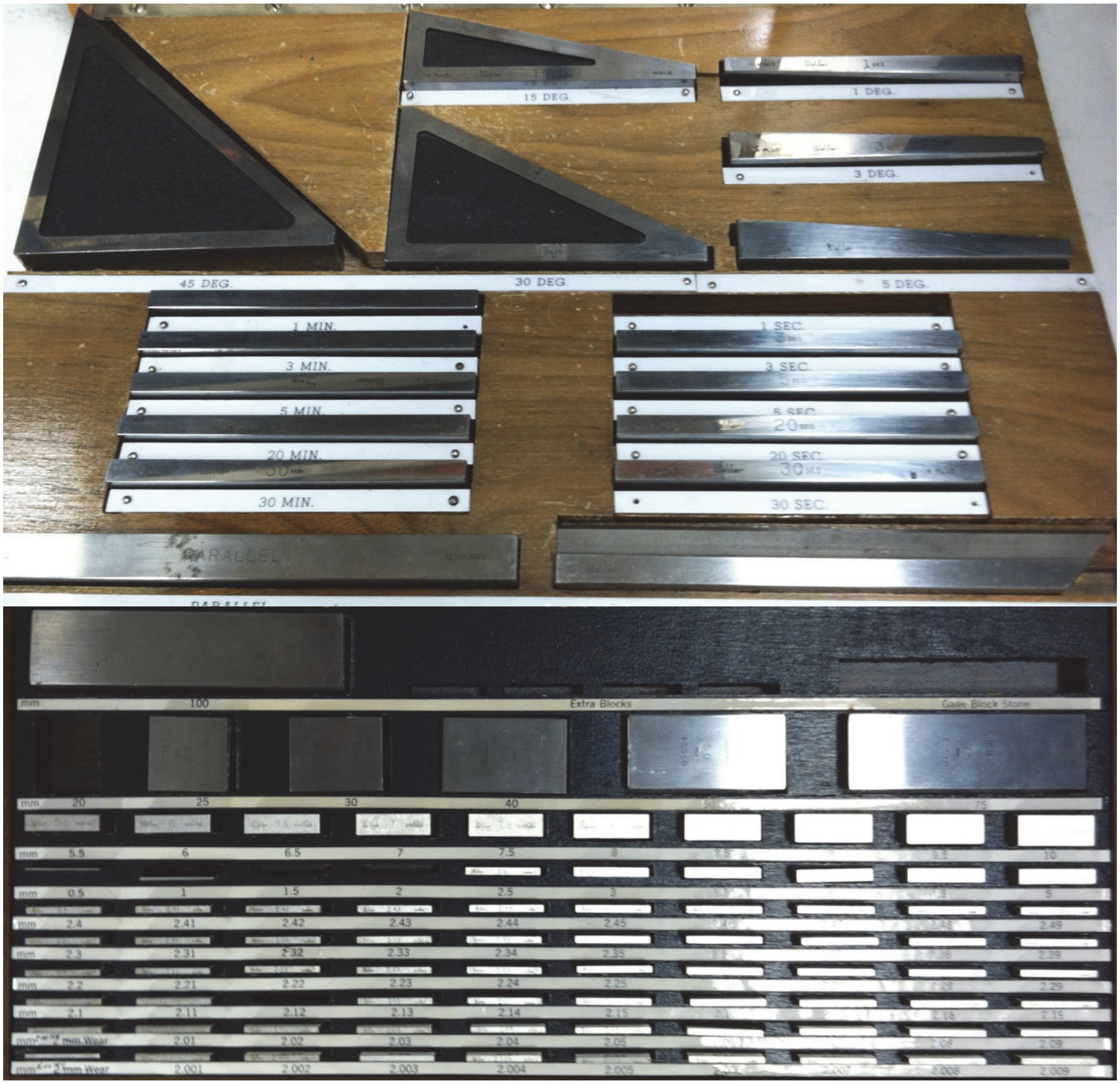


Figure 2-1 *In protective cases, precision physical distance and angle references called gauge blocks are shown here. (Photos courtesy Firas Almarzouk of Supply Chain Optics.)*

For instance, clear aperture (CA), covered in Module 2-1, is an optical parameter of a surface that must be measured and reported with respect to the surface's physical diameter or its coating's physical extent. (Of course, the coating's extent must meet or exceed the CA.) Clear aperture is often specified as a fraction of the physical diameter: e.g., CA shall be >90% of the 25.4-millimeter lens diameter, but it is usually reported as a physical diameter, centered at the optical vertex: e.g., a 23.7-mm CA was achieved for part serial number 009.

Another relatively straightforward physical parameter, the angles of optical features, may also be measured by comparison to a calibrated gauge block. However, angles are most often measured using collimated light that is emitted from a laser source or a point source that has been collimated by a telescope, reflected off the angled surface, and then measured with respect to another optical surface. The basic measurement of angles highlights two critical optical metrology tools: the laser and the alignment telescope. These instruments produce collimated light and they are used in many optical metrology techniques.

Metrology Sources

If a perfectly flat (planar) wavefront is input to the optical system under test, then the imperfections induced on that ideal wavefront must be due to imperfections in the optical system itself. It is crucial to recognize that aberrations may be introduced for a number of reasons, including (1) imperfections in each optical surface, (2) relative, surface-to-surface misalignments, (3) individual misalignments to the metrology equipment, or (4) residual aberrations of the optical design. That said, the test sources where the light originates must be high-quality and well-aligned when measuring optical system performance. In addition, the basic optical design must be understood—optical alignment is essentially the practice of locating each optical surface (or, equivalently, their centers of curvature) in an optical system under test exactly where the optical design specifies.

Collimated sources are indispensable for optical testing because they are a means of injecting a planar wavefront into the optical system under test. Figure 2-2 shows the two important parts of a collimator in the schematic, the source and the collimating optics.

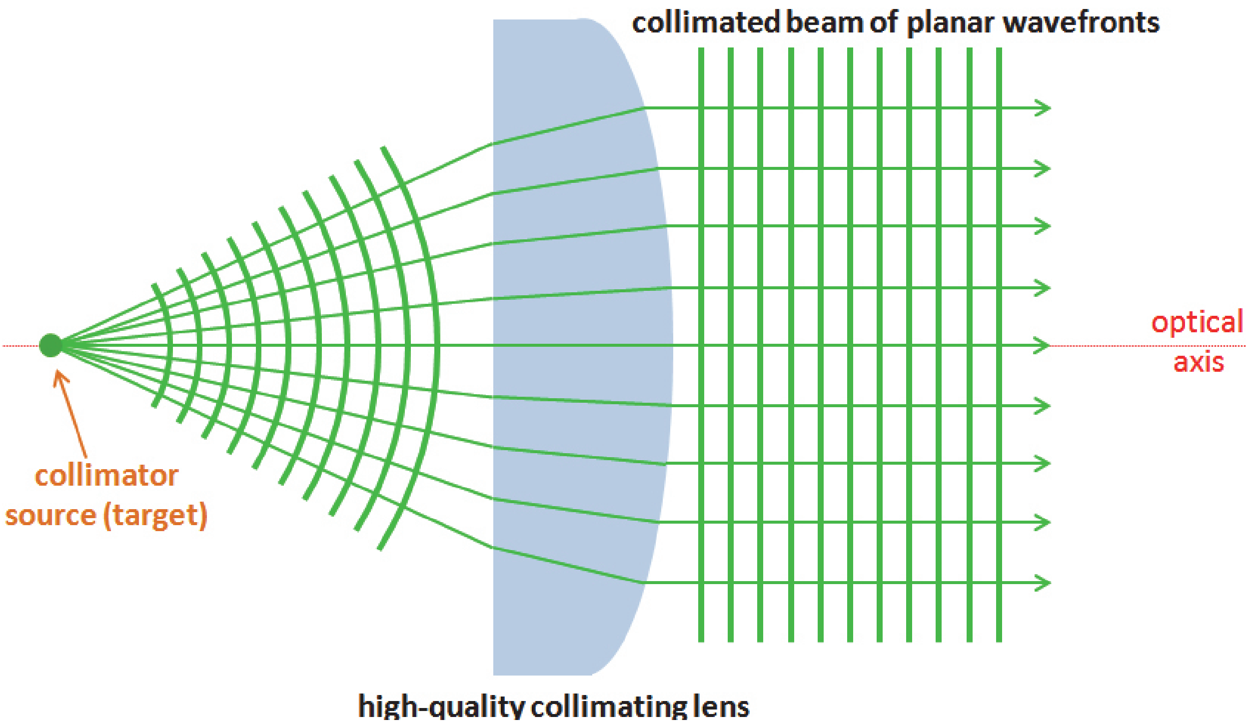


Figure 2-2 *A source of finite size, as given by the equation below, is collimated into a beam of planar wavefronts by the ideal lens that represents a well-corrected collimator*

Selecting an appropriate collimated source depends on the required measurement. Most lasers do not diverge appreciably over the usual distances required for measurement, so their beams may be expanded to larger-diameter collimated sources before they fill the optical system under test. Even unexpanded laser beams (sometimes called “pencil beams”) are often used for optical system alignment and measurement as they are directed down the optical axis, or, colloquially, the “gut” of the optical system.

Alignment telescopes, similar to the system shown in Figure 2-2, are extremely well-corrected optical systems. Because light propagates over identical paths whether it travels in the incident or outward direction, a special version of the alignment telescope called the *autocollimator*, or autocollimating telescope, includes an internal source that projects an internal source (sometimes called a target), out of the telescope to any distance at which the telescope is focused. (The prefix “auto-” denoting the fact that the light travels out of and back into the telescope.) Equation 2-1 gives a rule of thumb for calculating the ideal, diffraction-limited source size required at the input (object plane) of the collimator. This source may be a back-illuminated pinhole aperture, an LED, or a single-mode optical fiber tip. In this equation, the clear aperture (CA) is the limiting aperture in the system, which should be the pupil of the optical system under test—the collimated beam should overfill the system being tested.

$$source\ size \leq \frac{2.44 \cdot \lambda \cdot EFL_{collimator}}{4 \cdot CA} \qquad (2\text{-}1)$$

The autocollimator can be used to measure incident light or to project an image of its source. Autocollimators may be refractive, like a monocular, or reflective, like an astronomical telescope. In a metrology application, an autocollimator is always aligned to the optical axis of the optical system under test. Autocollimators have an additional versatility in that they can be defocused to project an image of its source on any surface within the optical system under test. This helps to align each element of the optical system on the optical axis.

When testing optical systems, an alternative to a collimated source is a point source, which is really just a local version of the collimated source. (Since a collimated source is really a point source located at optical infinity.) A few point-source metrology and alignment techniques are covered in the following sections. A versatile optical system metrology and alignment tool is called a point-source microscope (PSM), or an autostigmatic microscope. The PSM projects a point source into an optical system under test, thereby locating point images within an optical system, and measures its return position. (Like the autocollimating telescope, the prefix “auto-” denotes the fact that the light travels out of and back into the microscope.) This property makes the PSM extremely useful for centering spherical and aspherical optical elements to the optical axis because PSMs allow the optical features of each surface, rather than mechanical datums, to be used during alignment. The point source within a PSM is typically the tip of a single-mode optical fiber. The PSM also includes an internal camera sensor that is conjugate to (that is, in an image plane of) the point source that is output by the PSM. This camera shows the structure of each point image, further aiding in the optical metrology process. An example of a PSM is shown in Figure 2-3.

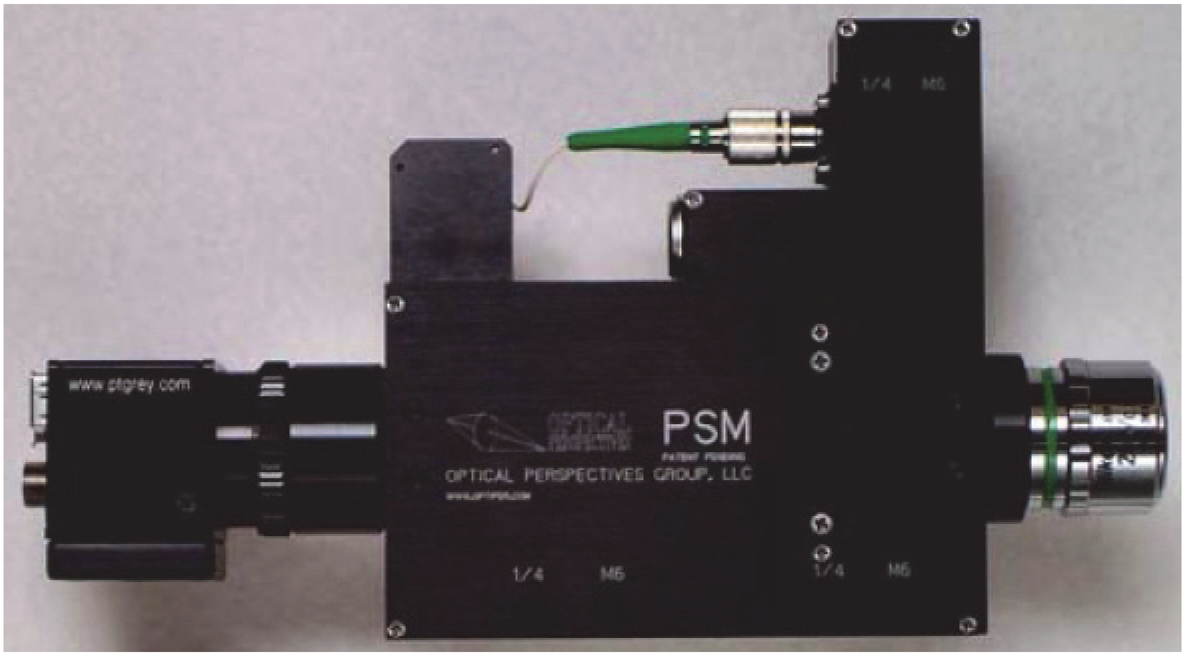


Figure 2-3 *The point-source microscope (PSM) is a valuable optical alignment tool acting as a point source for integration and alignment applications.*

Metrology Targets

In order to designate and locate the optical axis of each element, there are a variety of methods. Crosshairs may be attached directly to the surface of each optical element, or a small mark can be inscribed in the optical vertex of each element itself. (This can be accomplished during manufacturing when using diamond-turned mirrors, even for aspheres that include the parent surface's vertex.) A sequence of adjustable irises along the beam path is desirable when aligning a series of optical elements down a beam path using a "pencil" laser beam. Any of these center-point references will aid an optical alignment and, if they can physically remain a part of the integrated optical system, they are useful aids during all phases of optical metrology—they will help to ensure that the optical system under test is aligned to the metrology equipment.

The objects that are imaged during optical test applications are called targets. They may be double- or multiple-slit apertures of calibrated size and separation, or they may be Ronchi rulings (also called Ronchi gratings), which are glass plates with alternating opaque and transparent features, such as a series of metal stripes on a clear glass window. Figure 2-4 shows Ronchi rulings with features at 3 and 4.7 lines per millimeter, which may not be apparent if this image is printed or displayed at a low resolution. The calibration of all optical targets must be maintained with respect to a government standard, such as a NIST standard.

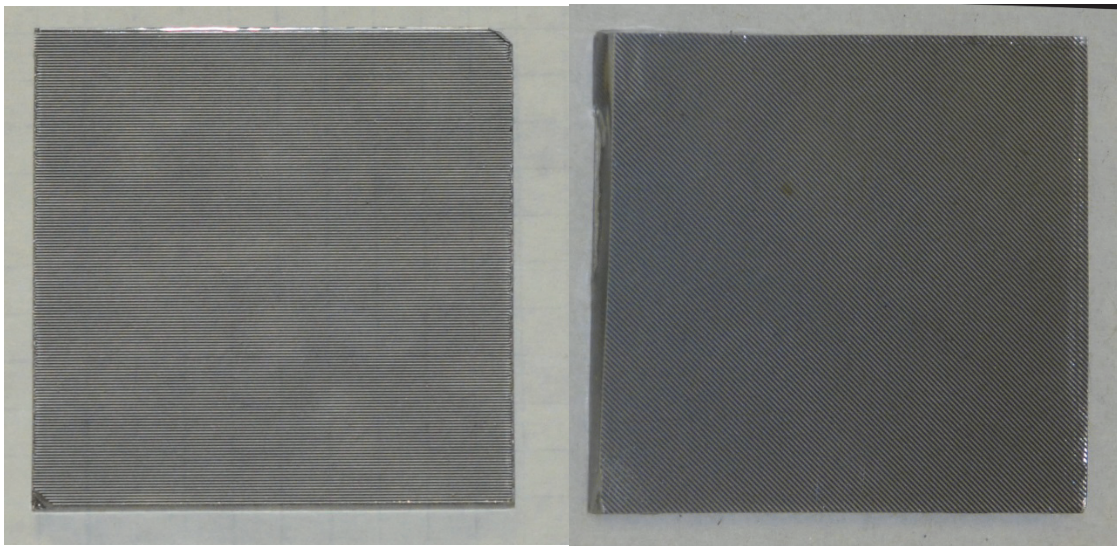


Figure 2-4 *Ronchi rulings like these are precision glass plates with periodically alternating transparent and opaque (or reflective and transmissive) regions. These Ronchi rulings have features at 3 and 4.7 lines per millimeter (l/mm), which may not be apparent if this image is rendered at a low resolution.*

An optical test target standard is the 1951 United States Air Force (USAF) Resolution Test Bar Chart (also called the "sixth root of two" or "three-bar" USAF Chart), which consists of a number of Ronchi ruling pairs (horizontal and vertical), each of a different size and spatial frequency packed into one convenient array, as shown in Figure 2-5. This is analogous to the well-known eye chart used for ophthalmology. Each Ronchi ruling element (pair) has a calibrated size relative to the next element—each element is larger than the previous element by the sixth root of two, a factor of ~1.122 (or 12.2% larger). Equation 2-2 shows how the resolution, in units of line pairs per millimeter [lp/mm], is given for each element of the 1951 USAF Bar Chart. This Bar Chart includes 12 groups: -2 through 9, with group -2 being the largest (upper left and lower right), group -1 (upper right) is next largest, and group 9 is the smallest. Each group contains six elements.

$$resolution = 2^{group+(element-1)/6} \tag{2-2}$$

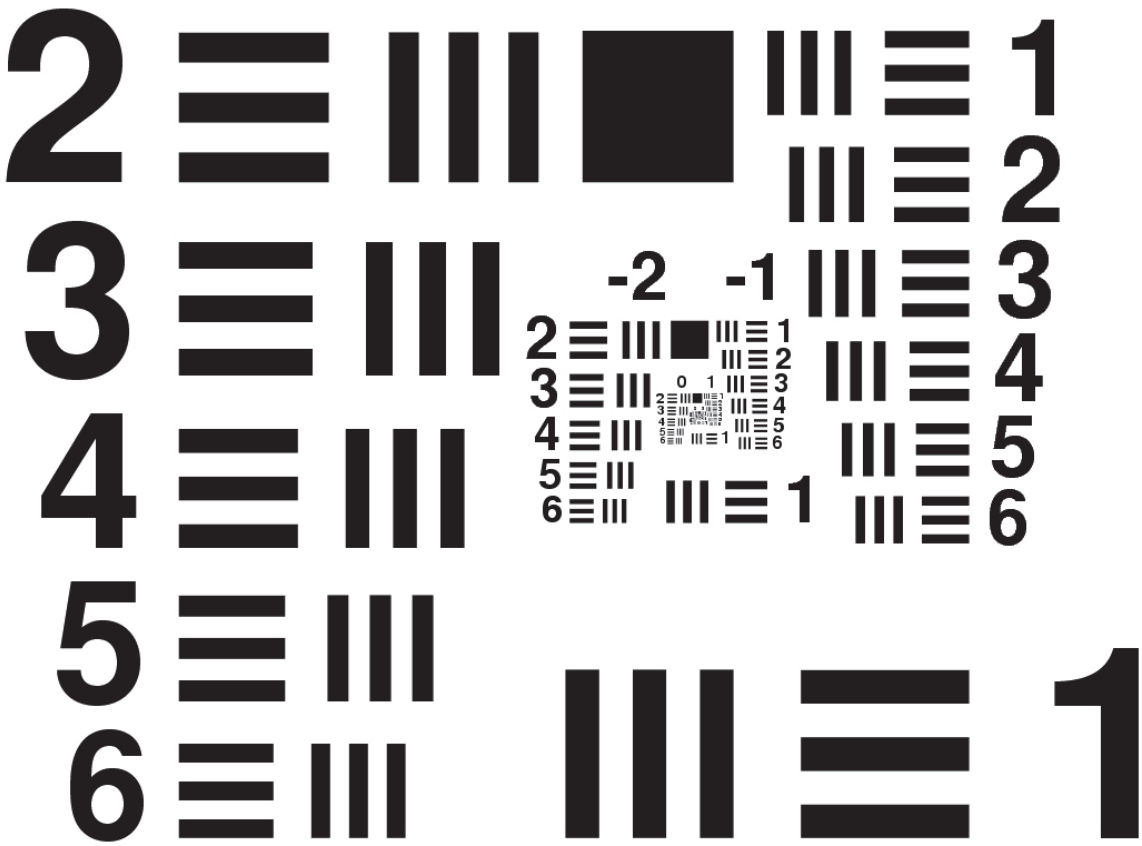


Figure 2-5 *The 1951 USAF Bar Chart: an array of Ronchi rulings is often used as the object or target during measurement of optical system parameters*

The following sections discuss high-accuracy techniques by which specific optical system parameters can be measured. Keep in mind that many optical system parameters may be calculated or derived from these measurements. For instance, an optical system's f-number and numerical aperture (NA) are derived parameters; the f-number is calculated as a simple ratio once the CA and effective focal length (EFL) have been measured (which is why it is sometimes referred to as the f-ratio).

Effective Focal Length (EFL) and Back Focal Length (BFL) Measurement

Some optical parameters can be estimated quickly and efficiently, but without accuracy. For example, a quick and straightforward method by which the focal length can be estimated is to image a distant light source such as a street light or the sun with a positive lens, forming an image of the distant light on a wall or on the ground. The distance between the principal plane of the lens and the wall or ground is approximately the EFL of the lens. (If the lens is thin, its principal plane is approximately at its center.) If this distance is measured from the final optical surface of the lens, this gives the back focal length (BFL); or if it is measured from the final mechanical feature of the lens mount, the flange focal length is measured. Of course, in an outdoor setting, this distance may be difficult to measure accurately, and the quality of the focused image is imprecisely estimated by eye. It is no substitute for the accurate methods discussed in the next few sections, but it is a useful and rapid metrology technique.

The following techniques are not mutually exclusive, in that one technique can be used to enhance the accuracy or ease of performing another. For example, some precision optics technicians use Ronchi rulings to improve the accuracy of the autocollimation technique; others might use a knife-edge technique for better accuracy. The technique used strongly depends on the geometry of the optical system being tested, the available test equipment, and the experience of the precision optics technicians conducting the metrology.

Autocollimation Techniques

The principle of autocollimation offers a simple test for measuring back focal lengths of optical systems with a positive focal length, and it is among the most straightforward technique used to measure negative focal lengths. Despite the name of the technique, it makes use of a point source, rather than a collimated source. It uses the optical system tested to collimate light from the point source. In the test setup, a point source (such as a laser focused into a pinhole or the output tip of a single-mode optical fiber) is located approximately one focal length away from the optical system under test. (This initial distance can be approximated by the crude technique mentioned in the opening paragraph of this section.) Immediately after the optical system, a flat mirror is aligned to reflect the light back into the optical system, all the way to the point source. When the mirror is slightly tilted, a focal spot (an image of the point source) will be apparent next to the point source itself. The distance between the final surface of the optical system and the point source will be adjusted to minimize the size of the focal spot image—once the smallest focus is obtained, this distance equals the BFL of the optical system. A Ronchi grating or a knife edge may be introduced (using a pellicle beamsplitter) to assess more accurately the size of the focal spot.

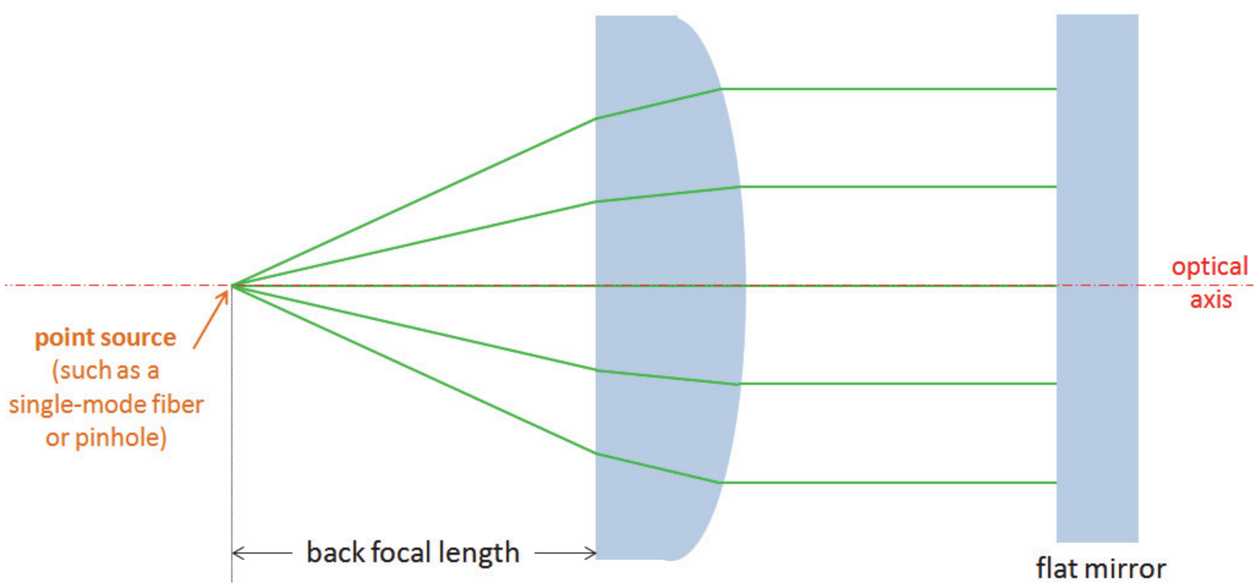


Figure 2-6 *This figure shows the autocollimation technique used to test an optical system with a positive focal length*

If a well corrected positive lens is available, a similar test setup can be used to measure the BFL of an optical system with negative power. Start by adjusting the point source-to-positive lens spacing to obtain the smallest focal spot image directly on the flat mirror (rather than back at the point source). Add the negative-power optical system under test between the positive lens and the flat mirror. Again, slightly tilt the flat mirror and adjust the separation between the optical system under test and the flat mirror by moving only the optical system under test. Observe and minimize the size of the focal spot image back at the point source. Once the minimum spot size is obtained, the distance between the flat mirror and the final surface of the negative optical system under test equals its BFL.

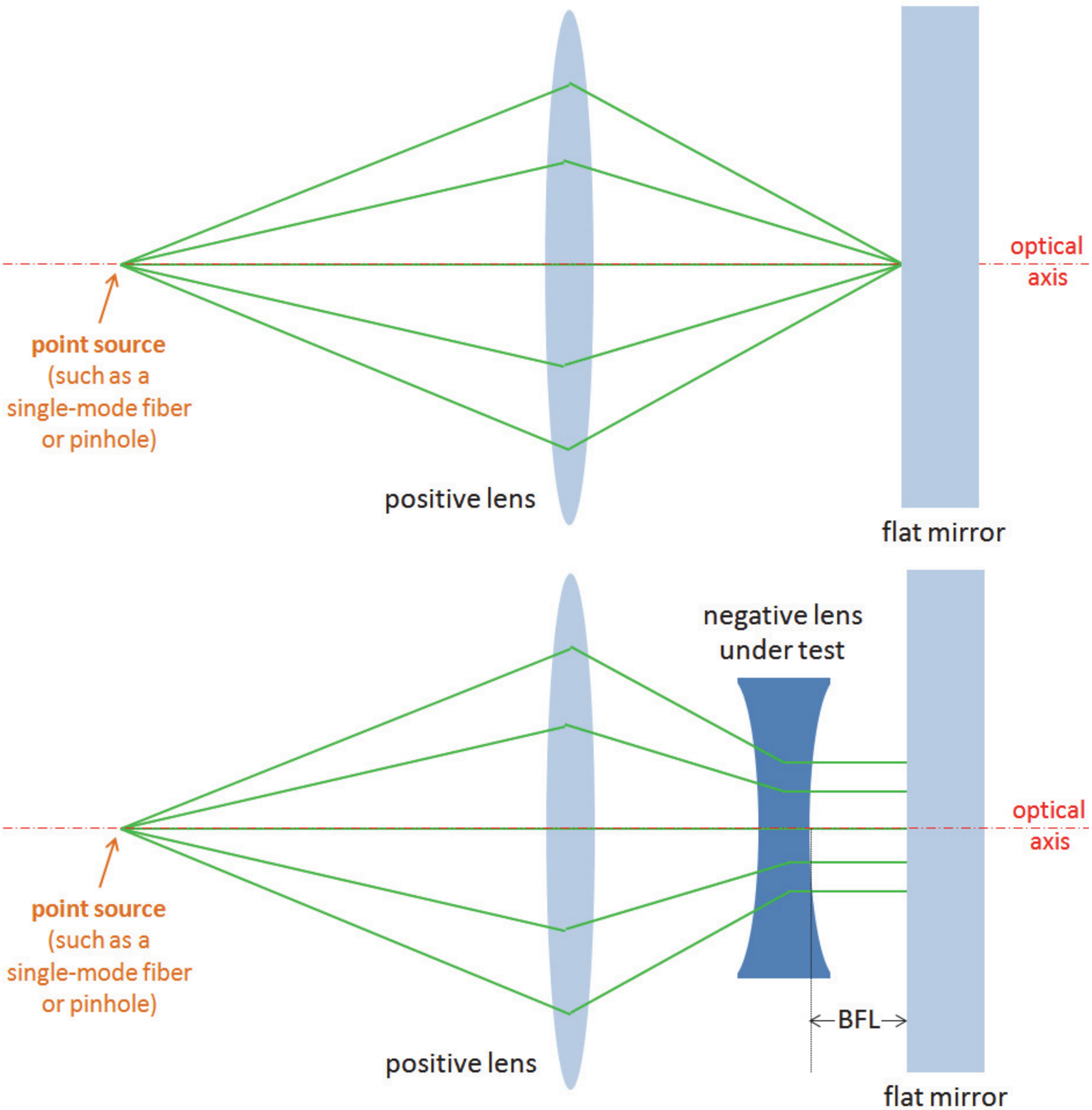


Figure 2-7 *This figure shows the autocollimation technique used to test an optical system with a negative focal length*

Ronchi-Ruling Techniques

First applied to optical testing in Italy in 1923, Ronchi rulings (also called Ronchi gratings) have alternating, equally sized opaque and transparent regions at various spatial frequencies. Coarse rulings have features on the order of millimeters, while fine rulings have features at the scale of tens of micrometers. Ronchi-ruling techniques are based on the diffraction of light. The fringe patterns produced in the application of Ronchi rulings are due to the Talbot effect that produces Moiré fringes (rather than the interference of light waves that produces interference fringes, which will be discussed later). The Moiré patterns known as *Talbot autoimages* or *Ronchigrams* are formed when the image of one Ronchi ruling coincides with a second Ronchi ruling, or when two Ronchi ruling images are superimposed. The structure of the Moiré fringes provides significant information about the optical quality of the system under test. The aberration information contained in Ronchigrams is specific to the plane perpendicular to the ruling orientation. To obtain complete aberration information about the optical system under test, several Ronchigrams must be measured with the rulings clocked to different orientations.

Such Ronchi ruling-based optical testing is often performed during the component fabrication process of an optical element because it is efficient to perform with the part still in a polishing configuration. The precision optics technician might use Ronchi rulings with increasing spatial resolution as the fabrication process progresses, thereby improving the accuracy of the tests as the fabrication matures.

Ronchi rulings are also used to characterize complete optical system parameters, such as EFL, and to measure the system's aberrations. In the traditional configuration for a Ronchi ruling-based test, the optical system under test is illuminated by a beam that fills its CA, and a Ronchi ruling is located on the optical axis in the converging (or diverging) beam. When testing mirror systems (the most common application of this test, shown in Figure 2-8), the Ronchi ruling is imaged onto itself as viewed at the ROC, producing a Moiré pattern with a fringe frequency and orientation that provides information about the reflected wavefront's curvature (and therefore, the EFL) and aberrations.

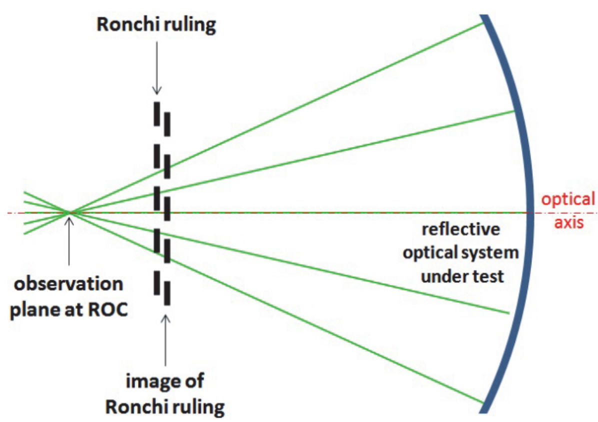


Figure 2-8 *This traditional Ronchi test configuration for a mirror.*

Another robust and versatile test configuration that uses Ronchi rulings is presented by Malacara-Doblado, et al. in a 2010 SPIE *Optical Engineering* paper. In this test setup, the optical system under test is again illuminated by a collimated beam that fills its CA, and one Ronchi ruling is located in this collimated beam, at a distance of approximately twice the EFL in front of the optical system under test. Light transverses the optical system and comes to a focus, and a second Ronchi ruling is located at a distance beyond the focus where the beam has expanded again to the size of the entrance pupil. The first Ronchi ruling will be imaged atop the second. The separation of the first Ronchi ruling from the optical system under test is adjusted to optimize the contrast of the Moiré fringes. The separation of the second Ronchi ruling from the optical system under test is adjusted to minimize the frequency of the Moiré fringes. When a high-contrast, null fringe is obtained, the distance between the focal spot and the second Ronchi ruling is measured by a calibrated rail or a vernier caliper to yield the optical system's EFL. As with other Ronchigrams, some of the optical system's aberrations may be revealed by the structure of the fringes measured.

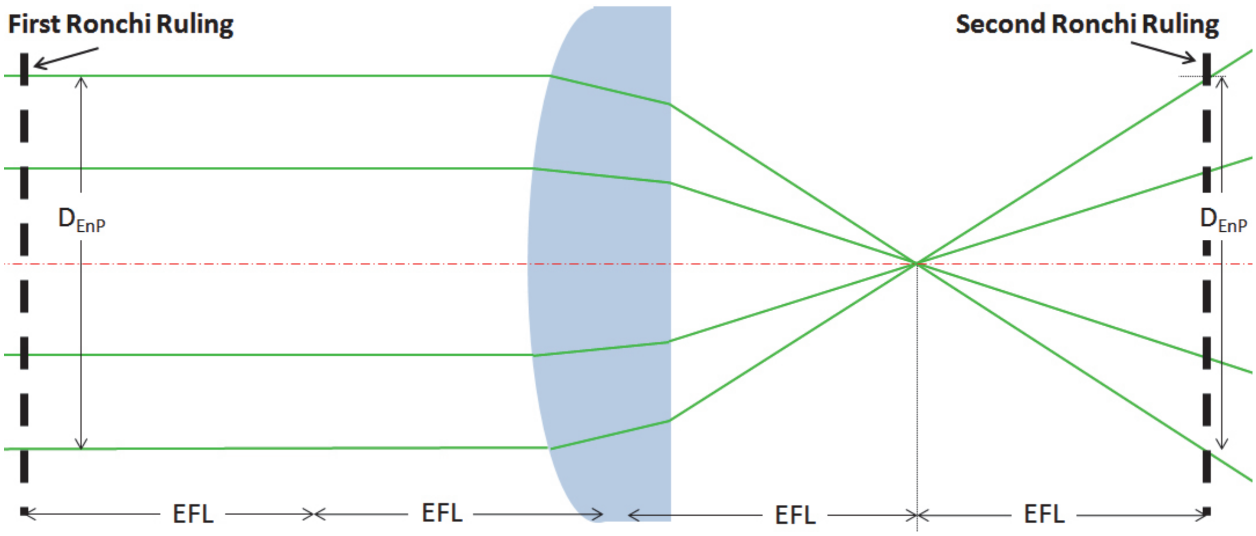


Figure 2-9 *This novel and robust test configuration, conceived by Malacara-Doblado, et al., uses Ronchi rulings to measure the EFL and other optical properties of an optical system.*

The Nodal Slide

A traditional method of measuring focal lengths makes use of a property of optical systems called nodal points. For an optical system in air, the nodal point is where the principal plane of the optical system intersects its optical axis. When an optical system is rotated about its nodal point, input rays (from the object) and output rays (to the image) will not change angles. This is seen simply with a single thin lens, where the nodal point is essentially the center of the lens. If the lens is rotated about its center (its nodal point), the image location does not significantly change because the output rays are at the same angles as the input rays with respect to the optical axis. Therefore, the distance between the nodal point and the focal point is easy to determine, yielding the lens's EFL.

However, more complex (longer, larger, more elements, etc.) optical systems often have nodal points that are located within the optical assembly, making them difficult to access and determine. Special test equipment is useful for these systems, called a *nodal slide* (or *nodal bench* or *Kingslake lens bench*, after the designer of the original system in 1932). This system uses a collimated input light source, such as the projected reticle from an autocollimator or a laser beam that has been expanded to a diameter that fills the optical system's CA. As illustrated in Figure 2-10, the optical system under test is then mounted on a long translation stage that is atop a rotation stage. The collimated light is aligned to be parallel to the optical system under test and the stage's translation axis. The optical system under test images the collimated light onto a distant screen, which must be adjusted to obtain an in-focus image. To provide a higher-resolution view of the image, light is input to a microscope that views the image directly (in air) without projecting it onto a screen, or a high-resolution camera sensor is used as the screen.

As the optical system is rotated using the rotation stage, the image of the collimated source is observed on the screen. If the image translates during the rotation, then the axis of the rotation stage is not coincident with the nodal point of the optical system, so the optical system must be translated along its optical axis (using the translation stage to which it is mounted) and the test repeated. For each translation of the optical system, the image must be refocused on the screen. The closer the optical system's nodal point is to the rotation axis of the stage, the less the image will translate upon rotation. Once the image does not translate with rotation, the nodal point has been located at the rotation stage's axis, and the distance between the rotation stage's axis and the image gives the EFL of the optical system. In most nodal benches, the rotation stage and the screen or microscope are mounted atop a calibrated rail to make this distance measurement straightforward.

Proper nodal slides include a T-bar to help guide alignment and to help measure accurately the distance between the rotation stage and the image. Since any rotation of the lens will slightly shorten the lens-to-image distance, T-bars compensate by keeping the observed image field flat, since the optical system's image field was most likely designed to be flat by the optical designer.

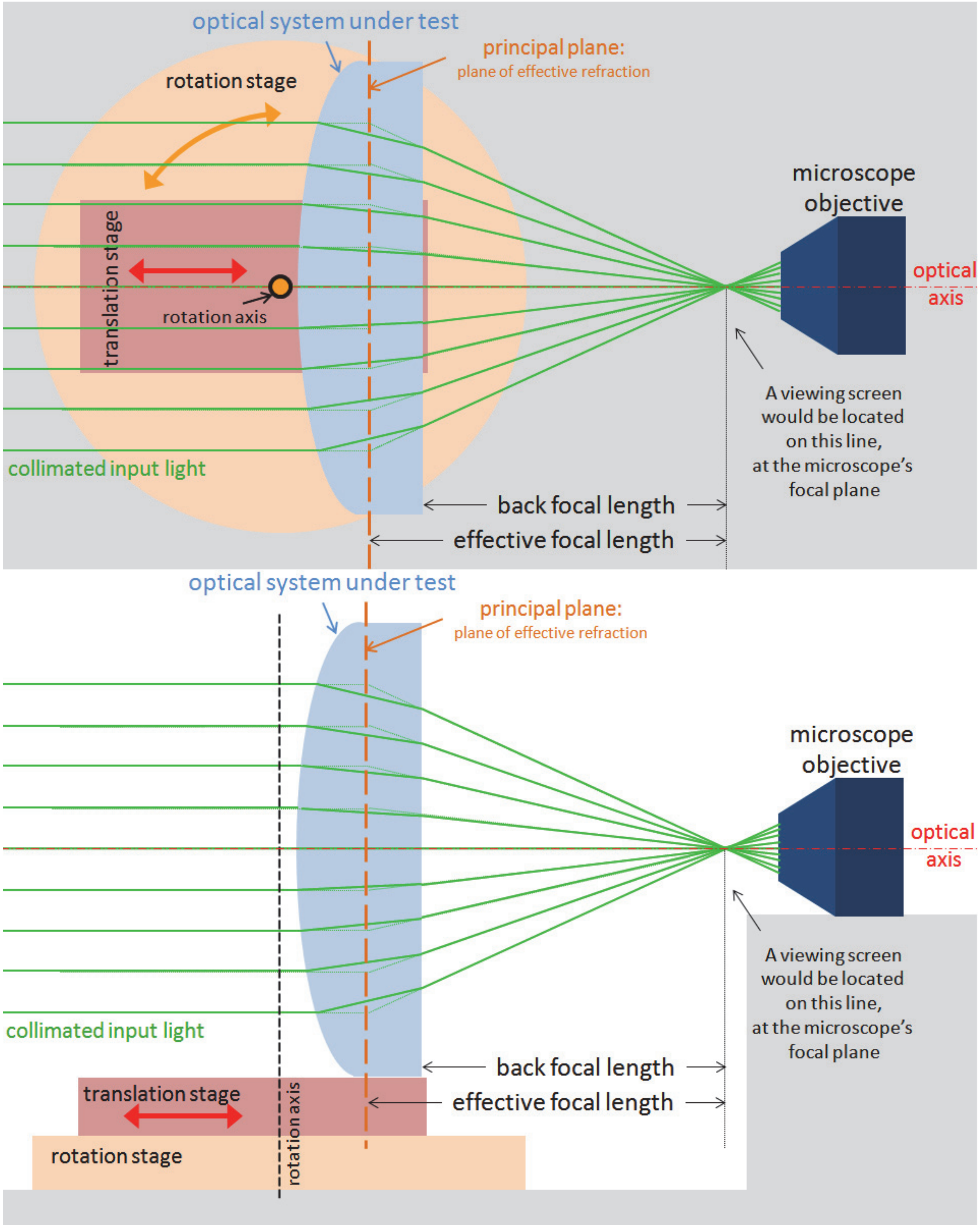


Figure 2-10 *This figure shows the plan and side view of a nodal slide with a microscope used to view the image in space—the finely dashed line represents the image plane that is viewed by the microscope or the plane at which a screen or sensor would be placed.*

Note that if the optical system is aberrating, rotating the optical system may cause the image to go in and out of focus, even if it does not translate. That said, nodal slides are useful for measurement of axial and lateral chromatic aberrations. For this purpose, the input light should be filtered to a certain wavelength range. An optical system with significant aberrations may not achieve an axial alignment that does not translate the image. This technique can therefore provide useful measurements distortion, field curvature, and astigmatism of the optical system under test.

The Focimeter

Often seen in optometrists' offices or at eyeglass merchants, the focimeter (sometimes "lensometer" or "focometer" or "vertometer") is a useful instrument to measure the back focal length of a thin lens. An example is shown in Figure 2-11. The focimeter is comprised of an alignment telescope that is aligned to image a distant reticle that is located at the focus of a well-corrected, calibrated, positive lens, as shown in Figure 2-12. The optical system under test is positioned after the telescope and before the positive lens by a distance $d_{focimeter}$, which is chosen to be equal to the EFL of the focimeter's positive lens, $EFL_{focimeter}$. Adding the optical system under test requires the technician to shift the location of the target to a distance $d_{reticle}$ to obtain an in-focus image through the telescope. Equation 2-3 gives the BFL of the optical system under test.

$$BFL = \left(\frac{1}{d_{focimeter}} - \frac{d_{reticle}}{{d_{focimeter}}^2}\right)^{-1} \quad (2\text{-}3)$$

Note that the focimeter can only be used to measure BFLs that are greater than $d_{focimeter}$. The accuracy of this technique is related to the focal length of the positive lens and the resolution by which the distance d_{target} is measured. In practice, this instrument is often calibrated to output the power of the lens, i.e., the reciprocal of the BFL, in units of diopters.

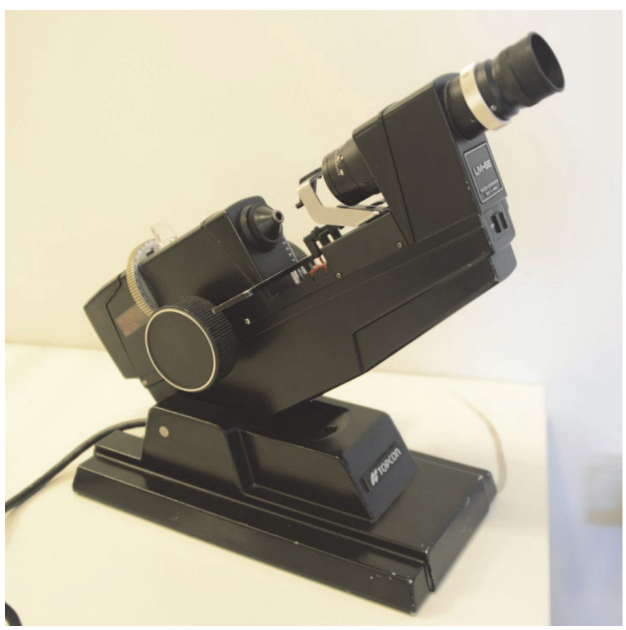


Figure 2-11 *A focimeter like the optical instrument shown here might be used in an optometrist's office or at an eyeglass merchant. Its layout resembles a microscope in that the user looks in the eyepiece, and the eyeglass lens under test is inserted in the gap at the center of the instrument.*

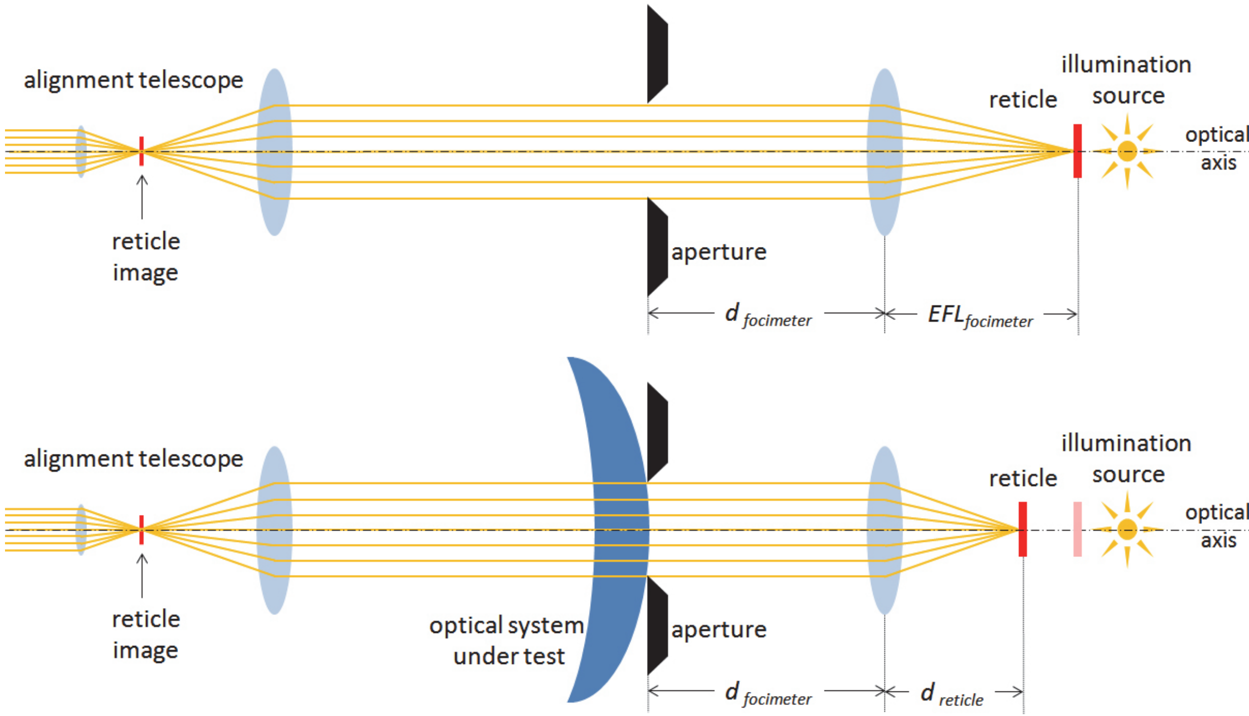


Figure 2-12 *This figure shows the operation of the focimeter without (top) and with (bottom) the optical system under test. The addition of the optical system under test moves the position of the reticle from* $EFL_{focimeter}$ *to* $d_{reticle}$*, thereby allowing calculation of the BFL for the optical system under test.*

The focimeter may also be used to assess the optical system's depth of focus (DOF), simply by reporting the axial range over which the measurements remain unchanged. The EFL can be estimated from the BFL since the optical design includes the axial distance from the principal plane to the vertex of the final optical element.

Magnification Techniques

Rather than simply providing collimated input light, an alignment telescope can be used to measure directly the EFL of an optical system. In this test, an alignment telescope is configured to image an object of size h_{object} (such as a calibrated 1951 USAF Bar Target or a pair of slit apertures) to optical infinity, as shown in Figure 2-13. This image is input to the optical system under test, which will form an image of this distant object at its focal plane with size h_{image}. The ratio of h_{image} to h_{object}, the magnification of the setup, equals the ratio of the EFL of the alignment telescope to the EFL of the optical system under test. If the EFL of the alignment telescope is well, known, and the object and image sizes can be accurately measured, the EFL of the optical system under test can be simply calculated as:

$$EFL_{optical\ system} = EFL_{alignment\ telescope} \cdot \frac{h_{image}}{h_{object}} \qquad (2\text{-}4)$$

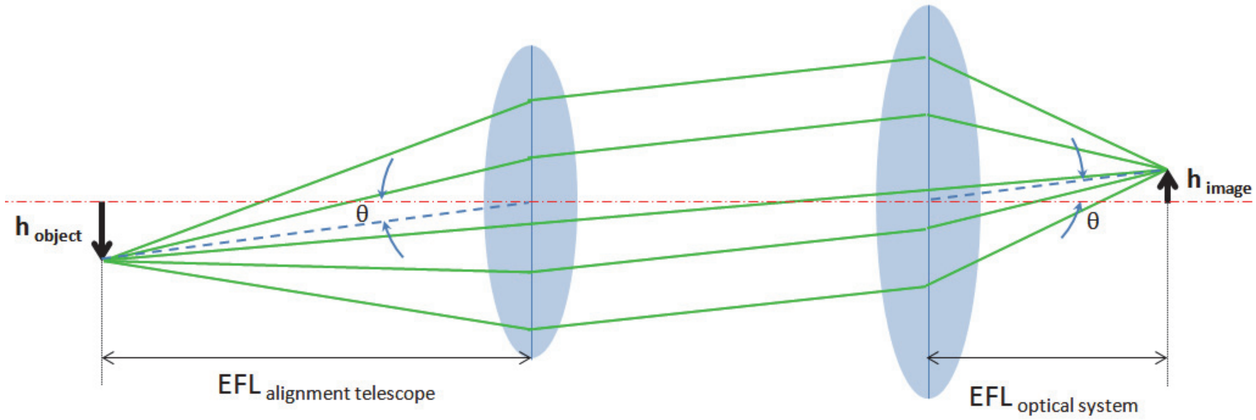


Figure 2-13 *Alignment telescope configured to image an object of size h_{object} to optical infinity*

This technique is helpful when nodal slides, focimeters, or Ronchi rulings are not readily available or able to be constructed, or when the nodal point cannot be accessed because the optical system under test has a principal plane that is distant from its optics, as may be the case for a long-focal-length telephoto optical system.

Reciprocal Magnification Technique

A unique and useful property of all optical systems is that, for every fixed object-to-image separation, an optical system will form images at two different magnifications, depending on the location of the optical system between its object and image. Of course, the optical system must be moved by some distance *d* to form the two different images of two different magnifications. This concept is illustrated in Figure 2-14.

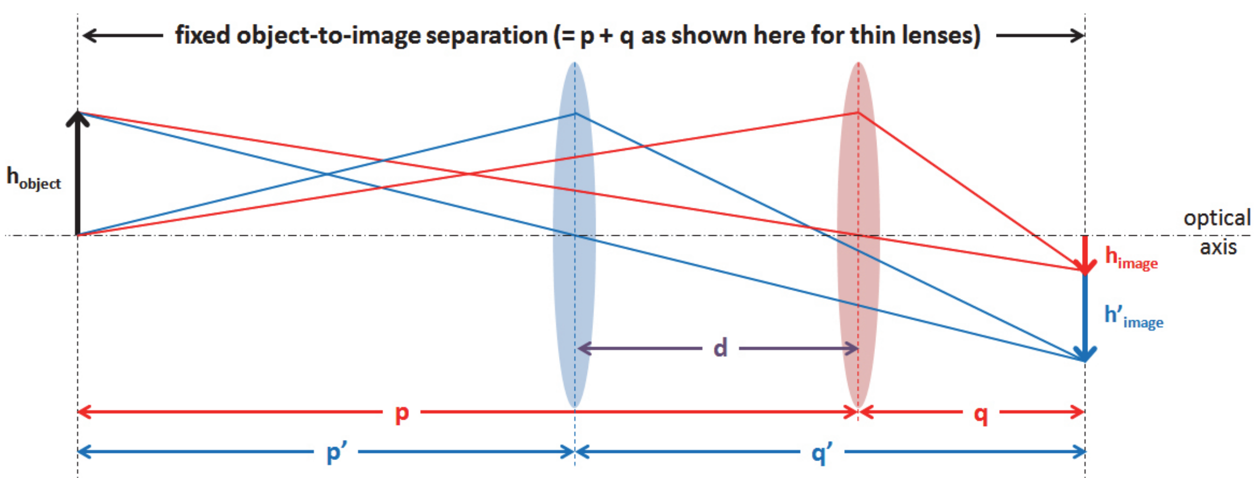


Figure 2-14 *For every fixed object-to-image separation, an optical system will form images at two different magnifications, depending on the location of the optical system between its object and image.*

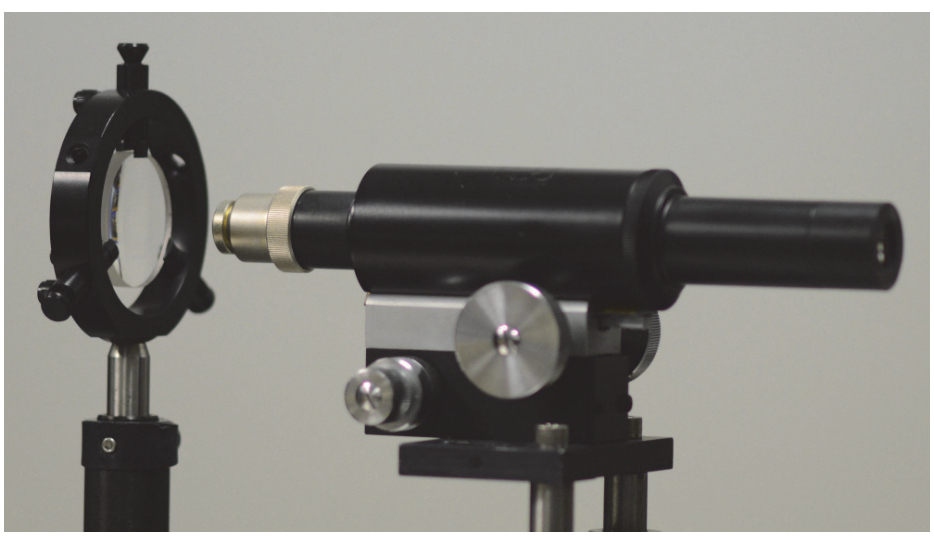
When an object is located distance *p* from the optical system under test, it forms an image at distance *q*. The magnification equation for this image is $mag = q/p$. Next, consider swapping the distances: the object can be located at distance *q* from the optical system under test, and a new image will appear at distance *p*. In this case, the magnification equals p/q, the reciprocal of the magnification determined in the first configuration, or $1/mag$. Remember that the object-to-image separation is unchanged: it is nominally, $p + q$ + the thickness of the optical system under test. This means that the optical system under test had to be moved by a distance *d* in order to find the second magnified image. The EFL of the optical system under test can be given by Equation 2-5 when the magnification, mag, and distance d are measured. The magnification may be measured by measuring p and q and taking their ratio, or it may be measured more directly by measuring the object and image sizes using a calibrated target for the object and a camera sensor to measure the image.

$$EFL_{optical\ system} = \frac{d}{mag - \frac{1}{mag}} \qquad (2\text{-}5)$$

Note that this technique works well for thin and thick optical systems, but it does require a precisely calibrated rail. It may be combined with the autocollimation technique to better locate the images.

Traveling Microscope Techniques

Microscopes are useful as metrology equipment in that they can focus directly on the surface to be tested, thereby locating the surface at its focal point. If this microscope is traveling, that is, attached to a translation stage that is aligned to its optical axis, then its focal point moves with it, thereby creating a non-contact optical probe located at a distance of the traveling microscope's BFL (sometimes called "working distance" for a microscope). This probe can be located on an optical surface directly, or light can be coupled into the traveling microscope, creating a point source. Therefore, by measuring with the traveling microscope probe the distance between two points in an optical system, (1) the vertex of the final optical surface and (2) at its radius of curvature (ROC), so that its BFL can be obtained. In fact, this technique is excellent for ROC measurements of a single optical surface, since that feature is actually being probed. Figure 2-15 shows a picture of a traveling microscope imaging the front surface of an optic, along with a schematic of the microscope in both configurations needed to make a BFL measurement of a concave mirror.



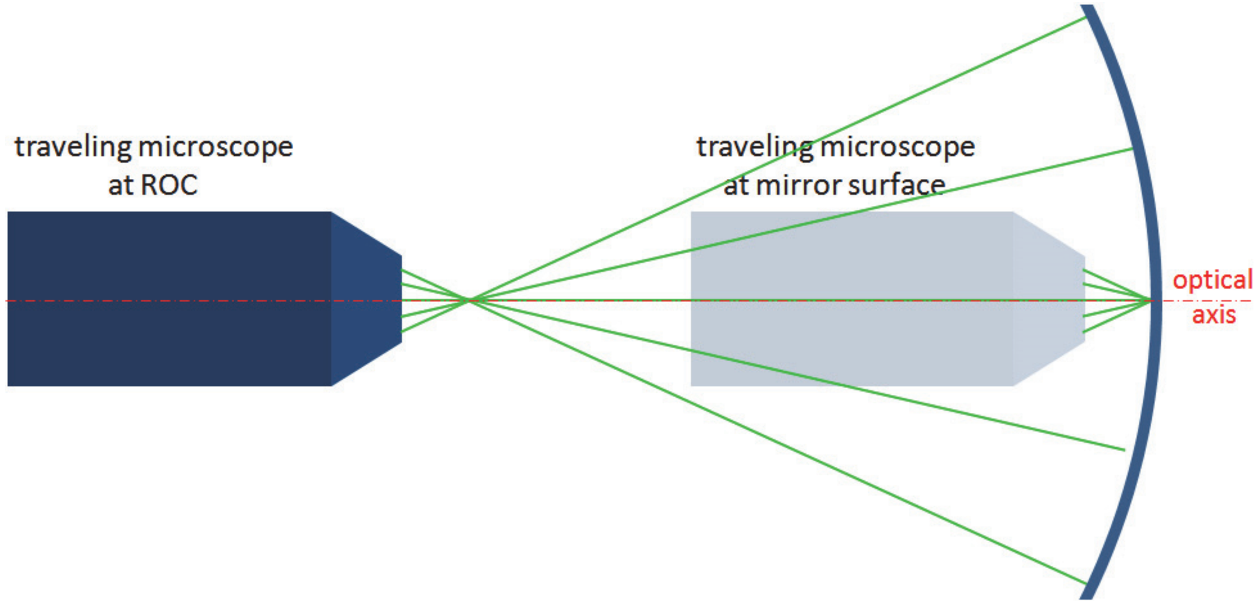


Figure 2-15 *The traveling microscope shown is focused on a lens surface. The microscope focuses on a point on an optic. It is focused in the schematic to a point on an optical surface in the right configuration, and at the surface's radius of curvature (ROC) in the left configuration.*

Of course, the range of the stage on which the traveling microscope travels must be longer than the BFL to be measured, and the resolution of the stage is the resolution of the measurement. The measurement resolution is also subject to the user's ability to determine exactly where the optical system's final surface or its focal point is in focus. This requires careful use of the traveling microscope when assessing an optical system's DOF, because the microscope objective's own DOF will add uncertainty. This is only an issue if the traveling microscope operates at a slow f-number, giving it a large DOF. Fast f-number (high NA) microscope objectives have a short DOF and are suitable for DOF measurement, especially if they are used in autocollimation. Finding the best focus, e.g., by contrast of an edge using a cross reticle, is quite precise with a fast f-number (high NA) microscope objective.

Point-Spread Function (PSF) and Line-Spread Function (LSF) Measurement

As discussed at length in Module 2-1, the point-spread function (PSF) of an optical system is an essential performance metric. The PSF is the distribution of energy at the focus of the optical system. The PSF's shape and uniformity will reveal valuable information about the quality of the optical system. However, it is tedious to measure directly the entire two-dimensional profile of an optical system's focal spot. The PSF was particularly difficult before the advent of digital camera technology. It was more common to measure a line scan cut through a focal spot, creating a line-spread function (LSF). The LSF is the summation of cross sections through the PSF, measured by scanning laterally across the PSF.

Many optical tests will measure multiple optical performance metrics simultaneously, and, as discussed in Module 2-1, many metrics can be calculated from another. For instance, the modulation transfer function (MTF) is often calculated from direct measurements of the LSF. (Although the next section discusses direct MTF-measurement techniques.)

The axial location of an optical system's focal spot (its BFL or EFL) is important to know, but the shape and structure of this spot, the PSF, reveals even more information about optical quality. In fact, if the PSF is well understood, it may include a focus term, thereby allowing calculation of the optical system's BFL or EFL. Beam profiling is a technique used to measure the shape of a focal spot, and two techniques are discussed here, via the knife-edge or Foucault test and via camera sensor.

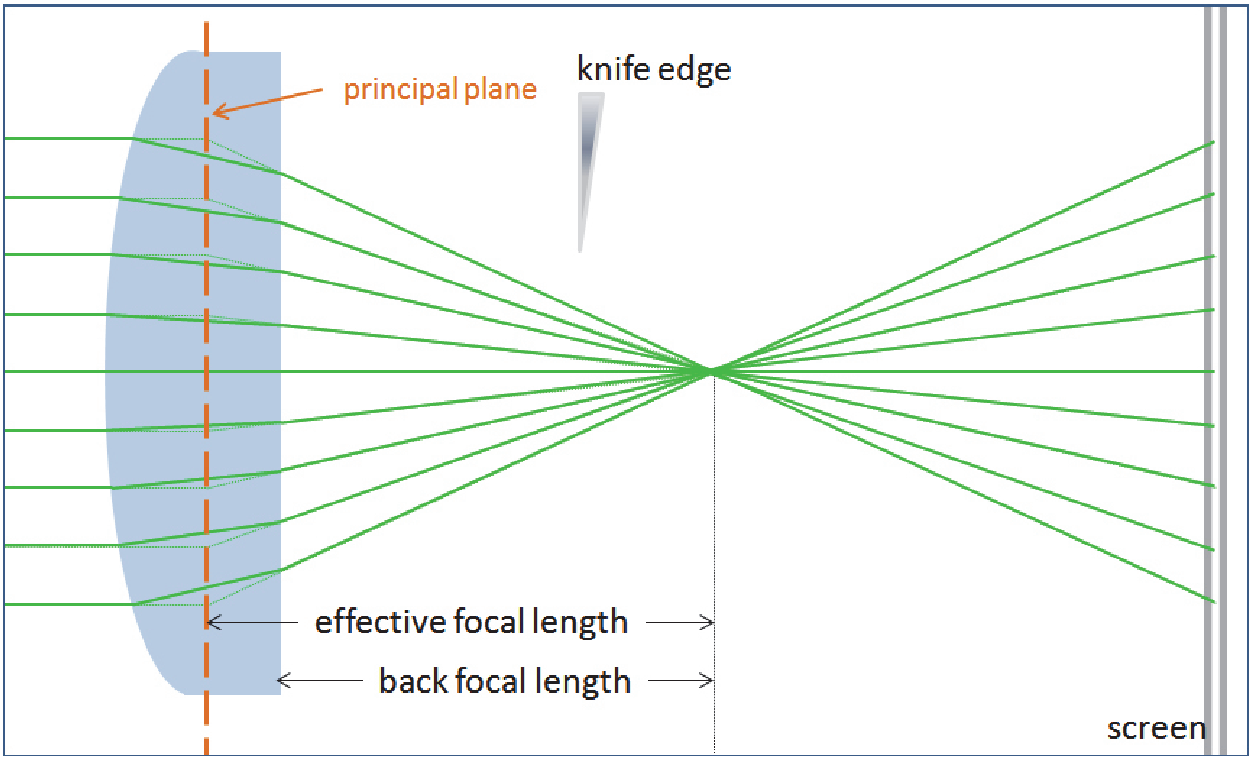
Beam Profiling via Knife Edge: The Foucault Test

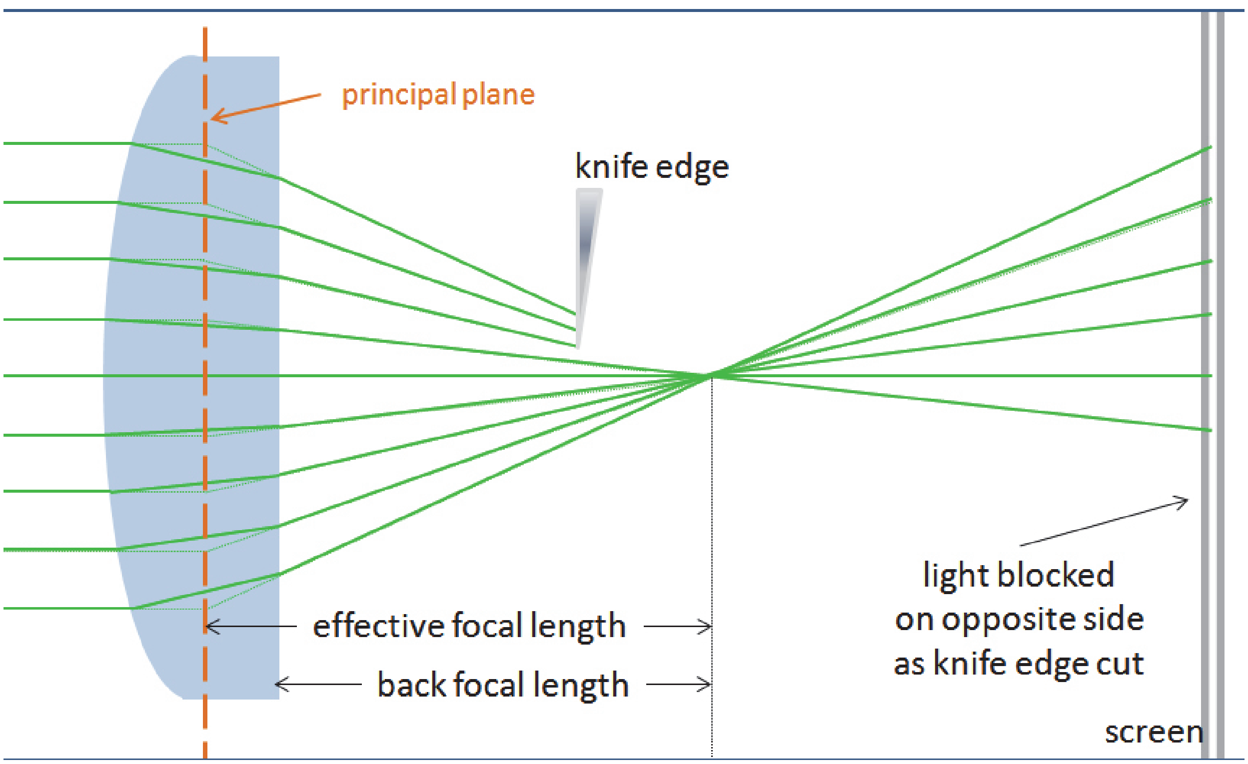
The knife-edge test or Foucault test (named for its inventor) is conducted using the optical setup shown in Figure 2-16. The full clear aperture (CA) of an optical system (in the case shown, a positive lens) is illuminated with collimated light, and a screen or a detector beyond the focus is illuminated. The screen or detector should be located at a distance where the irradiance is appropriate: if the irradiance is too low, the light spot cannot be seen or detected, and if the irradiance is too high, the light spot may be difficult to view or resolve its structure; the detector may saturate.

Once the screen and the optical system under test are configured, a knife blade is mounted to a linear translation stage and located near the optical system's focus (which may be coarsely located using the distant-source estimation technique described above). The blade is moved through the beam laterally, making multiple cuts through the beam near its focus. When the blade cuts the focusing beam of light between the lens and its focus, the blade will block light (create a shadow) on the opposite side of the cut. When the blade cuts the beam beyond the focus, light on the screen is blocked on the same side as the cut. The goal of this test is to locate the focal point, which is achieved when the blade cuts the beam exactly at its focus and light on the screen is blocked.

If this focus is precisely located, and the distance can be measured from the vertex of the final optical surface to the knife edge (using a vernier caliper, a metering rod, or a laser-based distance-measurement tool), and this technique then determines the optical system's BFL.

The focal length of an optical system with a negative EFL is much more difficult to test with this technique because it requires additional well-calibrated test optics, such as a positive test lens. This test lens effectively moves the virtual focus of the negative optical system into real space, so that the combined focal length of the test lens and the negative optic may be located with a knife edge. This technique and test setup are possible, but it is not common to configure. (Typical measurements for negative focal lengths are determined using the autocollimation or reciprocal magnification techniques discussed above, or via interferometer, as will be described in Module 2-3.)


principal plane
knife edge
effective focal length
back focal length
screen


principal plane
knife edge
light blocked
on opposite side
as knife edge cut
effective focal length
back focal length
screen

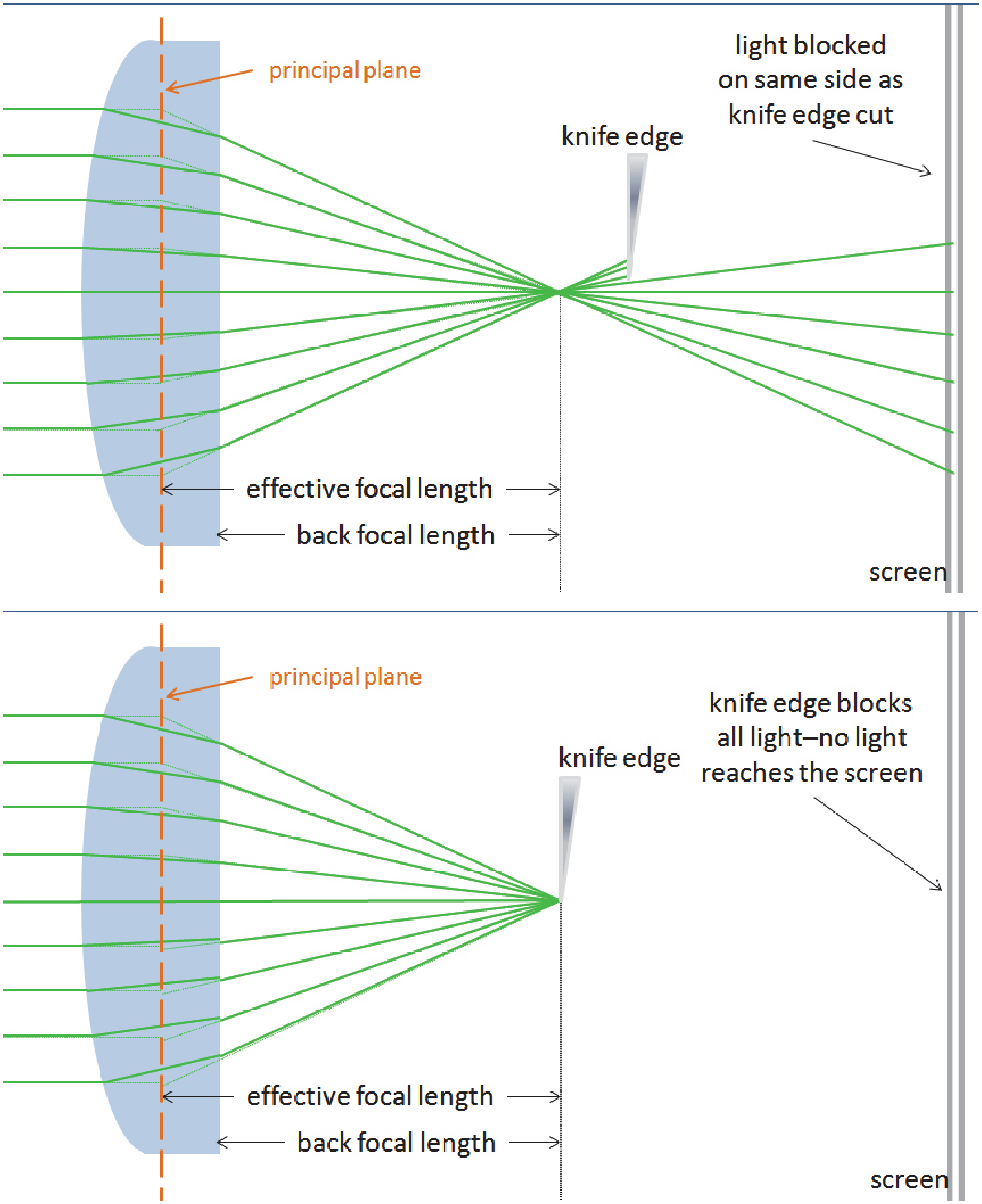


Figure 2-16 *The set up for the Foucault test is shown, illustrating the results that will be observed on a screen when the knife edge cuts the beam before, after, and at the focal point of the lens*

The most important information comes from the measurement of the irradiance as the knife edge cuts across the focal spot. Irradiance after the focus may be acquired using a single-element detector or a camera as the screen. In addition, the knife edge should be positioned via computer control of the linear translation stage that articulates it. The linear resolution of the stage becomes the resolution of this measurement. This will allow a more precise determination of the point at which light is completely blocked, because a sensitive detector is reporting the number of photons on the screen, not a human eye. In fact, if a sensor can capture the structure of this spot, information about the wavefront error of the optical system under test can be observed directly.

An LSF may be calculated by performing a mathematical operation (differentiation) of the data curve generated during a knife-edge measurement. This calculation gives a representation of the LSF that provides information about the aberrations in the optical system under test. For even more detailed information, the focal spot should be measured by multiple knife-edge cuts in different transverse directions (through the beam) and at different axial points along the focus (along the beam). In fact, the aberration *defocus* will be evident in knife-edge scans at different axial positions. This can lead to a more accurate determination of the optical system's EFL, if proper measurements can be made between the final optical surface and the knife edge.

Beam Profiling via Camera Sensor

An alternative beam-profiling technique requires the use of a high-resolution camera. The technique is simple—illuminate the pixels of the camera with a focal spot. To properly focus this test, either the camera or the optical system under test must be moved in small increments on the order of hundreds of nanometers. The camera pixels should be sufficiently small to sample the focal spot many times across its diameter, or auxiliary microscope optics must be used in front of the camera. This greatly limits the utility of this technique for fast optical systems and short-wavelength optical systems with very small focal spots. The smallest camera pixels are on the order of micrometers in diameter, so if the focal spot is only a few micrometers across (say, for an F/2 system for 450 nm light), the camera will not be able to adequately resolve the focal spot. This does provide a useful technique by which the PSF of slow (large F/#) and long-wavelength optical systems can be easily characterized.

Note that many commercial cameras come with software and hardware that is not well described in the user manuals. When testing, raw, unprocessed camera pixel data best represent the measured data, so any on-board image-processing or gain correction must be disabled. Additional (maybe unexpected) optical hardware is included within most cameras in the form of a thin (about 2-millimeters thick) protective glass window over the camera pixels. This glass window will add a significant amount of aberration to any beam-profiling measurement. For these reasons, many cameras are commercially available to be used exclusively for optical beam profiling. These cameras provide a windowless sensor and raw data output, and their software may even be configured to calculate live beam-quality metrics. .

Wavefront Error (WFE) Measurement

Interferometry is the most common technique by which an optical wavefront is measured, and that will be covered in Module 2-3. However, a number of unique WFE measurement methods exist that do not require interference. Note that the techniques covered above may also reveal the WFE of an optical system: data from both Ronchigrams and knife-edge profiles can be reduced to provide information about the WFE of the optical system under test, but it is not common to quantify observe high-order wavefront aberrations using these methods.

Wavefront Sensor (WFS) Techniques

An important means of measuring an optical wavefront consists of breaking the wavefront into segments across its surface. Properties of each segment are then captured and analyzed. This wavefront-measurement system is called a wavefront sensor (WFS). WFSs are typically used as integral components of astronomical systems and in ophthalmology when imaging the retina, but they are also employed to characterize the wavefront emitted from any optical system under test.

Many WFS designs have been conceived, and the most common was invented by R. Shack and B. Platt in the 1960s, based on simple aperture arrays conceived for optical testing by J. Hartmann in the 1900s. The so-called Shack-Hartmann wavefront sensor (S-H WFS) is deceptively simple—the wavefront output from any optical system under test is imaged through the WFS onto a camera. At the heart of the WFS is an array of holes in an opaque plate, or an array of tiny, identical lenses called lenslets. Each hole or lenslet captures the light within a *subaperture* of the full optical aperture. (Shack and his colleagues replaced the small holes of Hartmann's design with lenslets. Lenslets have the advantage of capturing a larger region than the holes.) The full wavefront through the optical system under test is then reconstructed by stitching together the information in each subaperture. The entire process of wavefront sensing works as follows.

Light is directed through the optical system under test with the lenslet array is located in a plane conjugate to its entrance pupil, such as its aperture stop. In each subaperture, the local tilt of the wavefront is measured when each lenslet forms a focal spot. In an ideal, unaberrated optical system, each focal spot forms in the exact center of its respective subaperture. If there is any local tilt—that is, tilt of the wavefront within the area of the subaperture—the focal spot will be shifted transversely. Since each lenslet forms a focal spot, the array of focal spots can be captured by (or optically relayed to) a camera sensor, and a wavefront map can be constructed for the optical system under test by stitching together the tilt (sometimes called the slopes) in each subaperture. Figure 2-17 shows the effect of subaperture tilt when an ideal wavefront is aberrated.

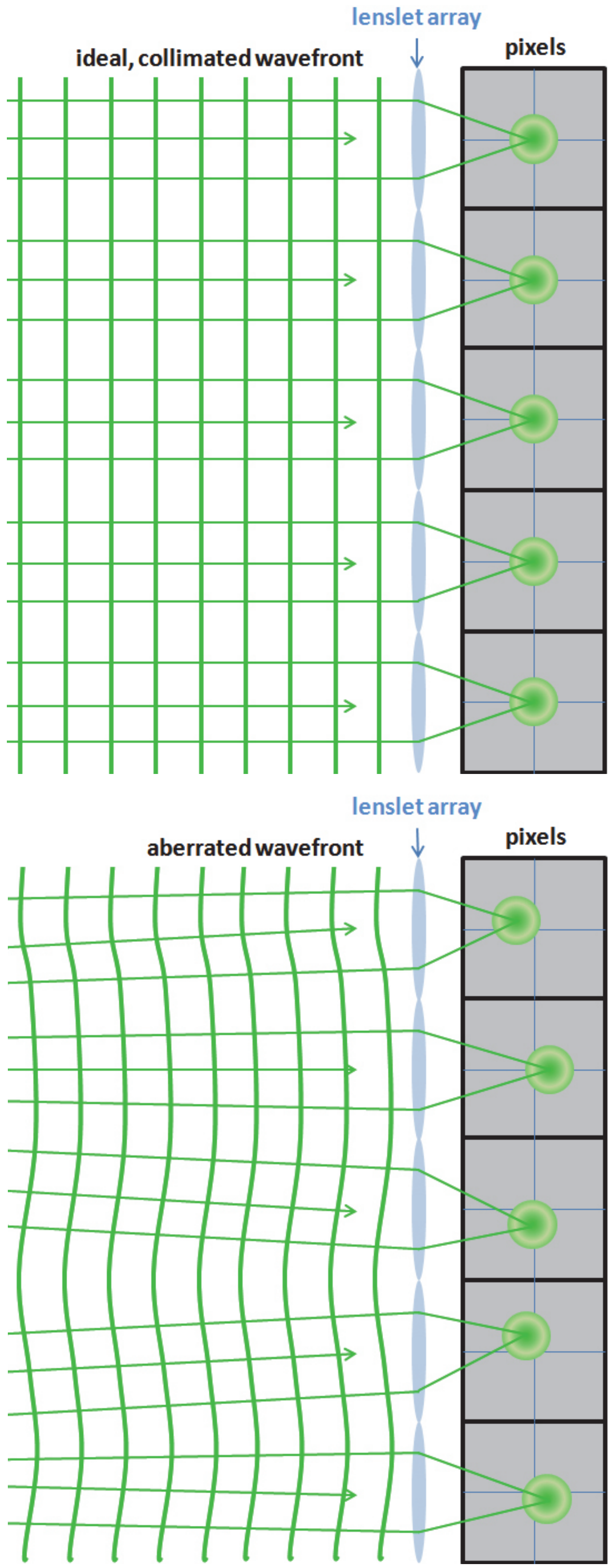


Figure 2-17 *These figures show (top) the ideal spot locations for a collimated, unaberrated plane wave, and (bottom) the spot locations for the different subaperture tilts of an aberrated wavefront in a Shack-Hartmann wavefront sensor configuration.*

The lenslet array is either sized to match the camera's pixel pitch, or an optical relay is aligned to exactly register the spots to the camera pixels. Focal spot locations are measured on the camera's pixels by calculating the centroid of each focal spot. This is accomplished by a centroid algorithm that uses many pixels (say, a 10-by-10-pixel region), or by using a simple 2-by-2-pixel region for each spot. Centroid algorithms are beyond the scope of this test, but the latter technique is called quad-cell detection. The location of a focal spot is determined by how much light is present in each pixel using Equation 2-6, in which *L* is the length of the full detector (two pixel widths), and *A*, *B*, *C*, and *D* are the measured optical power values in each of the 2-by-2 pixels, as shown in Figure 2-18. (Note that a monolithic position-sensing detector (PSD) may be used in place of each 2-by-2-pixel region in the quad-cell technique. An array of PSDs may replace the camera pixels for high-speed WFS applications.)

$$x_{coordinate} = \frac{L}{2}\frac{(A-C)+(B-D)}{A+B+C+D} \qquad y_{coordinate} = \frac{L}{2}\frac{(A-B)+(C-D)}{A+B+C+D} \qquad (2\text{-}6)$$

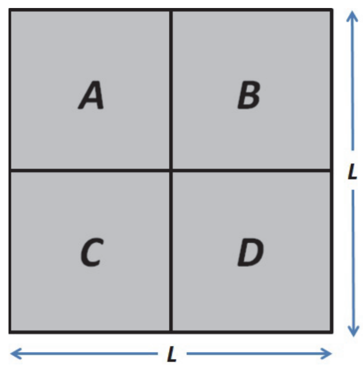


Figure 2-18 *Each of the four small squares represents a camera pixel. The transverse (x, y) location of a spot that illuminates this 2-by-2 pixel region will be determined by Equation 2-6, in which A, B, C, and D are the optical power values in each of the pixels.*

Once the x- and y-coordinates are known, the subaperture tilt is known, and the entire wavefront can be reconstructed. Wavefront reconstruction is like tiling tilted tiles together to form the big picture of the entire wavefront. An ideal, unaberrated wavefront will be completely flat. A measurement made by one subaperture is assumed to have a phase that is continuous with adjacent subapertures, so that a continuous wavefront can be reconstructed. WFS measurements of wavefronts are said to have a phase ambiguity of 2π that require unwrapping to form a continuous wavefront. Of course, the resolution of the wavefront measurement depends on the number of subapertures, but WFS measurements can be used to measure and correct the aberrations of an optical system via even a small number of subapertures, such as 16 by 16.

Another notable wavefront sensing technique is described as wavefront curvature sensing. This system requires a lenslet array like the S-H WFS, but rather than measuring the spot locations on an array, it measures the subaperture irradiance at two or more points along the beam passing through each subaperture. Subaperture wavefront curvature (rather than tilt) is calculated by observing how the irradiance drops off with distance along each beam, analogous to the distance-squared (R^2) fall-off that is observed when measuring any electromagnetic power. The subaperture curvature values are stitched together in a manner similar to that of the S-H WFS.

Surface-Contact Techniques

Measurement of a single optical surface will not reveal the WFE of an entire system, but such measurements can assist the manufacturing and alignment process, and it can even help to model system performance by incorporating measured data into a simulation. A useful technique involves the use of a coordinate measuring machine (CMM). This high-precision mechanical tool, an example of which is shown in Figure 2-19, is designed to guide an extremely hard probe (usually made of ruby or sapphire) over any structure to determine the shape of its surface. This relates to WFE because measurement of surface shape equals one half the reflected WFE, as described in Module 1-3. When the sensitive probe contacts the surface being measured, the probe's position is recorded by high-resolution position encoders. As the probe contacts many points across a surface, a so-called point cloud is formed; this maps the surface shape, providing information about the measured wavefront.

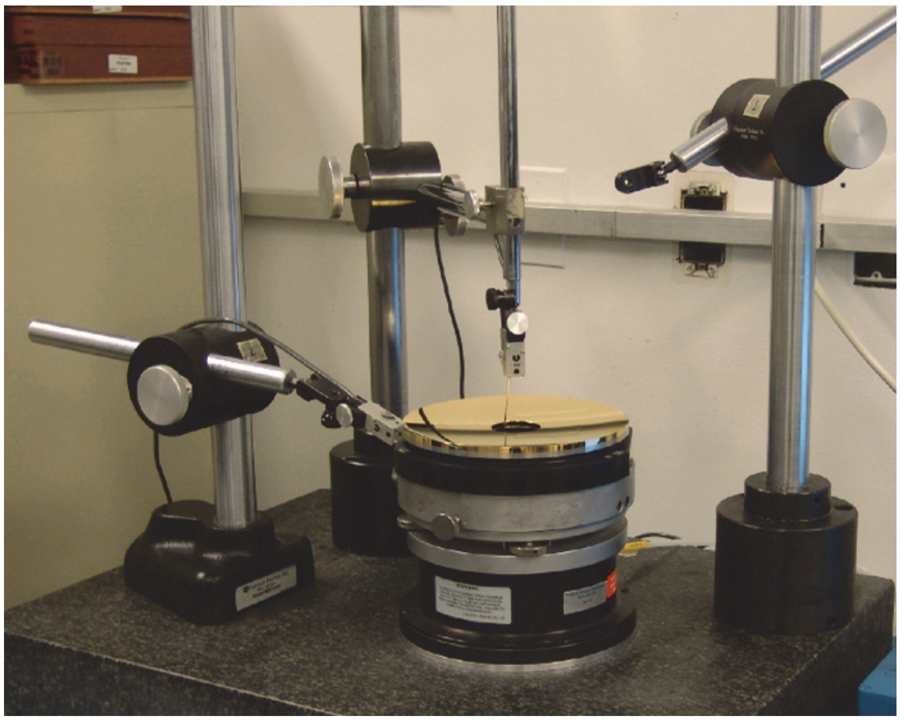


Figure 2-19 *The CMM shown in the figure is outfitted with multiple probes that measure the surface of the diamond-turned asphere. (Photo courtesy OPN.)*

A "frameless" CMM or a laser tracker may be used in a similar manner. This powerful alignment tool consists of a displacement-measuring interferometer (DMI) that projects a laser beam from a high-resolution gimbal. The laser beam is reflected back to the DMI, or retroreflected, using a spherically mounted reflector (SMR). An SMR is a precision optical element: it is a cornercube reflector with its corner precisely located at the center of a small sphere (usually with a 0.25" to 0.50" diameter) in which it is enclosed. Therefore, when the location of the center of an SMR is measured, the distance to the sphere's surface is measured. To make measurements with a laser tracker, an SMR is moved across the surface of an optical element or assembly. The laser tracker records the points at which the SMR is located and forms a three-dimensional point cloud, thereby mapping the surface under test. This can be used for measurement of optical surfaces (and wavefronts), but it is much more common to use these systems for optical integration and alignment applications.

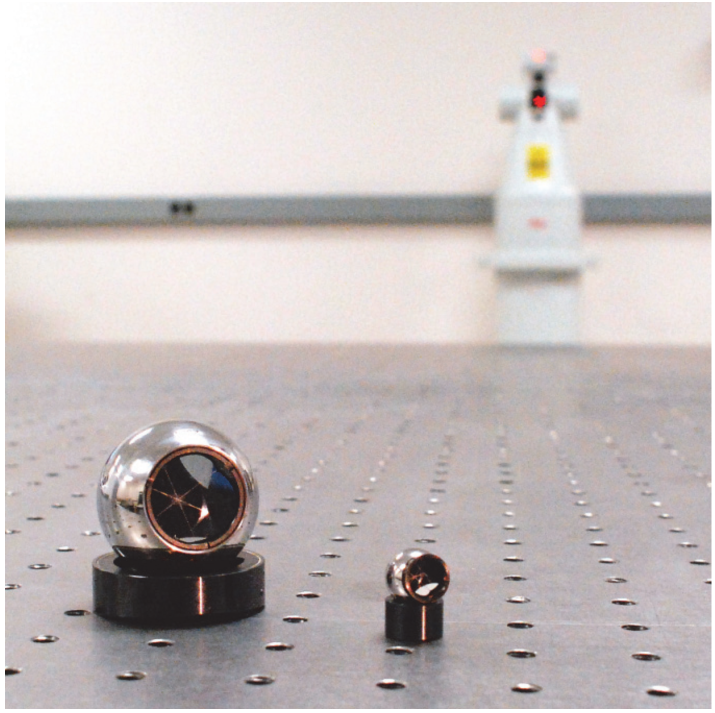


Figure 2-20 *A laser tracker is shown in the background on this image, and two SMRs are located on the optical breadboard in the foreground. (Photo courtesy OPN.)*

Modulation Transfer Function (MTF) Measurement

Image contrast is reduced as the spatial frequency of an object increases. This is illustrated in Figure 2-21. The top two figures are objects with different spatial frequency, and the figures directly below each represent how each is imaged—the image of the high-spatial-frequency object has far lower contrast than that of the low-spatial-frequency object. Diffraction and aberrations cause the image to be reduced in contrast, and these effects are more prevalent for high-spatial-frequency objects. As detailed in Module 2-1, the image contrast over a range of spatial frequencies is given by the measurement of the modulation transfer function (MTF) of the optical system under test.

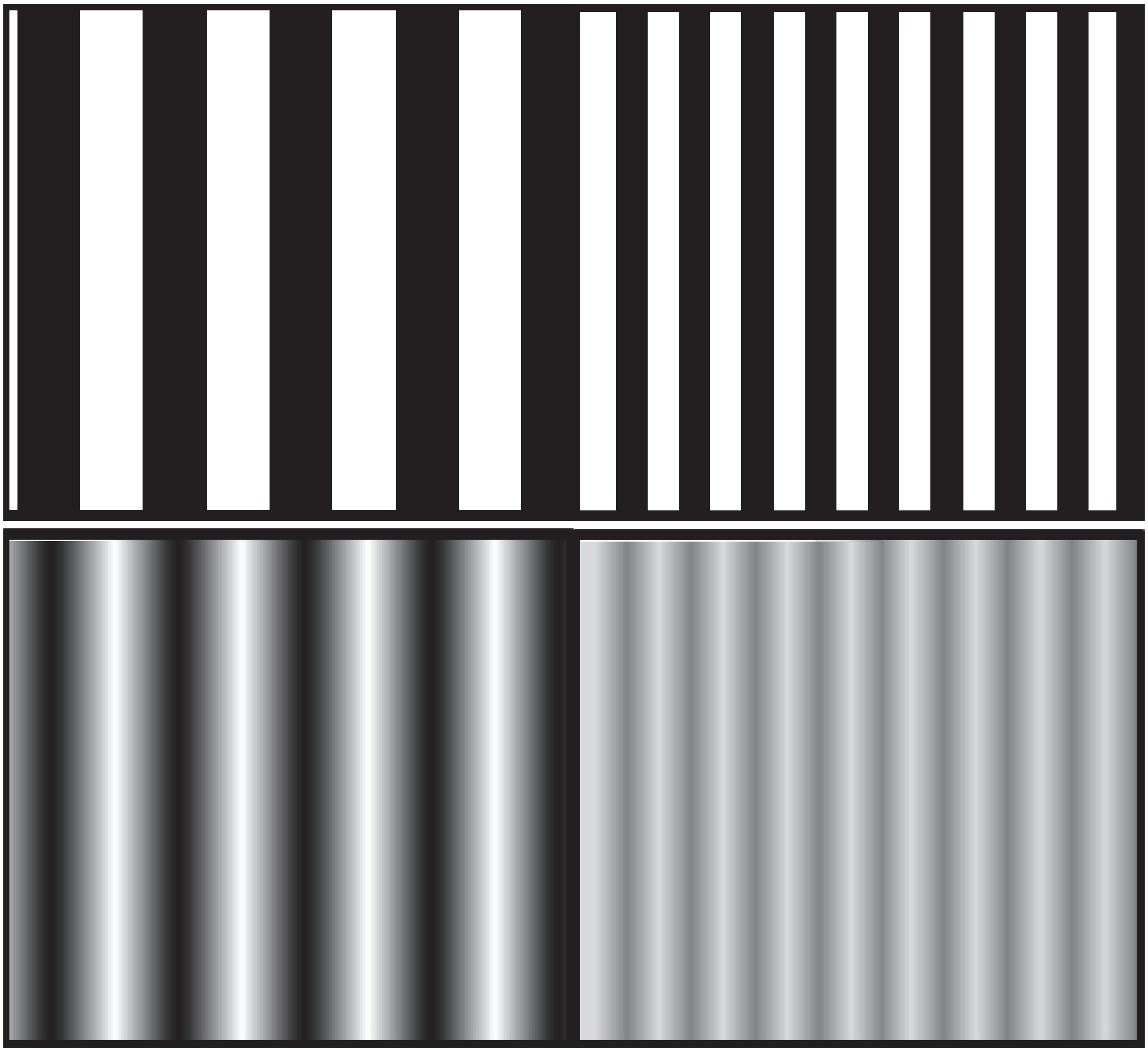


Figure 2-21 *These figures show how the contrast is more poorly imaged for objects with higher spatial frequency than for low-spatial-frequency objects.*

Optical Setups for MTF Measurement

An optical system's MTF is measured directly using the optical system under test itself to image objects of various spatial frequencies while recording the quality of the resulting images. The spatial frequency of the objects (traditionally called "targets") can be changed in a number of ways. As described above, the targets may be adjustable- or fixed-width slits (including Ronchi rulings as in the 1951 USAF Bar Chart, shown in Figure 2-5), so the object's spatial frequency is changed by changing the physical size of slits, or by sequential replacement with discrete targets of different spatial frequency. Even circular, radial, or grid targets may be used, depending on the application. For each measurement, a target with a single spatial frequency is tested. Each target is imaged through the optical system under test, and the image contrast for that particular spatial frequency is added to the MTF plot. The test is repeated using Ronchi rulings with different spatial frequencies or by adjusting slit widths until a complete MTF curve is constructed. Commercial MTF-measurement systems incorporate software to streamline the time-consuming process of imaging multiple spatial frequency targets.

MTFs provide an objective measurement of optical system performance that may be directly compared to optical design software output. Most importantly, MTF measurements are extremely versatile in that the optical system under test can be tested exactly as it will be used in application: the MTF for various imaging configurations, off-axis field angles (object sizes), spectral regions, and illumination conditions can be tested using the MTF-measurement technique, often in a single test setup. A block diagram of an MTF-measurement system is shown in Figure 2-22. In principle, the system is extremely simple: the object is input to the optical system under test, and the properties of the resulting image are measured. To test different field angles or object sizes, the optical system under test is rotated about the appropriate plane (perhaps a nodal plane or a plane corresponding to a mechanical mounting feature). To test different wavelengths, the target may be filtered with a spectral filter, or the illuminating source itself may be changed to output the appropriate spectral band(s). Often, to accommodate infrared testing, where transmissive optics are scarce, the input will be provided using a reflective collimator, such as an off-axis paraboloidal mirror with a point source at its focus. To test different input irradiance values, the target may be filtered with a neutral density filter, have its output regulated via voltage, or beam-shaping optical elements may form the proper energy distribution.

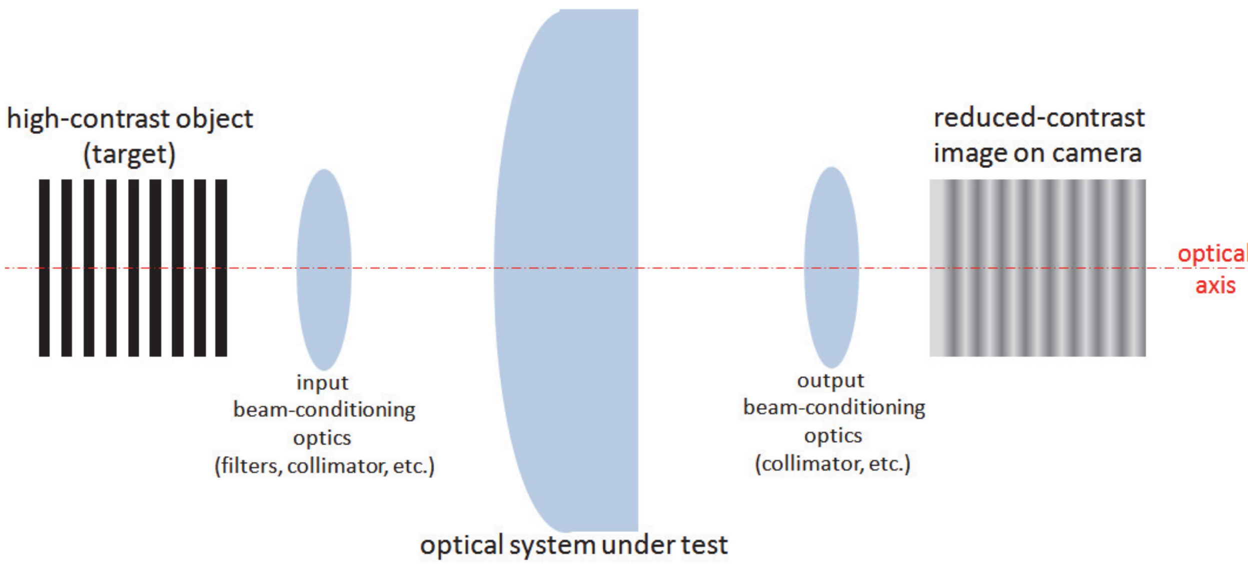


Figure 2-22 *Block diagram of an MTF-measurement system*

In addition, the MTF of different imaging configurations can be tested using the appropriate source-generation optics. The test setup is straightforward when finite objects are imaged to finite distances. But if the optical system under test is designed to operate with an object at infinity and form its image (conjugate) at a finite distance, then the target can be provided as a collimated input (projected from optical infinity), and the image sensor can be placed in the image plane of the optical system under test. Conversely, if the optical system under test is designed to form an infinite image of an object located at a finite distance, a well corrected collimator may be included after the optical system under test, in order to measure the image locally. (This is sometimes called a “de-collimator”.) If the optical system under test is designed to operate in an afocal mode (infinite object and image), a collimator may be used at the input, to project a target in from infinity, and at the output, to measure locally the infinite image that is produced by the optical system under test.

Data products of MTF Measurements

There exists an international standard for MTF measurement, ISO 15529:2010, which covers the related terms and techniques. MTF plots are the data of an MTF measurement, plotting contrast in units of line pairs or cycles per distance or angle (usually millimeters or milliradians) versus spatial frequency up to the cutoff frequency. These powerful plots highlight many aspects of system performance.

Foremost, an MTF plot should always include the theoretical diffraction-limited performance of the system. This reference curve represents the an ideal system, so if this curve is included on an MTF plot, deviations between it and the measured MTF curve are immediate evidence of optical aberrations. Deviations manifest themselves in a number of ways, and can provide insight to the origin of fabrication errors and optical aberrations. A notable example is that of mid-spatial frequency (MSF) error (or ripple or waviness), which is observed as a dip in the MTF curve for middle spatial frequencies. MSF error is evident in an interferogram by greater than 8 to 10 cycles across the optical system's clear aperture, as shown in the interferogram of Figure 2-23.

The cause of MSF error is often a fabrication error due to moderately sized ripples in the surface of one or more optical elements within the optical system under test. Therefore, the presence of MSF error in an MTF test might guide the precision optics technician during the fabrication process. Roughness and other higher-frequency surface effects may also manifest themselves in a measured MTF curve, often as degradations in the higher-spatial-frequency portion of the MTF plot.

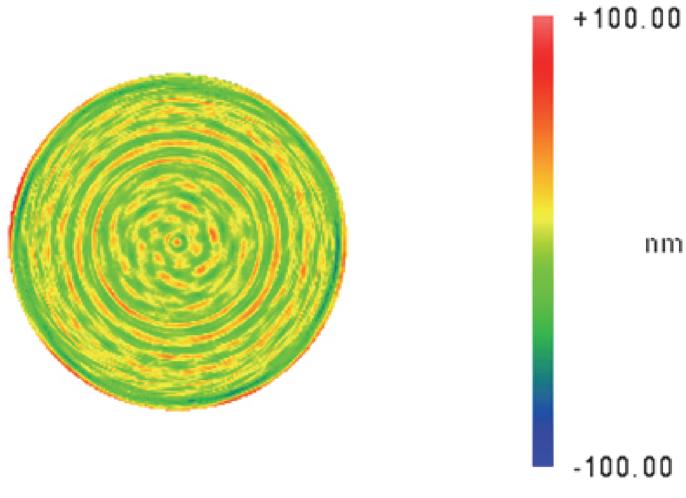


Figure 2-23 *Mid-spatial frequency error will manifest itself if ripples like those shown here are evident in an interferogram. (Courtesy R. Youngworth and U. Fuchs)*

An optical system's MTF may also be learned by measurement of another property that can be mathematically converted to MTF. For example, a similar configuration to Figure 2-22 may be used to test a system's line-spread function (LSF), which can be converted to MTF using the mathematical technique of Fourier transformation, which is typically accomplished within the software of the MTF-measuring system, or by processing the acquired data (known as postprocessing). Due to the Fourier transformation method, the MTF of all spatial frequencies can be theoretically calculated, limited only by the cutoff frequency, $1/(\lambda \cdot F/\#)$, and the sampling achieved on the imaging sensor's pixels.

Often, particularly when using the LSF method to obtain an MTF, a *through-focus MTF curve* will be measured. This curve plots, as shown in Figure 2-24, the MTF of a particular spatial frequency at different focus positions along the optical axis. The peak of this curve is the axial position of the best focus spot, that which transfers light with the highest modulation. This adds another layer of utility to MTF metrology, since it can be used to determine an optical system's EFL.

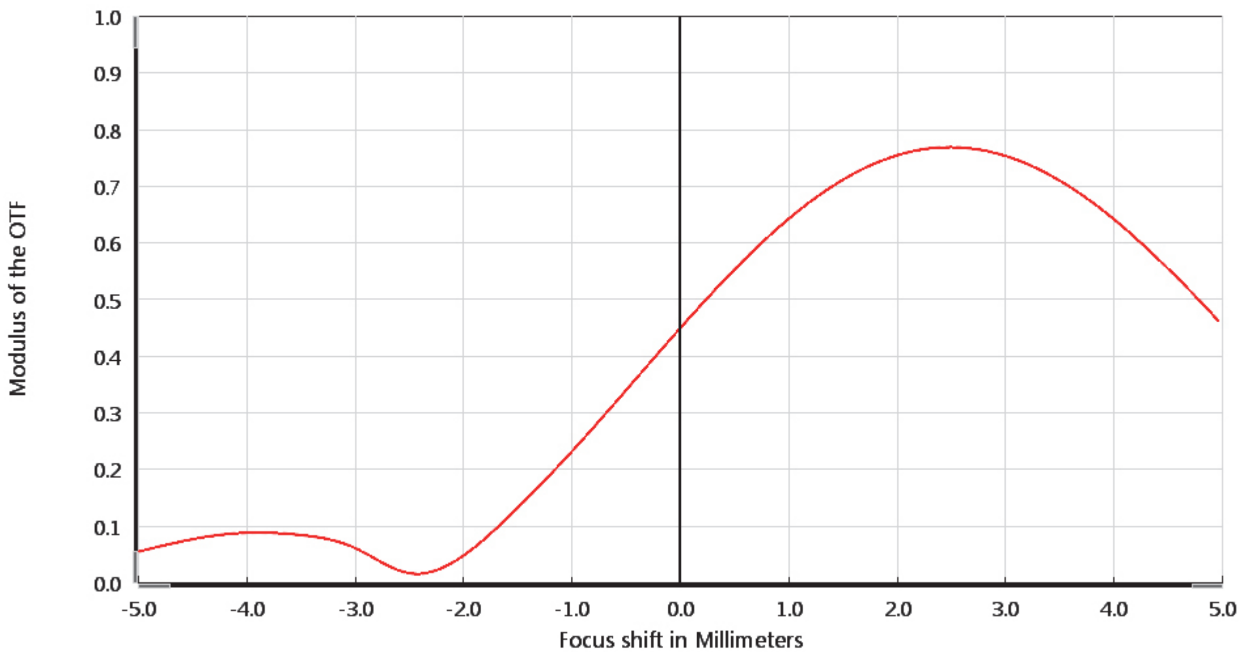


Figure 2-24 *The through-focus MTF of a simple lens system shows the MTF at a particular frequency (here, at 10 cycles/mm) over a range of focal plane locations, focus shifts from -5.0 to +5.0 mm. It is apparent that the modulation peaks for a focus shift that is approximately 2.5 mm from the nominal focal position.*

The Final Performance Metric of Optical Systems: Integration with Detectors in Application

Other metrics of optical system performance, including Strehl ratio, beam quality (M^2), and encircled energy, may be called out in optical system specifications, but the optical performance parameters described here are the most fundamental. Other metrics are often calculated from these fundamental performance measurements. Optical system performance metrics may be specified for a single element or for an entire assembled optical system. Optical assembly specifications should specify tests for an optical system even after its individual components have been measured independently. It is essential to understand the application of the optical system so that these tests can be planned with the correct conditions, and conducted using the correct spectral regions, illumination conditions, sources, and detectors.

Of course, the final proof of an optical system's quality comes when it is integrated with the detector that will measure the photons through the actual system. This detector sets the image plane of the optical system, so the final characterization of any optical system should be an evaluation of the image data product output from the system itself. Image quality assessment and processing is beyond the scope of this text, but it is common to take images of calibrated targets with the final detector and evaluate their quality. It should be verified that first-order aberrations (defocus and tilt) can be accommodated using mechanical features of the optical system, such as a focus mechanism, lens tip/tilt mount, or focal-plane shim. Third-and higher-order aberrations should be assessed in the image quality of a calibrated target. Some visual artifacts may be obvious, such as field curvature and chromatic aberrations, but all aberrations of the image should be documented so that their causes within the optical system can be investigated and corrected. The final performance of an optical system may be compared to a simulation that was created using the optical design. Such a comparison provides a useful metric to guarantee that the desired, designed optical system was indeed fabricated, integrated, aligned, and tested.

LABORATORIES

Laboratory 2-A
Metrology Source Generation

Theory

Well-characterized, well-aligned collimated and point sources are essential to optical metrology. The purpose of this lab is to construct both types of sources for use in later metrology laboratories and to learn about the minor errors that exist in even the best sources possible with the hardware available. (Collimated sources may be constructed in reflective configurations if materials are available. Such sources are important because reflective materials a broad range of wavelengths without chromatic aberration.)

Equipment

- optical rail or transportable breadboard (800 to 1200 mm long in the long dimension)
- mounted, adjustable visible laser (>5 mW)
- spatial filter mount for microscope objective (10x to 40x) and pinhole (15 to 25 µm diameter)
- well corrected positive lens (with a CA > 50 mm, 50 mm ≥ EFL ≥ 200 mm), such as an achromatic doublet, mounted in a releasable, kinematic lens mount
- translation stage
- shear plate interferometer
- viewing screen
- (optional) mounted, well corrected concave (positive) spherical or paraboloidal mirror with an EFL between 30 and 300 mm, and a CA >30 mm
- (optional) mounted, flat fold mirror ~25 mm in diameter
- (optional) a second mounted, adjustable visible laser, spatial filter mount for microscope objective and pinhole, as above. Alternatively, an LED source may be substituted.

Procedure

1. Atop the optical rail or breadboard, mount the laser, followed by the microscope objective and pinhole in the spatial filter mount.
2. Direct the laser through the threaded aperture of the microscope objective.
3. Spatially filter the laser by aligning its beam through the microscope objective, and then align the focal spot formed by the objective through the pinhole—this forms your point source at the pinhole.
4. Verify that everything is mounted down securely and stably.
5. Characterize the point source by observing its uniformity and divergence on a viewing screen. Note any irregularities with its irradiance distribution as it propagates—it should be an ideal TEM00 Gaussian beam.
6. In a kinematic lens mount atop a translation stage with its translation axis parallel to the optical beam axis, add the well-corrected positive lens at a distance nominally equal to its focal length in front of the pinhole.
7. Verify the collimation of the output from this positive lens using a shear plate. Adjust the lens position as required to achieve collimation.
8. Verify that everything is mounted down securely and stably.
9. Characterize the collimated source by observing its uniformity and divergence on a viewing screen. Note any irregularities with its irradiance distribution as it propagates—it should be an ideal TEM00 Gaussian beam.
10. On a separate optical breadboard, perform steps 1 through 5 again to create a second point source.
11. To reduce the obscuration in the reflected beam, add the fold mirror to direct the point source to one side—the only obscuration after reflection will then be the fold mirror and its mount.
12. Align the concave mirror at a distance equal to its focal length after the point source (taking into account the folded path).
13. Characterize the reflected, collimated source by observing its uniformity and divergence on a viewing screen. Note any irregularities with its irradiance distribution as it propagates—it should be an ideal TEM00 Gaussian beam.
14. Alternatively, you may use the LED source as the second point source. If you choose to do this, you will not need the laser, spatial filter, pinhole, or flat mirror. The fold mirror can direct the light back at the LED with minimal obscuration.

Laboratory 2-B
Autocollimation for Negative Lens Characterization

Theory

The measurement of the EFL of a negative lens is a more demanding process than the measurement of the EFL of a positive lens, but the autocollimation technique provides an efficient method. Contrast the autocollimation technique with the qualitative, visual negative lens measurement technique of QAPO Laboratory 2-C.

Equipment

- point source from laboratory 2-A
- well-corrected positive lens (20 mm ≤ EFL ≤ 200 mm)
- negative lens (-150 mm ≤ EFL ≤ -15 mm)
- flat mirror with the same or larger aperture as the negative lens

Procedure

1. Perform QAPO Laboratory 2-C to assess the focal length of the negative lens.
2. Construct the configuration of Figure 2-7 (top) using the positive lens to focus an image of the point source on a mirror. Verify that the beam is reflected back to the source, to ensure that the lens is focused on the mirror. This will be seen as a focal spot on the pinhole.
3. Add the negative lens between the positive lens and the mirror at a distance from the mirror approximately equal to the focal length determined in step 1.
4. Adjust the negative lens-to-mirror separation to determine the EFL of the negative lens.
5. Compare the accuracy and sensitivity of this technique to the subjective assessment you made in lab QAPO 2-C.

Laboratory 2-C
Reciprocal Magnification

Theory

Learn how the reciprocal magnification technique works.

Equipment

(PASCO basic optics kit will have all required equipment.)

- calibrated target and visible source
- viewing screen
- single positive lens (20 mm ≤ EFL ≤ 300 mm)

Procedure

1. Fix a target-to-screen (object-to-image) separation.
2. Place the positive lens between the target and the screen; move the lens to focus a clear image of the target on the screen.
3. Note the location of the lens required to form this image.
4. Measure the size of the target, the size of its image, the separation between the target and the lens, and the separation between the lens and the screen.
5. Calculate the magnification.
6. Move the lens to find the second image location at this fixed target-to-screen separation.
7. Note the location of the lens required to form this second image, and calculate the distance, d, between the two lens positions.
8. Measure the size of the target, the new (second) size of its image, the new (second) separation between the target and the lens, and the new (second) separation between the lens and the screen. The new (second) separation between the target and the lens should nominally equal the original separation between the lens and the screen for a thin lens. Likewise, the new (second) separation between the lens and the screen should nominally equal the original separation between the target and the lens for a thin lens.
9. Calculate the magnification with the lens at the second location.
10. Use Equation 2-5 to calculate the EFL of the positive lens.
11. Repeat the experiment with a different fixed target-to-screen (object-to-image) separation.
12. Use Equation 2-5 to calculate the EFL of the positive lens in the second target-to-screen separation, and compare this result to the one you found using the first configuration.

Laboratory 2-D
Arraying lenses for wavefront sensing

Theory

Lenslet arrays are tedious precision optical elements to fabricate. However, it is possible to construct simple lenslet arrays if a few identical lenses are available.

Equipment

- at least four identical, small, positive lenses (CA between 1 and 10 mm, focal length between 20 and 100 mm)
- beeswax
- two thin, flat, glass or plastic windows with CA >3 times larger than that of the small lenses (picture frame glass should be sufficient)
- collimated source from laboratory 2-A
- one well-corrected positive lens
- one uncorrected positive lens
- viewing screen or large-area (35 mm) CCD

Procedure

1. Atop one of the two flat windows, place the lenses into an array of at least 2 by 2 lenses, depending on how many are available.
2. Mount the small lenses together at their edges using the beeswax. Be sure to leave their clear apertures clear.
3. Sandwich the lenses (lenslets!) using the other window, and secure them with the beeswax.
4. Mount the lenslet array in front of the collimated source.
5. Measure the spot locations on the viewing screen or CCD.
6. Replace the well-corrected collimating lens with a uncorrected lens and observe how the focal spots shift for each lenslet.
7. Based on the WFS tilts, describe and document the orientation of the aberrations observed, and speculate about what aberrations are present in the uncorrected lens.

Laboratory 2-E
Ronchi-Ruling Metrology

Theory

Low-resolution Ronchi rulings are relatively easy to make with decent precision. They can be printed onto a transparency, and the Talbot autoimaging/Moiré effect will be the same. Ronchi-ruling metrology should first be employed to test single optics, such as mirrors, as shown in Figure 2-8, or thin lenses. Thereafter, the wavefront output by more complex optical systems can be tested.

Equipment

- computer with application for image generation, such as Microsoft PowerPoint, Microsoft Paint, Adobe Photoshop, or IrfanView
- transparency-printing material
- collimated source from laboratory 2-A
- mounted, concave (positive) spherical or paraboloidal mirror with an EFL between 30 and 300 mm and a CA >30 mm
- one well-corrected positive lens
- one uncorrected positive lens (likely a simple singlet)

Procedure

1. Construct the setup of Figure 2-8 using a concave (positive) mirror or a positive lens (in an unfolded configuration of the same figure). A second ruling is necessary with a lens: one at the input and another at the output to interfere with the image of the input ruling.
2. Based on the Ronchigram you observe, describe and document the orientation of the aberrations you observe, and speculate about what aberrations are present in the uncorrected lens.
3. Construct the setup of Figure 2-9.
4. Using the technique described in the text above on Ronchi-ruling metrology, measure the EFL of the poorly corrected and the well-corrected positive lens.
5. Based on the Ronchigrams you observe, describe and document the orientation of the aberrations you observe, and speculate about what aberrations are present in the lens(es) tested.

PROBLEM EXERCISES AND QUESTIONS

30. Describe the difference between a point source and a collimated source.
31. Discuss why a collimated source constructed using reflective materials such as mirror might be more desirable than one made of transmissive materials such as lenses.
32. How large should the collimator's source be if the optical system under test has a CA of 13 mm and the collimator has an EFL of 150 mm using NIR light?
33. Describe the application of a point-source microscope.
34. What is the resolution of group 5, element 6 of the 1951 USAF Bar Chart?
35. Describe why horizontal and vertical patterns are necessary when testing an optical system.
36. Name three calibrated target shapes that might be used for optical metrology.
37. What makes an alignment telescope into an autocollimator?
38. Describe the difference between EFL and BFL.
39. Explain why a positive lens is required to test the EFL or BFL of a negative lens.
40. The Moiré effect has other applications in addition to Ronchi-ruling optical metrology. Research some of these applications, and note some places where you have observed this effect in everyday life.
41. In a manner similar to Figure 2-8, refractive (lens) systems can be tested via Ronchi test. Sketch the test setup geometry required, including the number of Ronchi rulings necessary.
42. Explain why it might be difficult to use a nodal slide to test a 500 mm telephoto lens that measures 150 mm in length with a BFL of 100 mm.
43. While you visit your optometrist, you observe that she has to move the reticle by a distance of 50 mm to refocus after your prescription lens is inserted in her focimeter. Your lens was placed 100 mm from the focimeter lens. What is the BFL of your prescription lens?
44. Explain how why a negative lens moves the image of a focimeter's reticle one direction, while a positive lens moves it the other direction.
45. What will be the angle of the chief ray at the output of an optical system tested with a collimator if the object size is 10 mm and the collimator's EFL is 100 mm? Based on your answer, what is the EFL of the optical system if the image size is measured to equal 5 mm?
46. Explain how the reciprocal magnification technique might be used to test a concave mirror system.
47. A technician used the reciprocal magnification technique to test a lens. She measured the system magnification as 4.0 and the EFL of the optical system under test as 80 mm. Referring to Figure 2-14, find the distance d.
48. The objective lens of a traveling microscope has a numerical aperture of 0.15. It is being used to test a mirror system with a clear aperture of 30 mm and a focal length of 75 mm.

Explain why a different microscope objective might be desirable. What are the parameters of the objective that should be selected?

49. While performing the Foucault test of a positive lens, the shadow of the knife edge moves in the same direction as the knife itself. Is the knife inside focus (between the lens and its focal spot) or outside focus (between the focal spot and the screen)?

50. While a technician is performing the Foucault test of a positive lens, a 13 µm motion of the knife edge completely blocks the 532 nm light. The technician deems the lens to have diffraction-limited performance. Estimate the f-number of the lens.

51. You are asked to profile the focal spot of an optical system that operates at F/3.85 for NIR light. Explain why a beam-profiling camera with 50 µm pixels will not suffice for this test.

52. A quad-cell detector is used to measure subaperture tilts, and the spot is located so that cells (pixels) B and D measure equal power. What is the y-tilt?

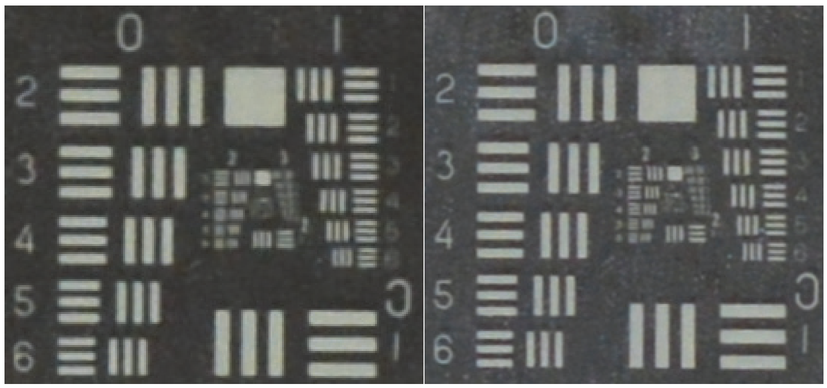
53. A quad-cell detector with 20 µm pixels is used to measure subaperture tilts. Explain why the f-number of the lenslets should exceed 17.4 to adequately make these measurements using 473 nm light

54. A single-point diamond tip (SPDT) was used to turn an aluminum mirror to its optical shape, leaving the optical surface covered in concentric ridges. How will this fabrication technique likely manifest itself on the MTF curve? That is, how will its MTF curve be diminished from diffraction-limited performance?

ADVANCED PROBLEM EXERCISES

55. Derive the formula for reciprocal magnification.

56. The images below show what this AF Bar Chart will look like when imaged through an actual optical system—the camera used to take these pictures. Explain why the image of the AF resolution chart on the right shows better optical performance than the AF resolution chart on the left.



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Using Interferometry to Measure Precision Optics

Module 3

of

Metrology of Optical Systems

PRECISION OPTICS SERIES

National Center for Optics and Photonics Education

Preface to Module 3

This is the third module in the *Metrology of Optical Systems* course. This course is designed for students seeking a basic understanding of the optical system measurement and testing techniques used to determine the overall quality of an optical system's performance. It presents a comprehensive review of measurement practices essential to ensuring the quality of optical systems. The course was designed to comply with the second edition of the *National Precision Optics Skill Standards for Technicians*.

Module 3, *Using Interferometry to Measure Precision Optics*, addresses interferometer-based measurements that describe the performance of an optical system. Topics include interferometric theory and techniques, light interference, reference optics, and test beam formatting. Additional interferometer topics include test setups, evaluation metrics, typical configurations, commercial systems, and measurement artifacts, along with first-, third-, and higher order alignment aberrations. Other interferometry topics discussed include displacement-measuring interferometers, laser tracker systems, interferometric sensors, and holographic interferometry.

The material in this course includes technical terms and measurement techniques that are often unique to the field of precision optics. To make certain that students have the vocabulary necessary to understand the concepts presented, a glossary of technical terms and scientific concepts is included at the end of the course. We highly recommend that you review this glossary before moving forward in this module. Terms in the glossary are italicized throughout the course material.

CONTENTS OF MODULE 3

Introduction 1
Prerequisites 1
Objectives 2
Scenario 3
Basic Concepts 4
  Using Interferometry to Measure Optical Systems 4
    Interference of Light 4
    Reference Optics for Spherical Wavefronts 6
    Reference Optics for Aspheres and Freeform Optics 7
    Test-Beam Formatting 9
  Using Interferometers for wavefront error metrology 11
    Interferogram Interpretation 11
    Interferometric Test Setups and their Scale Factors 12
    Beamsplitters 21
    Path-Shifting versus Wavelength-Shifting Interferometry 23
    Lateral Resolution of Interferograms 23
    Evaluation Metrics for Interferograms 23
    Using Interferograms to Measure Other Optical System Parameters 27
    Typical Interferometer Configurations 28
    Autostigmatic Testing of Aspheres 33
    Commercial Interferometer Systems 34
  Aberrations Observed during Interferometric Alignment 36
    First-Order Aberrations 36
    Third-Order Aberrations 38
    Higher-Order and Mount-Induced Aberrations 40
    Measurement Artifacts 40
  Other Applications of Interferometry 41
    Displacement-Measuring Interferometers (DMIs) and Laser Tracker Systems 41
    Interferometric Sensors 41
    Holographic Interferometry 41
Laboratories 43
Problem Exercises and Questions 47
Advanced Problem Exercises and Questions 49
References 50

Module 3
Using Interferometry to Measure Precision Optics

INTRODUCTION

The interferometer is arguably the most important and sensitive measurement system in common use, particularly for optical testing. To assess the performance of an optical system, the interferometer is an industry standard. A variety of interferometer sizes and configurations are available to test the wavefront through different types of optical systems. This module will start with the basic phenomenon of interference and lead the student to learn how this powerful, yet fundamental, principle is applied to make high-precision measurements of optical systems.

PREREQUISITES

OP-TEC *Fundamentals of Light and Lasers*: Modules 1-1, 1-2, 1-4, 1-5

OP-TEC *Quality Assurance of Precision Optics*: Modules QAPO-1 and QAPO-2

OP-TEC *Metrology of Optical Systems*: Module MOS-1

Students should be able to calculate ratios and angles, apply scientific notation, perform dimensional analyses of units, understand use of geometric equations to describe conic sections (parabolas, ellipses, etc.) Course prerequisites include high school algebra, geometry, and college algebra.

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OBJECTIVES

- Read and interpret technical drawings and specifications.
- Conduct optical metrology measurements and inspections for in-process work and final distribution
- Coordinate with quality assurance to ensure compliance to design specifications and documentation requirements
- Participate in the development of inspection plans that use the appropriate metrology for all measured specifications
- Test finished components by appropriate means, including test place or interferometric techniques, to ensure compliance with design specifications
- Use collimator or interferometer to measure focal length and on-axis aberrations
- Measure surface roughness using white-light interferometry or other optical means
- Use written instructions and specifications to determine and select appropriate packaging for protecting, storing, and shipping optics
- Document final inspection results according to instructions, procedures, and/or specifications to close-out job jacket or equivalent
- Maintain NIST-certified calibration standards and samples, use proper procedures to calibrate all-optical instruments, and maintain a calibration log
- Use statistical process control guidelines to sample finished components

SCENARIO

Three similar secondary mirrors were ordered for a telescope to be used in an aerospace application. Laura's job is to select the best of these mirrors to assemble into the final system. The vendor delivered the mirrors with a set of measured interferograms for each mirror. After inspecting their measurements, it was clear to Laura that all mirrors met the requirements for peak-to-valley reflected wavefront error and coating durability, but serial number 1 had a root-mean-square wavefront error that was a factor of three better than the other two mirrors. She knew this was likely the optimal mirror to select because she had learned in OP-TEC's Metrology of Optical Systems course that peak-to-valley was not the ideal metric of a high-quality transmitted wavefront. She knew she also had to examine the mirrors' measured roughness and mid-spatial frequency error parameters before selecting the best mirror of the lot.

Basic Concepts

Using Interferometry to Measure Optical Systems

An optical system is designed to perfectly transfer, via transmission or reflection, an optical wavefront of light from a source to a detector, from an object to an image, or from one optical system to another. There are countless ways to diminish the quality of an optical wavefront, thereby creating flaws known as aberrations or wavefront errors (WFEs)—deviations from a mathematically perfect wavefront. Though designers strive for perfection, some optical designs have residual aberrations. WFEs can be ingrained into an optical system during its manufacturing and alignment processes. If these generation processes are not conducted precisely, the system will impose deviations from the perfect wavefront intended by the design. Even the atmosphere through which light propagates will aberrate the wavefront. For these reasons, it is important to measure an optical system's WFE during its manufacture, alignment, and application. An entire optical wavefront can be tested by means of optical interferometry, an accurate, non-contact optical-testing technology.

Interference of Light

When two or more coherent waves exist in the same place at the same time, they interfere with each other. Wave crests (or troughs) constructively interfere with other wave crests (or troughs, respectively), and wave troughs destructively interfere with wave crests. Light waves interfere like any wave, including all electromagnetic waves, liquid surface waves, and even acoustic waves. Constructive interference of light waves results in a local bright region, while destructive interference of light leads to a local dark region. Between the brightest bright of constructive interference and the darkest dark of destructive interference lie all "shades of gray" (which are actually shades or saturation levels of the color of the interfering light). Each region of transition from brightness to darkness is known as a *fringe*; many fringes manifest as curvy bands across the plane of interference.

Equation 3-1 gives the formula that describes the interference of two light beams. The first two terms are the irradiance (***E***) values of each individual interfering light wave (wave 1 and wave 2, in this case). Optical detectors can detect only the power or irradiance (power per area) of the light beam, so irradiance is most often used to describe interference. (Irradiance is often incorrectly called "intensity," but intensity is a different radiometric quantity that describes units of power per solid angle. Intensity may also be used in this formula, but in application, irradiance is most common.) During an interferometric test, the first term represents the irradiance from the optical system or surface under test, and the second term represents the irradiance from a calibrated ("ideal") reference wavefront. The phase difference between the two wavefronts of light leads to the interference term, which is the third term of Equation 3-1.

$$\boldsymbol{E_{interference}} = \boldsymbol{E_1} + \boldsymbol{E_2} + \boldsymbol{2 \cdot V} \cdot \sqrt{\boldsymbol{E_1 E_2}}\,\boldsymbol{cos}(\Delta\boldsymbol{\phi}) \qquad (3\text{-}1)$$

When using interferometry to test optical systems, it is important to include the brightest bright regions and the darkest dark regions (and all the shades in between) to give the measurement the most dynamic range possible—this is known as *fringe visibility or fringe contrast*, and it provides the term ***V*** in Equation 3-1. Ideal contrast of 100% modulation is possible only when the irradiance of both beams is equal. Fringe visibility is actually represented by the same formula, Equation 3-2, as the equation for modulation transfer function (MTF).

$$\textit{modulation} \text{ or } \textit{visibility} \text{ or } \textit{contrast} = V = \frac{(E_{max} - E_{min})}{(E_{max} + E_{min})} \qquad (3\text{-}2)$$

Notice that if both beams have equal irradiance, the fringe visibility equals one. Recall from Module 2-1 that the phase difference between two wavefronts is given by the optical path difference (OPD) that the two light sources traveled, as in Equation 3-3.

$$\Delta\boldsymbol{\phi} = \frac{\mathbf{2\pi}}{\boldsymbol{\lambda}}\, \boldsymbol{OPD} = \frac{\mathbf{2\pi}}{\boldsymbol{\lambda}}(\boldsymbol{n_2 d_2} - \boldsymbol{n_1 d_1}) \qquad (3\text{-}3)$$

Therefore, most modern optical systems that measure interference—so-called interferometers—do so by inducing a phase shift between the wavefront being tested and a reference wavefront. The reference wavefront provides an OPD to the test wavefront, so it should be a *best-fit sphere* to the test wavefront so that the OPD is minimized. That is, the reference wavefront should closely match the test wavefront. A collimated (flat) reference wavefront should not be used to a test a wavefront with a 100 mm radius of curvature (ROC), because the resulting OPD would be unnecessarily large toward its periphery. If the calibrated best-fit reference sphere (sometimes called a "master") has an ROC equal to 100 mm, then the measured OPD best represents the aberrations of the test wavefront with a nominal ROC of 100 mm.

Lasers or filtered spectral-line sources are used in interferometers because a long temporal coherence length is necessary to test optics when the reference and test beam paths are unequal. For example, a helium-neon (HeNe) laser, the most common interferometer laser, has a coherence length greater than 10 meters, and a filtered mercury-vapor lamp, the common interferometer source before the invention of lasers, has a coherence length on the order of millimeters. Laser diodes require special stabilization to be used as interferometer lasers, since their temporal coherence lengths are typically sub-millimeter. When conducting an interferometric test, it is essential to know the source's coherence length because it determines the maximum OPD allowed between the calibrated, best-fit reference wavefront and the test wavefront. Some optical systems require the test beam to traverse many optical surfaces over a long path, while the reference-beam path is short, contained inside a small cavity near the source. The difference between these paths cannot exceed the coherence length of the laser. Interferometers lasers are typically unpolarized so that the test and reference beams will interfere even if the optical system under test induces polarization-state changes to the light (which can happen upon reflection off many coated optics and all uncoated optics).

When one beam of light interferes with another, the phase difference between the two beams determines whether the interference creates a bright or dark interference spot. However, an entire wavefront of light can have a diameter that measures a few millimeters (for microoptics or narrow laser beams) or many meters (for large telescopes and optical lithography steppers). This leads to an interference distribution across the entire wavefront's diameter. This distribution is known as an *interferogram* or a *fringe pattern*. A typical interferogram is shown in Figure 3-1. Each band from bright to dark is called a *fringe*. Like the height-contour maps that mountaineers use, fringes represent phase differences across the wavefront—the OPD is constant along each fringe. The next section examines interferograms in detail. Fewer fringes represent less total OPD across the aperture tested and a "flatter" wavefront. "Flat" is a term commonly used to describe high-quality interferograms, but it does not mean that the test wavefront is actually flat, only that its deviation from the best-fit reference sphere is minimal.

Optimal interference is obtained when a single fringe exists across the entire interferogram—this is known as a *null* fringe.

Figure 3-1 *The brightest regions are those of complete constructive interference, and the darkest regions are those of complete destructive interference, varying through all of the shades of lightness in between. When cast on a screen, the bright regions will be the color of the laser source used to create the interferogram and the dark regions will be dark. However, most interferometer detectors output fringe data as grayscale plots like this, or they might output false-color plots that grade the amount of OPD by color.*

Reference Optics for Spherical Wavefronts

To use interferometry to test an optical system, two wavefronts must interfere. (Multiple wavefronts certainly may inadvertently interfere, but two wavefronts provide the most easily interpreted measurements.) The wavefront required for interferometric testing is the wavefront that traverses the optical system itself—this is the wavefront being measured, the test wavefront. The second wavefront is the reference wavefront; this comes from an ideal *reference optic* that is external to the optical system under test. This wavefront is usually a spherical wavefront that represents the best-fit sphere to the test wavefront. It is produced by an optical system that creates a diffraction-limited point source. If a planar reference wavefront is desired, it can be produced by a diffraction-limited collimated source (a planar wavefront is a spherical wavefront with an infinite ROC). The quality of the reference optic limits the accuracy of an interferometric test, so a reference optic must be precisely calibrated to demanding standards, often traceable to a national standards laboratory, such as the United States National Institute for Standards and Technology (NIST), or another authority in measurement precision. All surfaces of a reference optic must be high quality, but one particular surface of the reference optic is measured and calibrated to provide the diffraction-limited reference wavefront. This ideal wavefront will interfere with and therefore be compared with the wavefront from the optical system under test. The interferometric measurement will contain information about both wavefronts, but the influence of a well-made, calibrated reference optic's wavefront is (should be) negligible, so the measured interferogram represents the wavefront of the optical system under test.

Reference optics come in many shapes and sizes, and the appropriate one to use depends on the optical configuration required by the optical system under test. It is the final surface of the reference optic (the surface closest to the test setup) that is ultimately compared to the optic under test. The reference optic should match not only the radius, but also the f-number (or, equivalently, the numerical aperture) of the wavefront that is emitted from the optical system under test. For instance, optics that output collimated wavefronts require flat reference optics, so the reference optic should be a planar surface. Components including flat mirrors, multi-surface windows, beamsplitters, prisms, and retroreflectors are all tested using a planar reference optic. This reference element is typically called a *transmission flat* (TF) when used with an interferometer. Optical systems designed to produce collimated output (afocal) systems are also tested using a planar reference optic. When testing optical systems with collimated output, the size of the planar reference optic's aperture should be equal to or larger than the beam diameter output from or input to the optical system under test, so that its entire clear aperture is measured.

Accurate interferometric measurement of optical systems that produce converging and diverging spherical wavefronts require spherically curved reference optics. When measuring curved, spherical wavefronts, it is essential to align the center of curvature of the reference optic to the center of curvature of the wavefront input to or output from the optical system under test. Precision optics manufacturers may maintain an inventory of curved reference optics called *test plates* that are common for testing individual optical surface shapes, as discussed in QAPO 1-1. But an assembled optical system should have its output wavefront interferometrically compared with a calibrated *reference sphere*, often called a *transmission sphere* (TS) when used with a commercial interferometer. Reference spheres may operate in transmission, by creating a curved wavefront that matches the wavefront input to the optical system under test, or they may operate in reflection, shaped and aligned to match the wavefront output from the optical system under test. Reference spheres may be precision spherical mirrors or lenses, or they may be actual spheres used as mirrors, such as precision ball bearings composed of a durable, stable material such as silicon nitride. For an optical system that produces a converging output wavefront, the reflective reference sphere may have calibrated a convex or a concave surface, depending on whether the reference is placed before (convex) or after (concave) the converging light going through focus. For a diverging optical system, the calibrated reflective reference must be concave and aligned to its focus (which will be virtual).

When testing curved wavefronts, the size of the reference sphere only has to be as large as the beam diameter at the location where the reference optic is aligned. For example, if an optical system that has a 50 mm clear aperture and a 100 mm EFL (thereby operating at F/2) is tested using a reference sphere with a 10 mm ROC, the reference sphere only has to have a 5 mm calibrated aperture to reflect the entire wavefront under test. It is properly aligned when its center of curvature is located at the focus of the optical system under test so that all rays are normally incident on its surface.

Reference Optics for Aspheres and Freeform Optics

When testing optical surfaces that are more complex than spherical shapes, such as aspheres and freeform optical surfaces, special optics are required to manipulate the reference and/or test beams. For aspheres that are nearly spheres, a spherical reference optic may be used as described above, and the asphere's departure from that best-fit sphere will be measured via interferometry.

Particular aspherical shapes can be configured for test in a way that uses their geometrical properties as the basis of the test configuration. These techniques use the focal points for each aspherical shape, as shown in the following figures. Each asphere has its own unique geometrical properties. To test an asphere, a point source (which emits a spherical wavefront) must be precisely located at the asphere's focus. Ellipsoids and hyperboloids have two foci, as shown in Figures 3-2 and 3-3, so a point source located at one focus will produce a point image at the other. These are difficult tests because it is often difficult to position a point source at one focus while retaining access to the other focus. However, the image formed can be tested using a PSF-metrology technique, as discussed in Module 2-2, or a spherical mirror can be used to reflect the image back to the surface and then to the interferometer, in a double-pass configuration. This technique is described below, in a discussion of null optics—custom beam-formatting optics must be used to modify the *test* beam.

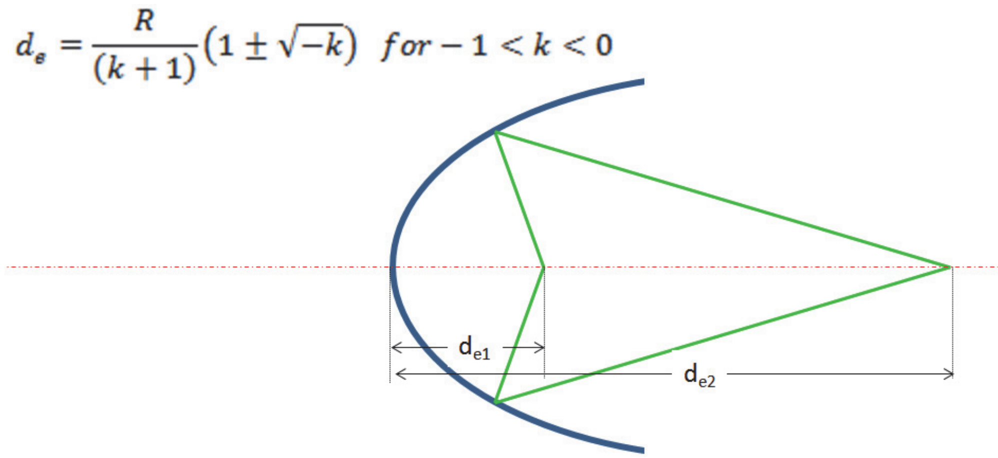


Figure 3-2 *The foci of an ellipsoid are located at d_{e1} and d_{e2}. Note that it is difficult to position a point source at one of these foci while retaining access to the other focus.*

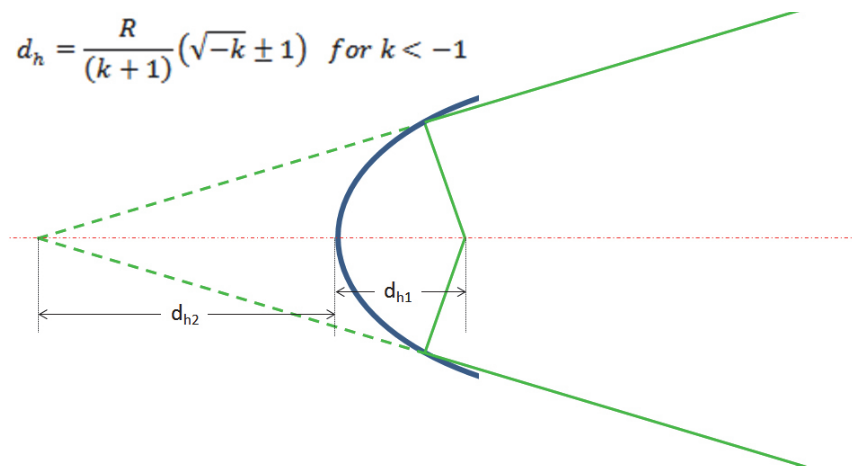


Figure 3-3 *The foci of a hyperboloid are located at d_{h1} and d_{h2}. Note that it is difficult to position a point source at one of these foci while retaining access to the other focus.*

Paraboloids are unique in that they have one focus located at optical infinity. This means that a collimated source may be used to test a paraboloid, or a spherical point source may be created at its finite focus and the paraboloid's wavefront tested via its collimated output, as shown in Figure 3-4. Both types of test are accomplished in a double-pass configuration.

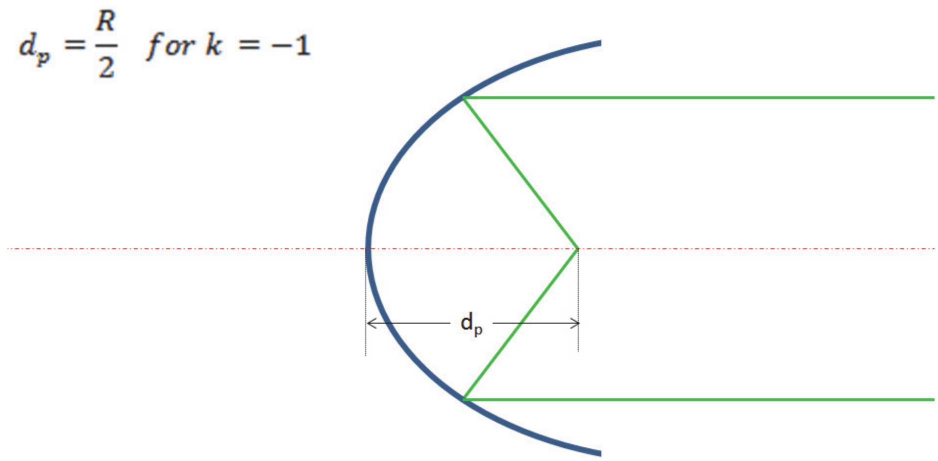


Figure 3-4 *The foci of a paraboloid are located at half the radius, R, of the best-fit sphere and at infinity. Note that a point source can be located at the finite focus and the paraboloid can be tested via the reflected, collimated light with only a minor obscuration of its clear aperture. Alternatively, a collimated input can be used to test a paraboloidal surface if the source is reflected by a spherical reflector centered at the paraboloid's finite focus.*

The distance, d_{foci}, to the foci of an asphere, given its conic constant, k, and it radius of curvature, R, is given by Equations 3-4, 3-5, and 3-6. These formulas are useful when locating foci and spacing optics within interferometric test setups.

$$d_p = \frac{R}{2}\ for\ k = -1 \qquad \text{(3-4, paraboloid focus)}$$

$$d_h = \frac{R}{(k+1)}\left(\sqrt{-k} \pm 1\right)\ for\ k < -1 \qquad \text{(3-5, hyperboloid focus)}$$

$$d_e = \frac{R}{(k+1)}\left(1 \pm \sqrt{-k}\right)\ for -1 < k < 0 \qquad \text{(3-6, ellipsoid focus)}$$

Test-Beam Formatting

Reference optics produce diffraction-limited wavefronts that are planar or spherical and intended to interfere with the wavefront output by the optical system or surface under test. In many cases, the interferometer output used to create the test beam must be formatted to match a complex optical surface shape or output wavefront.

One type of specialty optic that alters the test beam is called a *null optic* or *null lens*. It is fabricated to the optical shape required to produce a null interferogram—one that is perfectly aligned, with zero high-order fringes. Spherical surfaces may be used to make the null lens, so that the test wavefront will produce an interferogram that contains only the first-order aberrations of defocus and/or tilt when it reflects from or transmits through the asphere under test. Null lenses are expensive to make because they must be extremely precise and are custom-built for each asphere. This makes other test techniques more desirable.

A certain type of null optic, the Hindle sphere (sometimes Hindle shell), presents a creative way to test an asphere. Hindle spheres are concave or convex spherical mirrors used to test a subaperture of a convex or concave asphere surface that is hyperboloidal or ellipsoidal. Hindle spheres must be positioned to locate their center of curvature at one focus of the asphere under test, while a point source from an interferometer is positioned its other focus. Hindle spheres have a disadvantage in that they may need to be very large to test a full clear aperture. Alternatively, they may be constructed to test only a part of the optic's clear aperture—a *subaperture*. Then the subaperture measurements may be stitched together to recreate the entire surface or wavefront measurement. Wavefront stitching of this nature has been commercialized, creating a powerful technique by which large test apertures can be measured using an interferometer with a smaller reference aperture. Wavefront stitching is performed within the interferometer software after multiple overlapping measurements across a large surface have been made.

A powerful null-test technique that has become an industry standard uses a *computer-generated hologram* (CGH) null optic to create the required test wavefront via diffraction. The CGH is located in an interferometer's path at a prescribed distance from the optical system under test. (Equations 3-4 through 3-6 are often used to help design and locate the CGH.) The interferometer's light is then diffracted into a wavefront that is matched to the optical system or surface under test, and the first diffraction order (m = +1) is used for the test. Since diffraction forms multiple beamlets, this diffraction order has to be diffracted to a large enough angle so that it can be spatially filtered (separated) from the other orders using an iris aperture before it is directed to the optical surface or system under test.

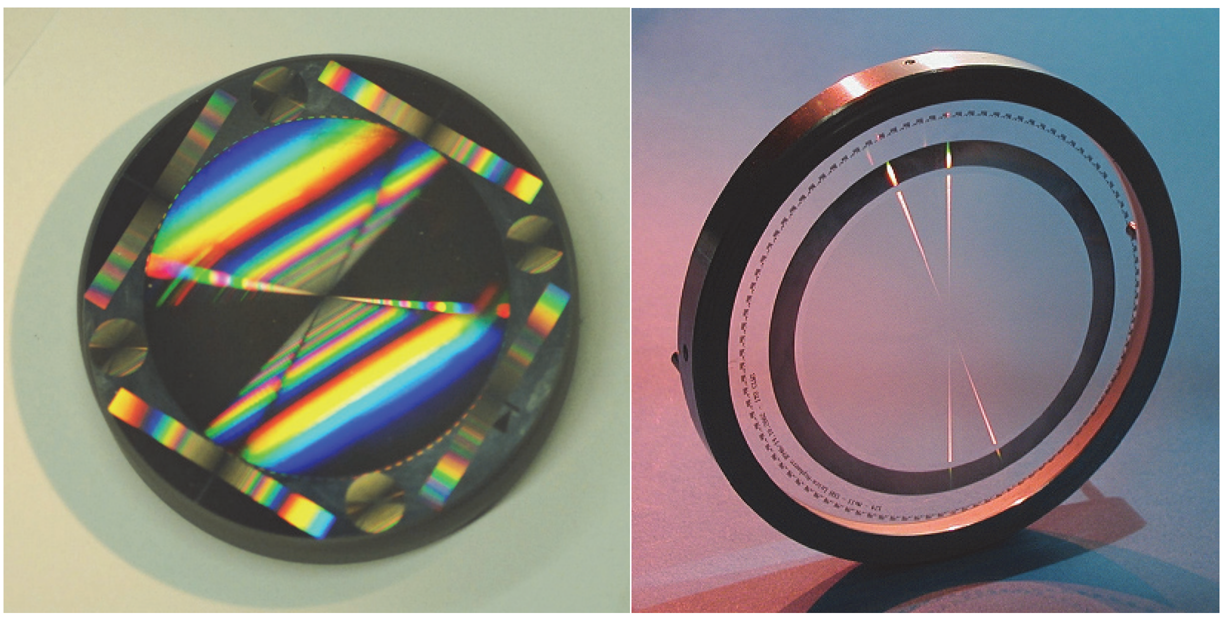


Figure 3-5 *These are photos of two different CGHs. These diffractive optical elements shape a reference beam in an interferometer application.*

CGHs can be manufactured as amplitude or phase-diffraction gratings. The former type is inefficient (~10%—that is, 90% of the light is lost to other orders and absorption), since it diffracts light using alternating strips of opaque (metal) and clear rulings. The latter type is a volume-diffraction grating operating at efficiencies around 40%. Phase-grating CGHs are more common for this reason. Amplitude-grating CGHs are created using optical or electron-beam lithography (such as a printed circuit board). Both types are written at line widths on the order of micrometers that are accurate to tens of nanometers.

Placing CGHs in a collimated beam space of an optical test setup makes the setup less sensitive to alignment errors. Though it is desirable to locate the CGH in a collimated beam, it is not always practical; often the CGH must be, by design for better diffraction efficiency, placed in a diverging or converging beam path. To ensure that proper element-to-element separations are attained during test, CGHs are delivered with detailed instructions that provide a step-by-step procedure by which to test the optical surface or system using the CGH. Most CGHs come with fiducial marks such as crosshairs, bull's-eye patterns, or other structures (located outside the clear aperture to be tested). These marks help CGHs achieve their precision alignment in an interferometer's beam.

When testing an asphere, the goal of a CGH, like any null test, is to produce the prescribed number of pure tilt and/or defocus fringes. CGHs are typically used to test single asphere surfaces, rather than entire optical systems, but some complex optical systems, such as optical relays, output wavefronts that may require an interferometer test beam shaped by a CGH.

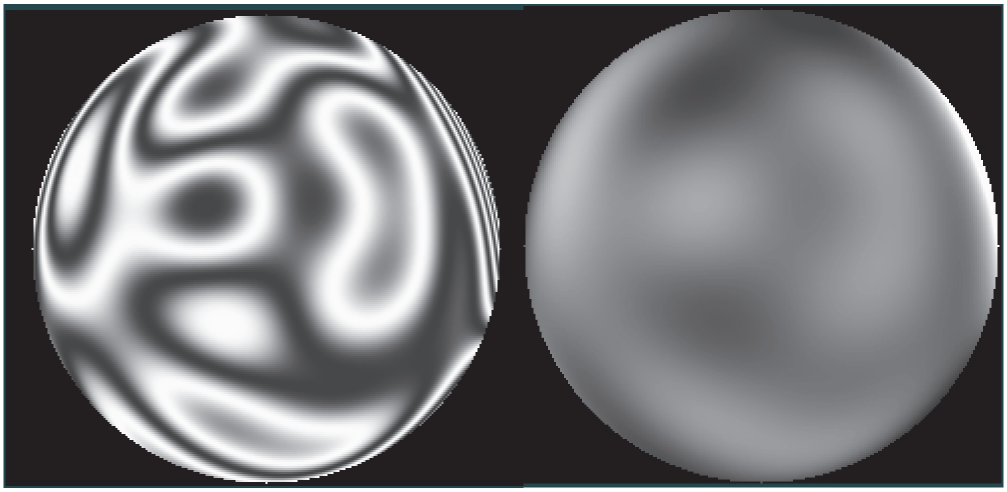
Using Interferometers for wavefront error metrology

Interferogram Interpretation

Interferometry may produce a number of different measurement results. If a single surface is directly measured, interferometry produces the *surface figure*. This may also be called the surface's *irregularity*, *flatness,* or *waviness*, and it is analogous to the topography of the surface—a direct map of the surface's ups and downs. When an optical system is measured, the *transmitted* or *reflected wavefront error* (TWFE or RWFE, sometimes TWE or RWE) of the entire system may be unveiled by the interferogram as the measurement result. At the most fundamental level, interferometry reveals phase relationships across a wavefront.

Accurate conversion of the striped fringe patterns shown in Figure 3-6 to a map of height differences that provides information about the measured wavefront or surface shape is an essential procedure in the practice of phase-shifting interferometric metrology. Before digital image processing was common, interferograms were interpreted into wavefronts by hand. Optical engineers used wire grids to help indicate the fringes' deviation from linear tilt fringes, thereby revealing the higher-order aberrations of the optical system. For this assessment, varying, known values of tilt were deliberately introduced during the measurement to help observe higher-order aberrations.

In modern interferometers, interferograms are captured by digital cameras, and the fringes are digitally *unwrapped* into wavefronts. This process is based on the fact that adjacent fringes are modulo 2π. That is, the fringes will repeat every cycle of the wavefront phase, which has a period of 2π radians. In effect, this is the *scale* of the interferogram fringe heights, just as a mountaineering map requires a contour scale. The fringes measured are interpreted by image-processing software and unwrapped to form a continuous surface, so that the fringes of Figure 3-6a reveal the actual measured wavefront of the optical system under test, shown in Figure 3-6b. Neighboring pixels are unwrapped so that they do not have a phase difference greater than π or, equivalently, an OPD of $\lambda/2$. It is helpful to think of this as a sequential "smoothing" of the interferogram from fringe contours into a wavefront. As each fringe changes from dark to light, the surface is unwrapped upward or downward (as determined by appropriate interpretation of neighboring fringes) to create a smooth map of the height differences across the wavefront or surface.



Figures 3-6a (left) and 3-6b (right) *The brightest regions now represent the highest parts of the wavefront or surface map, and the darkest regions represent the lowest parts of the map, varying through the shades of gray in between. However, most interferometer detectors output fringe data as false-color plots so that the shades of gray can be easily interpolated.*

Interferometric Test Setups and their Scale Factors

Interferometry is a powerful optical testing technique in that only two wavefronts need to interact, which allows for an accurate, non-contact measurement of a surface or system's optical quality. An interferometer measures a fringe map that is unwrapped and scaled to the measured wavefront's phase or a height difference. These fringe maps have different *scale factors* that depend on the interferometer's hardware configuration. Many types of interferometers can be configured to measure optical wavefronts. The following discussion describes these different interferometers' operation, gives their associated scale factors, and shows their layouts.

A Fizeau interferometer configuration (see Figure 3-7) is the most robust and common type of interferometer found on the optical fabrication shop floor and in an optical engineering lab. It is used in a Newton configuration to test single surfaces that are moderately curved or flat—many fringes result if the test surface is too steeply curved, and too many fringes cannot be resolved by eye. Its operational principle in this configuration is simple: an OPD is created between a well-calibrated master reference surface and the optical surface under test, which are in direct contact. The best measurement is when the reference closely matches the optical surface under test—when it truly is a best-fit sphere or flat. This creates radial fringes known as *Newton's rings*. These rings are used to determine a single optical surface's radius of curvature, *R*, by Equation 3-7.

$$R = \frac{r_m^2}{\lambda(m+{}^1/_2)} \qquad (3\text{-}7)$$

In this equation, m is the ring number and r_m is the radial distance from the center to ring m. The wavelength used to create the interference is given by λ. This creates a straightforward test for concavity: if the reference optic is pushed slightly and the fringes expand, then the optical surface under test is concave; if they contract, the surface is convex.

In an optical test that uses Newton's rings, the reference is often a test plate that has been fabricated and calibrated to an exact radius. The following equation, Equation 3-8, gives the difference, ΔR, between the radius of the test plate, R, and the radius of the surface under test. CA is the clear aperture of the optic under test.

$$\Delta R = \frac{4 \cdot m \cdot \lambda \cdot R^2}{CA^2} \tag{3-8}$$

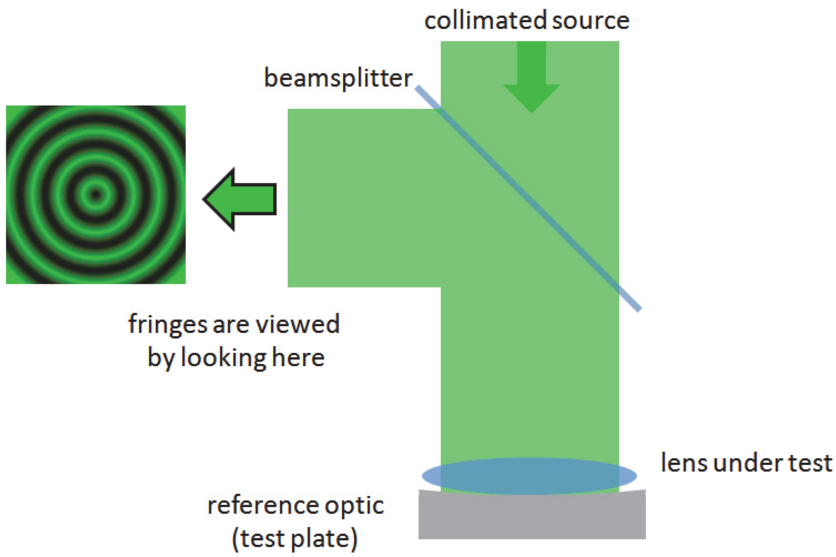


Figure 3-7 *As this schematic demonstrates, the Fizeau interferometer can be used to produce Newton's rings like those shown in the idealized interferogram.*

Newton's rings may be observed as linear fringes when testing flat optic (see Figures 3-8 and 3-9). In the Newton configuration, the OPD created between the reference and the test surface gives rise to fringes of spacing S. When optical measurements are made, small deviations in the straightness of the fringes, Δ, may be observed. The surface-height variation, h, induced by the defect is given by Equation 3-9.

$$h = \frac{\lambda}{2}\frac{\Delta}{S} \tag{3-9}$$

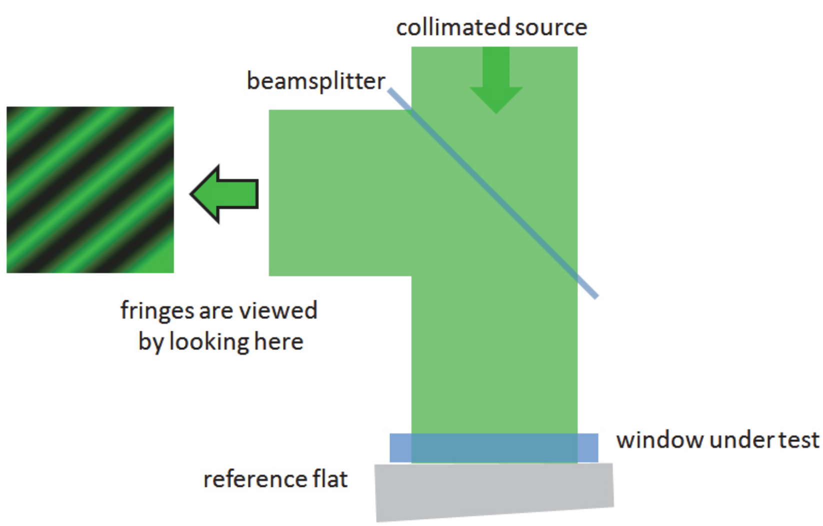


Figure 3-8 *As this schematic shows, the Fizeau interferometer can be used to test a window, producing linear fringes like those shown in the idealized interferogram. Figure 3-9 shows actual fringes*

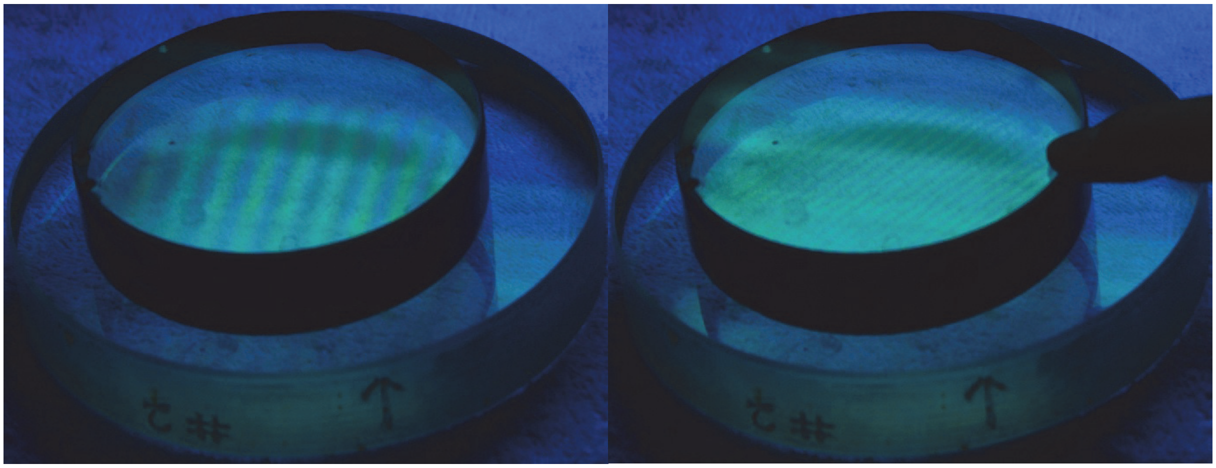
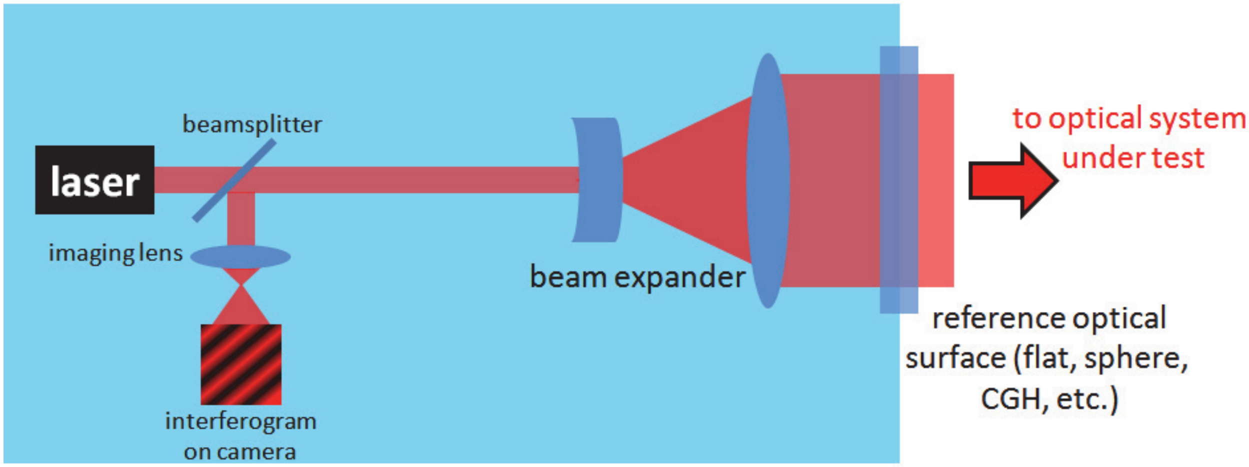


Figure 3-9 *These images show Newton's "rings" as parallel fringes between a calibrated reference flat and a (nearly) flat window. Additional tilt fringes are added in the figure on the right by lightly pressing on the optic under test. Additional fringes indicate that a greater optical path is created by pushing. If there was a surface-height defect of size h in the test surface, it would have created fringe deviation Δ, given fringe spacing S.*

In Equation 3-9, the factor $\lambda/2$ is the *scale factor* of the Fizeau interferometer in a Newton configuration. This is a conversion from the fringe count to the physical deviation/surface height error. A scale factor of $\lambda/2$ means that every fringe indicates a wavefront variation of $\lambda/2$. For example, with an interferometer that operates at $\lambda = 546$ nm, every fringe indicates a displacement of 273 nm.

Fizeau interferometers were used with filtered spectral-line sources for over forty years before the invention of the laser, but all modern Fizeau interferometers use stabilized laser sources for their long coherence length. The reference and test beam paths do not need to be equal length due to the long coherence length of the laser source. Helium-neon lasers at 632.8 nm are usually used, unless the application requires a particular wavelength. (For example, infrared laser-based interferometers may be used to test rough, ground surfaces, even *during* these coarse portions of the fabrication process. Carbon dioxide lasers at 10.6 μm may be used for these *in situ* tests.) Classic Fizeau/Newton interferograms are viewed by eye using mercury-vapor sources filtered to mercury vapor's green spectral e-line at 546.074 nm. Some optics-fabrication cleanrooms have their lights filtered to a particular wavelength to enable easy testing of freshly polished optics anywhere in the shop, without a custom test setup. Modern Fizeau systems use digital cameras to capture the interferogram created when the optical surface under test is compared with a calibrated reference.

Laser-based Fizeau interferometers can be used to test a much wider variety of optical surfaces, and they are the industry standard for interferometric testing of optical systems of almost any f-number. Figure 3-10 shows a schematic and a photo of a common Fizeau interferometer (the Zygo GPI). It can be used to test optical surfaces and mirrors after a single reflection or lenses and optical systems after a double-pass through the lens or system.



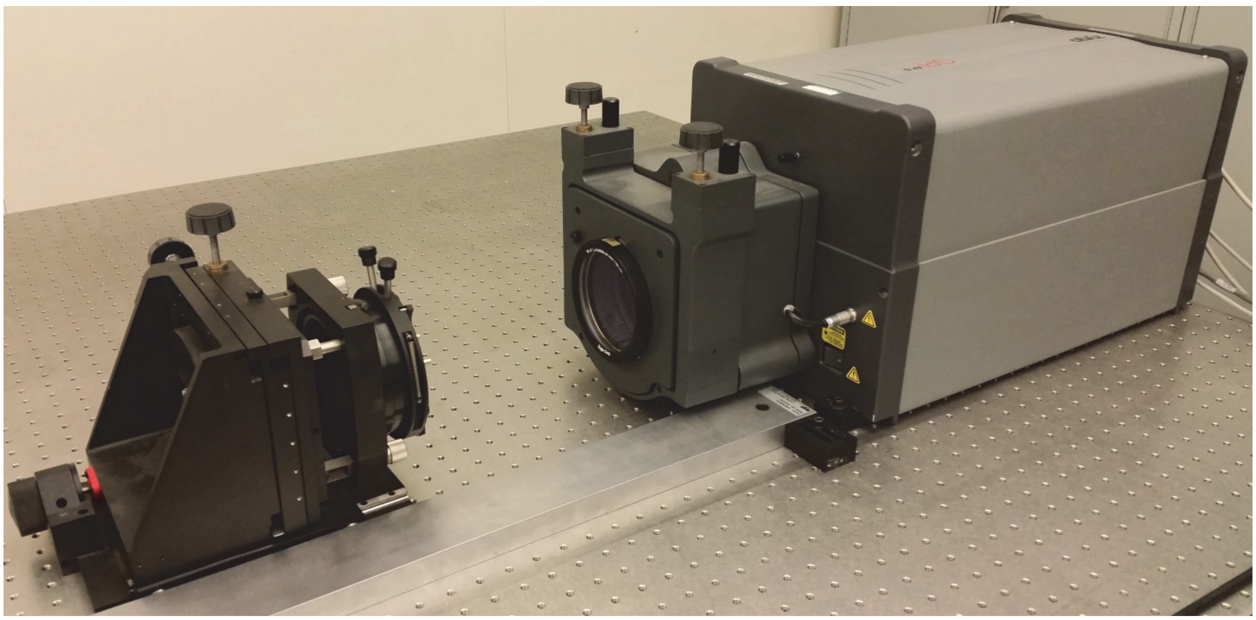


Figure 3-10 *The schematic (top) and the photograph (bottom) show that with a radial-slide module and three-point optic mount, the laser-based Fizeau interferometer can be used to test optical systems with long optical paths, even though the reference path is relatively short.*

Another useful type of interferometer is known as the Mach-Zehnder. Figures 3-11 and 3-12 show its basic layout using a laser source. It has an advantage when testing windows and optics at various angles of incidence. Figure 3-11 shows a reflective optic under test at 45°. A transmissive optical component or system can also be compared to a reference optic using a setup like the one shown in Figure 3-12. Note how the transmissive optics might be rotated to test arbitrary angles of incidence in this configuration.

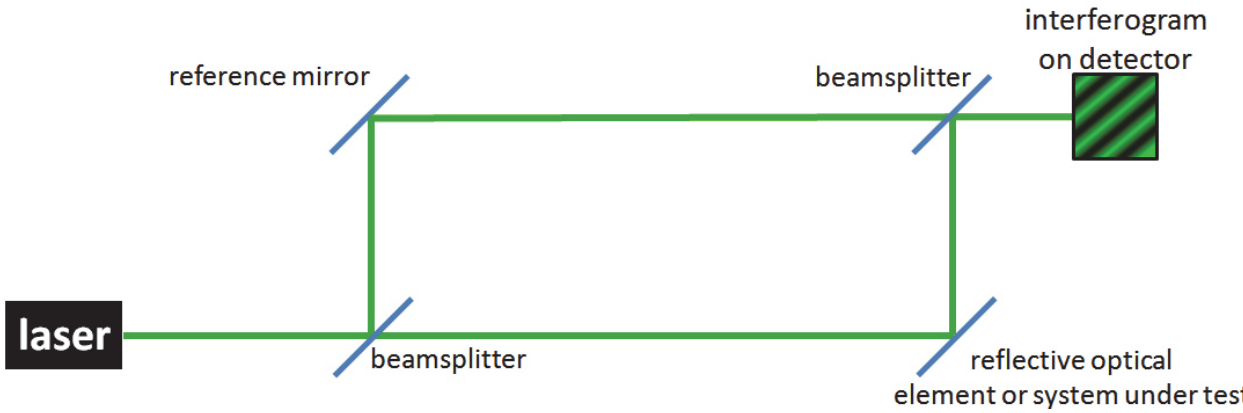


Figure 3-11 *This schematic shows a Mach-Zehnder interferometer used to test a reflective optical component or system.*

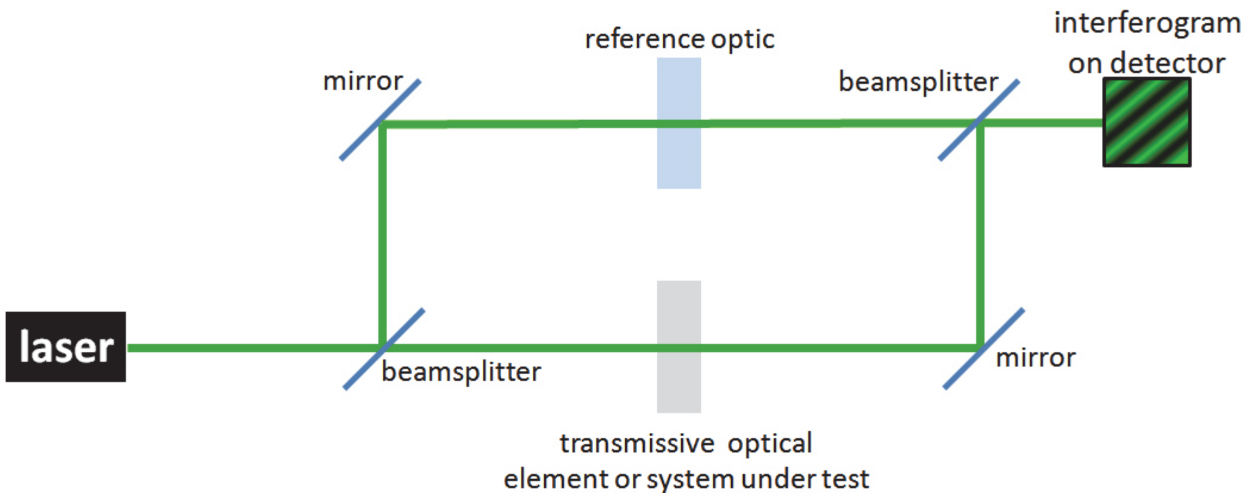


Figure 3-12 *This schematic shows a Mach-Zehnder interferometer used to test a transmissive optical component or system.*

To really understand the scale factor, it is necessary to count the number of times the light traverses the optical component or system under test. Most optical systems are tested in double pass—that is, the light is sent through the system twice. This may be necessary because the interferometer co-locates the light source and the detector, so the light must be returned to the interferometer beamsplitter.

In a single-pass configuration, an interferometer will have a scale factor so that each fringe measured equals one-half the wavelength of the light. In the double-pass configuration, each fringe measured equals one-quarter wavelength. For example, if five tilt fringes are measured across an interferogram in a single-reflection configuration of 632.8 nm light, this means that there is a height difference of 1.582 µm across the surface. In a double-pass configuration, an identical interferogram indicates a height difference of 791 nm across the surface.

Figure 3-13 shows interferometer scale factors for common test setups. For example, when measuring the wavefront of reflective optical systems in a double-pass configuration, every fringe equals one-quarter wave (1 fringe = $\lambda/4$). If an off-axis angle of incidence, θ, is tested, every fringe becomes equal to one-quarter wave divided by the cosine of θ, or 1 fringe = $\lambda/(4\cdot\cos\theta)$.

optical property measured	optic tested	interferometric test setup	interferogram scale factor
reflected wavefront error (RWFE)	reflective optcal component	normal angle of incidence θ = 0, single reflection (single pass)	**λ/2**
reflected wavefront error (RWFE)	reflective optical component	angle of incidence θ ≠ 0, single reflection (single pass)	**λ/(2·cosθ)**
reflected wavefront error (RWFE)	reflective optical system	normal angle of incidence θ = 0, double reflection (double pass)	**λ/4**
reflected wavefront error (RWFE)	reflective optical system	angle of incidence θ ≠ 0, double reflection (double pass)	**λ/(4·cosθ)**
transmitted wavefront error (TWFE)	transmissive optical component	normal angle of incidence θ = 0, single transmission (single pass)	**λ**
transmitted wavefront error (TWFE)	transmissive optical system	normal angle of incidence θ = 0, double transmission (double pass)	**λ/2**

Figure 3-13 *This chart shows the scale factors for common interferometer setups.*

Another simple, common interferometric configuration is known as the Michelson interferometer, shown in Figure 3-14. It creates interference by splitting a collimated, large-diameter laser beam into two paths, usually via a cube beamsplitter (though a pellicle or even a plate beamsplitter may be used with a compensator plate, as discussed in the discussion on beamsplitters below). The first beam continues through the beamsplitter, forming one “arm” or “wing” of the interferometer. The second beam reflects from the beamsplitter, forming the other arm. Along each arm, light interacts with mirrors that reflect the light back along the same path: the first beam now reflects off the beamsplitter and is directed to an detector plane; the second beam now transmits through the beamsplitter to the same detector plane, creating an interferogram in this plane. One of the mirrors will be translated along the beam path, creating a path shift between the two beams—this path shift manifests as a change in the interferograms fringe distribution. Any linear fringes represent the tilt between the two mirrors. Additional structure to the interferogram indicates other aberrations. For instance, concentric circular fringes (a focus aberration) indicate a curvature difference between the two mirrors.

The Michelson may be used to test flat mirrors, and it is often used as a sensor with its path-shifting mirror as the sensing element. It can also be applied as a sensor by measuring the optical properties of the beam path in one of its arms with respect to the other.

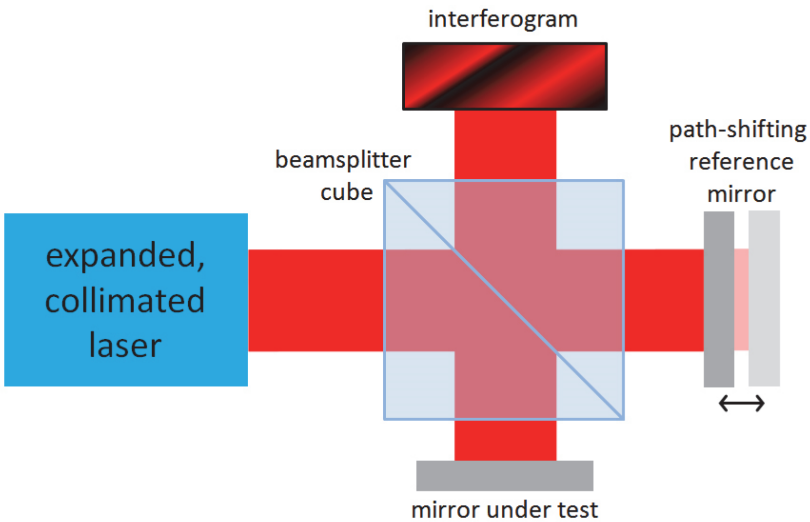


Figure 3-14 *The relatively simple layout of a Michelson interferometer usually uses an AR-coated cube beamsplitter. It can be applied in versatile ways, including as a sensor, where one arm of the interferometer may be used as the sensing element.*

A more useful configuration of the Michelson interferometer is known as the Twyman-Green interferometer. Though most commercial interferometer systems are laser-based Fizeau interferometers, custom Twyman-Green interferometers are quite versatile and are still used in industrial applications. They are also quite instructional and easy to configure in academic settings; Figure 3-15 shows the Twyman-Green interferometer layout. Like the Michelson, the reference beam is created by a flat mirror that allows for phase shifting by translation along the beam path. However, the mirror under test in the traditional Michelson is replaced by an optical system under test that may be reflective or transmissive, as long as the test beam is eventually returned to the interferometer by reflection. The beam returned must also match the wavefront curvature created by the reference mirror. In the case shown in Figure 3-15, the reference mirror returns a collimated wavefront from a flat mirror. In more complex configurations, curved test wavefronts may be measured using curved reference optics.

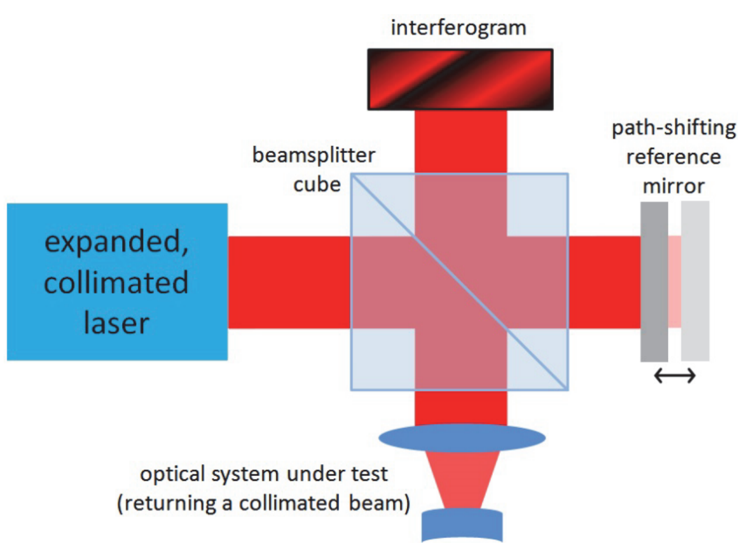


Figure 3-15 *This configuration of a Michelson interferometer is known as a Twyman-Green. This configuration allows the interferometer to test an arbitrary optical system that returns a wavefront that matches the wavefront of the reference (which, in the case shown, is a flat reference mirror).*

The Sagnac interferometer is a ring interferometer. It may be found in sensor applications, ring lasers, and fiber or laser gyroscopes. Figure 3-16 shows two configurations of a Sagnac interferometer: a three-mirror, square-loop interferometer (any number of mirrors may be used) and a fiber interferometer. In both cases, the source and the detector are located at the same point of the ring, and the source is split, traveling in both directions around the loop. If the interferometer is stationary, nothing interesting will happen: the light traveling around the loop in one direction has a zero OPD with respect to the light traveling around the loop in the other direction. However, when the loop is rotated, the light traveling in one direction increases in speed by a value equal to the ring's rotational speed, and light traveling in the other direction decreases by the same amount. This creates a phase shift between the two beams; it is the premise on which modern laser gyroscopes operate.

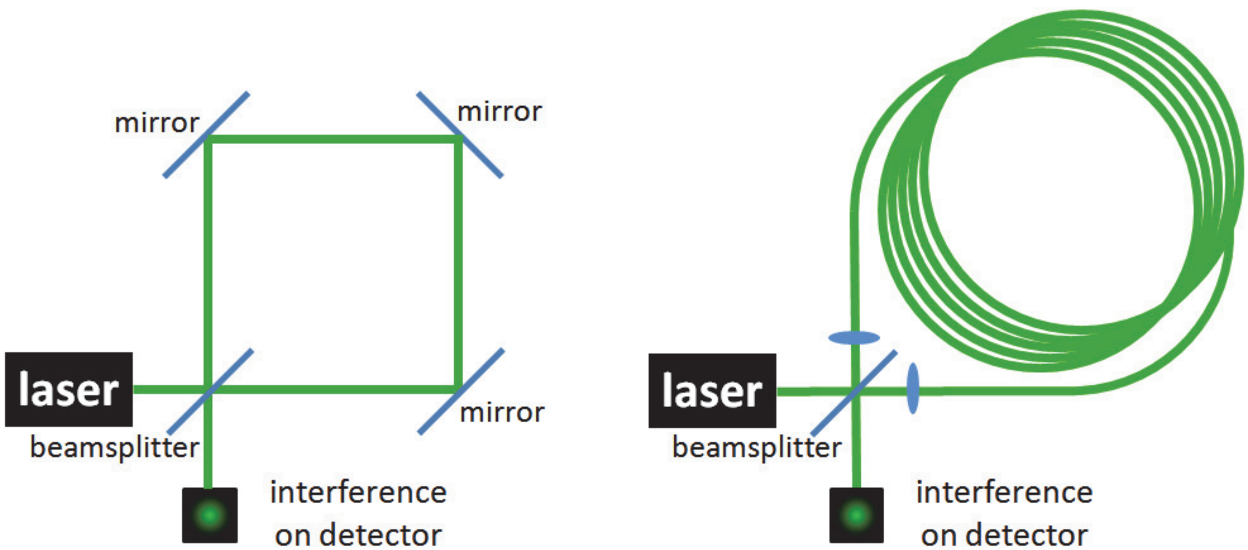


Figure 3-16 *The schematic on the left shows a three-mirror ring Sagnac interferometer, but any number of mirrors can be used to close the loop. The schematic on the right shows the Sagnac interferometer geometry as light propagates in opposite directions through a coil of optical fiber. Rotation of either ring creates a phase shift and, therefore, interference.*

The final type of interferometer that we will describe is shown in Figure 3-17, a schematic of a Fabry-Perot (F-P) interferometer or *etalon*. This interferometer exploits multiple-beam thin-layer interference effects. The light from one surface interferes with the light from a second surface placed in close proximity, creating fringes of equal chromatic order. Equation 3-10 describes the conditions required to create these fringes constructively: n is the refractive index of the gap between the etalon surfaces, θ is the light's angle of incidence, m is the order of the interference, and λ is the wavelength of light.

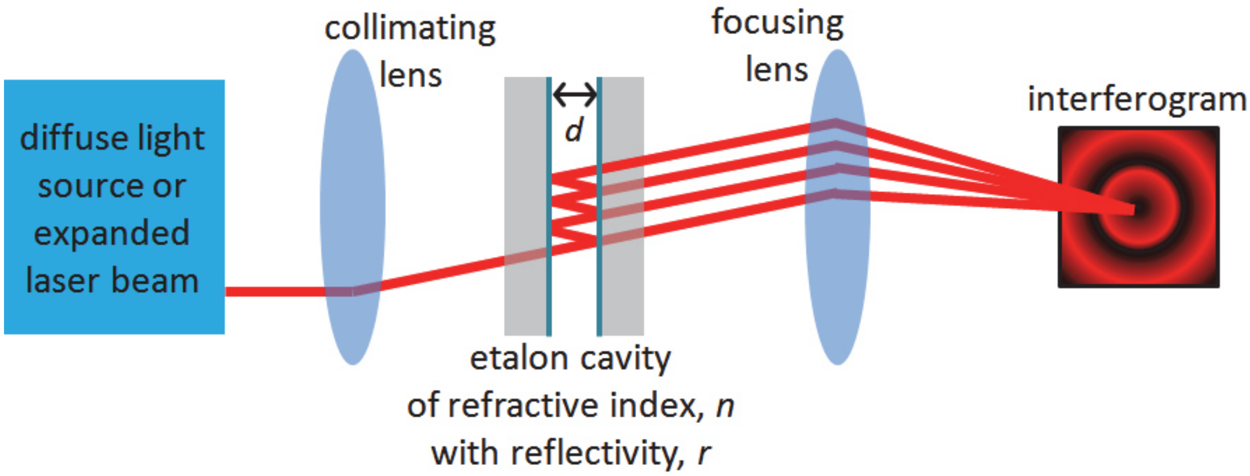


Figure 3-17 *An extended, diffuse source or an expanded laser can illuminate a Fabry-Perot interferometer (or etalon) cavity as shown, using a second lens to localize fringes on a screen.*

$$n \cdot d \cdot \cos\theta = \frac{m \cdot \lambda}{2} \quad (3\text{-}10)$$

Quite a few parameters are used to quantify the performance of a Fabry-Perot interferometer. The coefficient of finesse, shown in Equation 3-11, is not to be confused with the etalon's finesse of Equation 3-12. In both equations, *r* is the reflectivity of the etalon surfaces; therefore, these are both terms associated with the reflectivity of the etalon cavity. The next two equations define the etalon performance: Equation 3-13 gives the etalon's free spectral range (FSR): this parameter defines the separation of the spectral peaks resolved by the etalon, as shown in Figure 3-18. Finally, Equation 3-14 shows the relationship between the etalon's finesse, its FSR, and the full-width at half maximum (FWHM) of the spectral lines (Δλ). It is remarkable that all these parameters are derived from only the basic characteristics: the reflectivity (*r*), etalon spacing (*d*), and the refractive index (*n*).

$$F = \frac{4r}{(1-r)^2} \quad (3\text{-}11)$$

$$\mathcal{F} = \frac{\pi\sqrt{F}}{2} = \frac{\pi\sqrt{r}}{1-r} \quad (3\text{-}12)$$

$$FSR = \frac{\lambda^2}{2 \cdot n \cdot d} \quad (3\text{-}13)$$

$$\mathcal{F} = \frac{FSR}{\Delta\lambda} \quad (3\text{-}14)$$

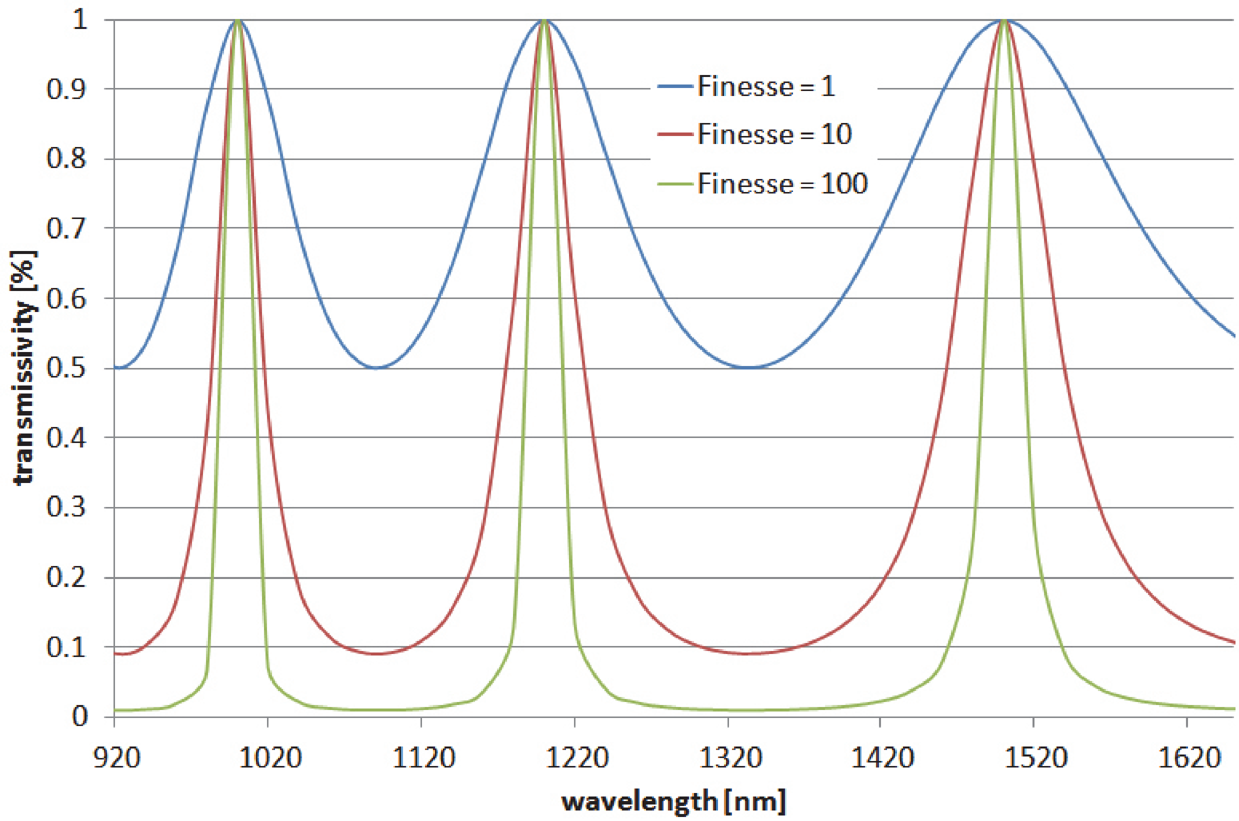


Figure 3-18 *These plots show the characteristic performance of an etalon for various values of finesse from 1 to 100. It is evident that the higher the finesse, the narrower the spectral resolution. However, higher finesse leads to lower light transmission.*

Fabry-Perot etalons have a variety of applications, typically related to spectrometry and sensing. They can be used to create very narrow bandpass filters, laser cavities, and wavemeters, and they are the heart of high-resolution spectrometers because they allow spectral resolution down to femtometers. They are used to sense changes in pressure and electrical characteristics when the etalon spacing is changed by application of a voltage (usually via a piezoelectric transducer).

Beamsplitters

To better understand the internal components of interferometers, it is helpful to understand that the *beamsplitter* plays an essential role in all interferometers: it splits the power (amplitude) of the interferometer's laser light in (at least) two directions. Beamsplitters may also be coated to act as out-of-band rejection filters, mitigating stray light.

There are three types of beamsplitters commonly used in interferometers: the cube beamsplitter, the plate beamsplitter, and the pellicle beamsplitter, as shown in Figure 3-19. Each has its own features and drawbacks. Diffraction gratings may be used as beamsplitters, but they are not common in interferometry, aside from the application of CGHs (which are diffractive holograms).

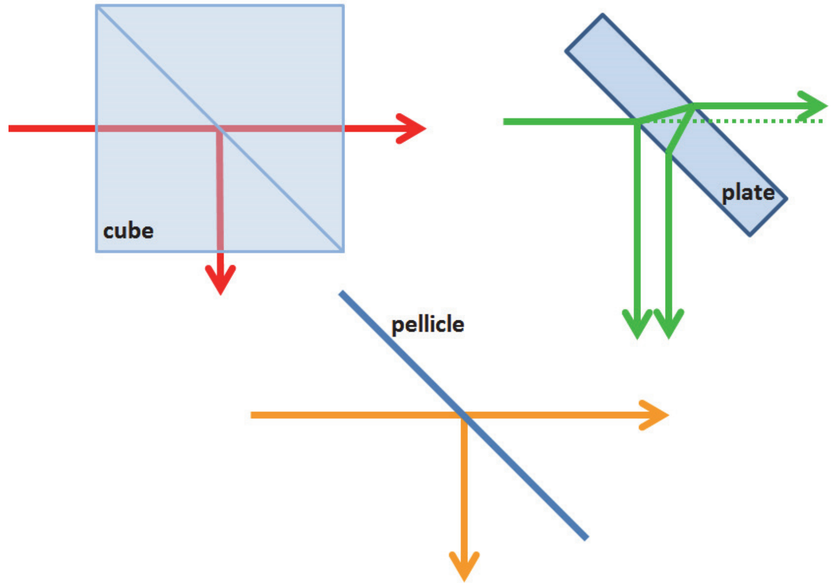


Figure 3-19 *This schematic shows three types of beamsplitters common to interferometers: cube, plate, and pellicle.*

Cube beamsplitters are composed of two solid right-angle prisms that are optically bonded (cemented) together. This solid, robust construction allows the beam to be split without deviating it from its initial direction. However, these consume more space in an optical system than the other options, and they must be made with extreme precision to ensure that the optical path lengths are equal in each direction. A portion of the incident is also reflected back to the source, off the front and back surfaces of the cube beamsplitter. Antireflective (AR) coatings can reduce this. Cube beamsplitters can be polarizing, reflecting s-polarized light at 90° while transmitting p-polarized light. So-called polarizing beamsplitters (PBS) can be combined with waveplates to control the polarization state of the light used for the optical metrology.

Plate beamsplitters are optical windows with parallel or wedged surfaces. They have two effects that must be considered in implementation: (1) they necessarily split the beam into three beamlets (one transmitted and two reflected), and (2) they displace the beam with respect to the incident beam direction as indicated by the thin dashed line of in Figure 3-19. Plate beamsplitters may be coated to minimize spectral reflection at either surface, and they made be wedged to change the angles of the output and reflected beams. Because the transmitted beam must traverse the additional optical path of the beamsplitter's thickness, a compensator optic in the path of the reflected beam is necessary. This compensator element should be identical to the beamsplitter substrate so that identical effects (aberrations, attenuations, and beam deviations) are imposed on both the reflected and transmitted beams.

To resolve these issues with plate beamsplitters, extremely thin pellicle beamsplitters were conceived. These delicate membranes neither deviate a beam nor produce a secondary reflection, so they do not require a compensator optic. However, due to their fragility, they are used sparingly in optical systems. They are typically about ten micrometers thick and coated with an appropriately thick layer of metal to split a beam to the desired proportion (e.g., 50% reflected/50% transmitted, 4%R/96%T, 70%R/30%T, etc.).

Path-Shifting versus Wavelength-Shifting Interferometry

All the interferometers described above create different conditions of interference as the optical path is shifted using a method called path-shifting, in which an optic within the interferometer is physically moved by a small amount to change the physical path, thereby changing the OPD. This is usually accomplished by using a piezoelectric transducer or actuator that pushes and pulls an optical element by a very small amount, on the order of tens of nanometers. Typical path-shifting intervals are in $\lambda/8$ increments to provide resolution for the phase-unwrapping software algorithms. In practice, path shifting is accomplished via path-stepping or path-ramping. In the former technique, an interferogram is acquired for discrete OPDs; whereas path-ramping measurements continually change the path (and therefore the phase and OPD), and the interferogram integrates (adds up) the signal over a range of reference beam position. The path-stepping method produces higher-visibility fringes, but it is considerably slower than the path-ramping technique.

Upon examination of Equation 3-3, it can be seen that it is possible to create interference and configure an interferometer that shifts not the path, but the source wavelength, while keeping the path constant. After all, the goal of interferometry is to create an OPD between the test and the reference beams, and OPD is composed of two variables: path length and wavelength. Wavelength-shifting interferometers are usually designed for specific applications because they require unique sources that are monochromatic with a variable wavelength, such as a tunable laser, or they have multiple wavelength sources. For instance, the piezoelectric actuators used in path-shifting interferometers cannot reliably move a large reference optic, which is necessary for apertures greater than approximately 400 mm. In addition, when multiple surfaces within an optical system are to be tested, the range of a piezoelectric actuator (tens of millimeters at most) may not be long enough to span the distance between the surfaces to be tested. In these situations, wavelength-shifting interferometry is required.

Lateral Resolution of Interferograms

It is critical to understand the height indicated by each fringe, but the lateral resolution provided by the camera acquiring the interferogram is also an important parameter. The interferometer itself is an optical system that creates an image, so the number of pixels that can sample the image (the interferogram) will determine the smallest spot (fringe width) that can be measured. For example, if there are aberrations that induce high-frequency fringes, they will be measured as individual fringes only if a number of pixels are available to sample each thin fringe. Otherwise, many high-frequency fringes that fall on a single pixel will just be averaged to one result.

Interferometers with high-resolution sensor arrays can provide information in addition to the typical WFE or surface-figure measurement. Spatial structure of the wavefront may be discerned, and even roughness measurements are possible using high-resolution systems. In particular, white-light interferometers have been applied commercially to measure surface roughness and the fine structure of a wavefront.

Evaluation Metrics for Interferograms

An interferogram must be carefully evaluated, because it conveys a great deal of information about the quality of the wavefront transmitted through or reflected by an optical system. This in turn, indicates the quality of the optical system itself.

The interferometer software will mathematically fit measured interferograms to Zernike polynomials (as covered in Module 2-1). This provides the technician with the Zernike coefficient terms of the fit; these terms indicate the character and quality of the wavefront errors. There are a finite number of terms used in a practical Zernike fit, though many terms can be requested of the interferometer software. A typical fit uses 36 Zernike terms, of which only the first 9 or so are used during optical fabrication and alignment. When software is used to evaluate interferograms, the Zernike terms of the fit will be calculated and a wavefront map of those Zernike terms will result, along with a *residual wavefront error map*—this is the difference between the raw measurement and the smooth mathematical surface described by the (say, 36-term) Zernike polynomial. Figure 3-20 shows a measured interferogram broken down to its Zernike fit and a residual WFE map.

The Zernike fit is the wavefront-error map that likely results from either (a) manufacturing errors, (b) the fact that the wavefront under test was not located precisely where it should have been with respect to the reference surface, or even (c) so-called design-residual aberrations. The QAPO text offers a detailed discussion of sources of manufacturing errors (a). Alignment errors (b) may be due to coarse positioning errors, random effects such as thermal conditions or turbulence in the lab, or predictable biases such as gravity sag or mounting errors (e.g., three-point mounts induce the aberration trefoil). Design-residual aberrations (c) are errors that the optical designer was not able (or willing) to remove from the prescription. After a Zernike fit to a measured interferogram is achieved, the quality of the interferogram must be documented and reported in a simple, meaningful way. The following discussion describes some common interferogram-evaluation metrics.

The residual aberration map contains high-frequency errors that may be due to non-uniformities in the manufacturing of any of the optics used for the test, including those in the interferometer itself. These errors can even be caused by dust and other surface contaminants. Often, diffractive effects are obvious as bull's-eye patterns in a residual aberration map—coherent point laser sources diffract around dust and scratches along the path. (Some such patterns can be seen in the residual WFE map portion in the lower right of Figure 3-20. Because of these effects, it became popular to instrument commercial interferometers with annular ring sources that do not produce diffractive interferogram artifacts.)

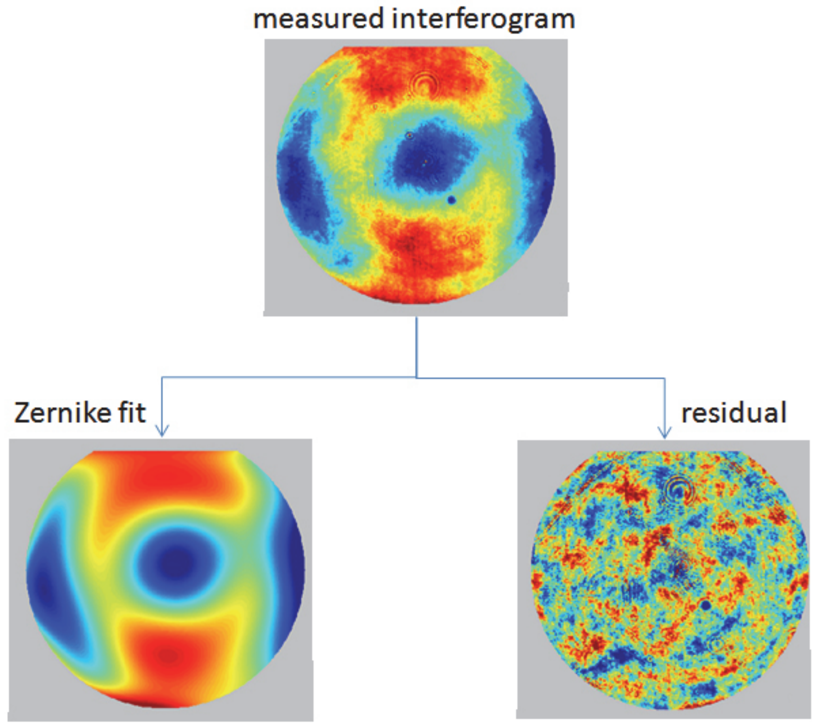


Figure 3-20 *This figure shows a measured interferogram (top), along with a 36-term mathematical Zernike polynomial fit (lower left) and the residual WFE map (lower right) that results.*

Before delving into interferogram metrics, it is important to understand how to express their dimensions. These metrics are best reported in any physical distance units that the interferometer measures, such as nanometers or micrometers. Unfortunately, reporting metrics in units of "waves" is common in practice. Waves are multiples of the interferometer test wavelength—a 2-wave error (often written $2 \cdot \lambda$) is equivalent to an error of 1265.6 nm if the interferometer test wavelength is 632.8 nm. However, this reporting practice is confusing when the optical system under test operates at a different wavelength from the interferometric test wavelength. Though a HeNe interferometric test wavelength of 632.8 nm is common, it cannot be assumed. In particular, this wavelength cannot be assumed if the interferometric test wavelength is unspecified on an ISO10110 optical drawing, because the default for unspecified wavelengths on an ISO10110 drawing is 546.07 nm (per ISO 7944)—a wavelength not used in any common commercial interferometer. This example emphasizes that physical distance units (nanometers, micrometers, etc.) are direct and unambiguous.

The simplest and most common interferogram-evaluation metric reports the difference in height between the highest and lowest points of an interferogram, known as its *peak-to-valley (PV) error*. However, this metric takes only two data points (of many) in the interferogram, thereby concealing many details within the measurement.

A more thorough interferogram-evaluation metric is the *root-mean square (RMS) error* of the interferogram. Every point (pixel) of an interferogram represents a departure from an ideal wavefront—an error. The measured wavefront's RMS error is calculated by a mathematical process known as *adding in quadrature*: the error at each interferogram point is squared, these errors are added together, and then the square root of that sum is taken to produce one single number known as the RMS error. (Errors are statistical quantities called standard deviations, so they are combined in quadrature.) RMS error is more representative of the wavefront's variation in structure than PV error is.

PV and RMS errors are common but imperfect metrics because they can be affected by spurious data points. For instance, a speck of dust on the surface of an optical element under test can create an artificially high point in an interferogram, therefore causing a superficially large PV error to be reported. Similarly, a deeply rippled surface (which is optically undesirable) can have a very low RMS error because the highs cancel the lows. To improve data evaluation, engineers have calculated superior interferogram-evaluation metrics that involve further data processing. These metrics are intended to remove outliers (extreme data points) by setting certain thresholds within the interferogram data. To calculate these advanced metrics, the interferogram-processing software must first fit a Zernike polynomial to the data, as usual.

To calculate an engineered metric known as PVr, the first 36 Zernike terms are fit to a measured interferogram, and the PV error of that fit is calculated, producing PV_{36}. The RMS of the residual aberration—that which remains after this 36-term fit is subtracted from the measurement—is given by $\sigma_{36,residual}$. The PV error, PV_{36}, is added to three times the residual RMS error, $\sigma_{36,residual}$ to produce the metric PVr, as shown in the Equation 3-15. These calculations are performed in software, and the PVr metric can be reported directly. PVr error has been shown to be more robust than simple PV error with respect to various measurement conditions, from wavefront aberration type and surface geometry to interferometry type and detector resolution. For this reason, PVr earns the distinction of a robust metric.

$$PVr = PV_{36} + 3 \cdot \sigma_{36,residual} \qquad (3\text{-}15)$$

It is also common to threshold data by removing the extremes of the data set. Outlier-removal metrics such as PV_q and RMS_q remove the highest 10% (or 5% or 2%, depending on the software calculation setting) of the data and report the PV_q or RMS_q as the PV or RMS of the remaining data. These are examples of application-dependent metrics that can be adjusted depending on processing parameters and the data-reporting conventions of a particular optics shop.

Optical designers may have reasons for specifying any, even custom, interferogram-evaluation metrics, and there is no direct scaling among them, since they are independently calculated. However, a rule of thumb used on optical shop floors is that the PV error is approximately five times the RMS error. It is important to note that optics fabricated via small-tool processes, such as magnetorheological finishing (MRF) or diamond turning, produce surfaces that do not approximate the 5:1 rule.

The interferogram's metric is usually specified directly on an optics drawing—the drawing itself will call out, for example, <30 nm RMS WFE across the clear aperture. In fact, Part 5, *Surface Form Tolerances,* of drawing standard ISO10110 specifies the surface form via an interferometer-evaluation metric.

Part 5 of ISO 10110 drawings uses the indicator **3/ A(B/C)**. The units for all parameters under ISO 10110-5 are fringes. The parameter **A** is the maximum allowed sagitta error, such that no more than **A** fringes shall be present when measuring the surface sag—that is, when comparing the surface to a flat test plate. If the surface's radius has an assigned tolerance, this parameter should be written as a dash (–), since these specifications would be redundant. The parameter **B** is the maximum allowed peak-to-valley (PV) irregularity of the surface; that is, no more than **B** fringes shall separate the highest high and the lowest low. The parameter **C** is the non-spherical, rotationally symmetric error, a parameter indicating a rotational symmetry of **C** fringes of the surface form error. Alternatively, this ISO 10110 indicator may specify the RMS surface form error, either with or without the parameters **A**, **B**, and **C**. RMS specifications are written in a number of ways. The indicator **3/– RMSt < D** indicates that the total RMS deviation from the nominal surface specified by the radius shall be less than **D** fringes. The indicator **3/– RMSi < D** indicates that the RMS irregularity shall be less than **D** fringes. The indicator **3/– RMSa < D** indicates an RMS symmetry of less than **D** fringes is required after spherical and rotationally symmetric irregularity have been removed. In all cases of RMS specification, the dash (–) may be replaced by the parameters **A(B/C)**, providing extreme detail on the surface form required.

Note that the parameters **A**, **B**, **C**, and **D** have units of fringes according to this specification. Again, this is a cumbersome, nonphysical unit that requires that the wavelength **must** be specified on the drawing; otherwise, it is assumed to be 546.07 nm (per ISO 7944). For example, the specification **3/ 5(—) RMSi < 1** specifies sagitta errors of less than 5 fringes and RMS irregularities of less than 1 fringe for the left and right surfaces.

Note that before interferogram metrics are calculated, aberrations that accrue during alignment should be removed from the raw, unwrapped interferogram. When evaluating flat wavefronts, all wavefront errors should be assessed after the aberrations piston and tilt have been removed. Usually, tilt is not a part of the optical system under test—rather it is an alignment-induced aberration that could have been removed mechanically by better aligning the optical system under test to the interferometer. In addition, all wavefront errors should be assessed with respect to the best-fit sphere when evaluating curved (spherical and aspherical) wavefronts. Pure mismatches to best-fit spheres manifest as the aberration focus. Removal of the best-fit sphere is accomplished by use of the proper source curvature, as discussed above.

Using Interferograms to Measure Other Optical System Parameters

Optical design drawings may call out other optical system performance metrics, in addition to interferogram-evaluation metrics. Many of these other metrics can actually be gleaned from the interferogram. One such specification is midspatial frequency (MSF) error (which can be derived from a measured MTF curve). An MSF error specification will call out a range of frequencies over which the modulation has to be above a specified value. However, MSF error will manifest in an interferogram as (usually concentric or linear) ripples. There is no Zernike term that fits a rippled surface shape, so it is often seen in the residual WFE map. To quantify the MSF error, the interferogram data can be interpreted to calculate (via software) the MTF curve. The MTF curve is a mathematical representation of the curve that would have been constructed had the MTF been directly measured.

Slope error, or gradient, is another metric that may be included on an optical design drawing. Slope error is related to regional changes in a wavefront, defined by a relatively large OPD over a small transverse displacement. This specification is similar to indicating the grade of a steep highway. Slopes can be due to ripples, spirals, and other high-frequency artifacts of modern manufacturing processes. Its specification is not explicitly covered under the ISO 10110 standard, but it is an important parameter to understand, particularly when working with aspheres.

Slope error is typically specified as an allowable slope over a transverse distance. It is typically measured by examination of an unwrapped interferogram. Its units are surface height change per lateral distance change (nanometers RMS per millimeter, waves PV per centimeter, etc.) or an angular unit (PV or RMS. The choice of units often depends on the application of the optic under test. Commercial Fizeau interferometer software packages report slope error if the output interferograms are calibrated for lateral size. These measurements depend on the interferometer camera's resolution and interferogram sampling. Surface profilers (both contact and non-contact) can also be used to measure slope error. Slope error is important to understand because it ultimately degrades image quality at low spatial frequencies (the low-frequency part of an MTF curve).

An optical material's surface texture or surface finish generally describes its *roughness*, that is, its microscopic structure. Roughness can be measured by a variety of techniques, as discussed in *Quality Assurance of Precision Optics* Module 1-3. Some of these techniques are interferometric in nature. An interferogram can also reveal information about the surface finish. In particular, high-resolution interferograms can show the high-frequency surface structure associated with surface roughness, and the roughness can be quantified by examining the fringe height variation and spatial frequency.

Typical Interferometer Configurations

There are a number of test configurations for interferometry, the most common of which are highlighted here, shown schematically for a Fizeau interferometer. We first describe reflective surfaces and optical systems and then discuss transmissive optical systems, highlighting some nuances of prism testing. In its most basic configuration, an interferometer can be used to measure the RWFE of a simple flat mirror via the setup shown in Figure 3-21.

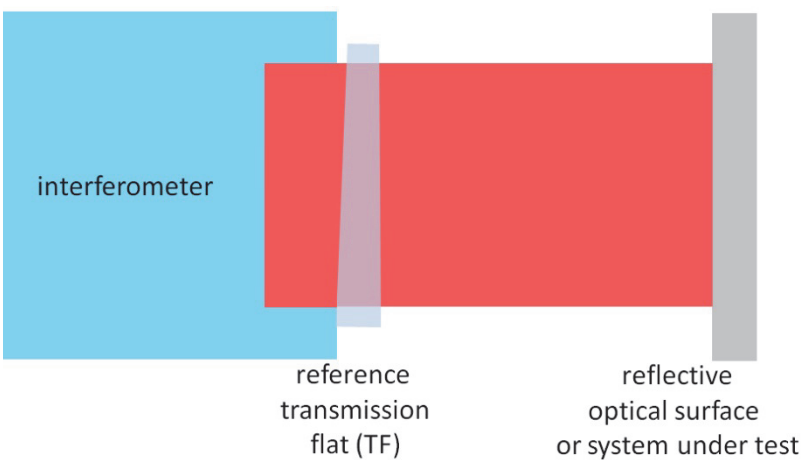


Figure 3-21 *This setup could be used to measure the RWFE of a flat mirror.*

To measure the surface figure or RWFE of a reflective optical surface or system, the setup shown in Figure 3-22 can be used. An alternative setup for RWFE measurement is shown in Figure 3-23.

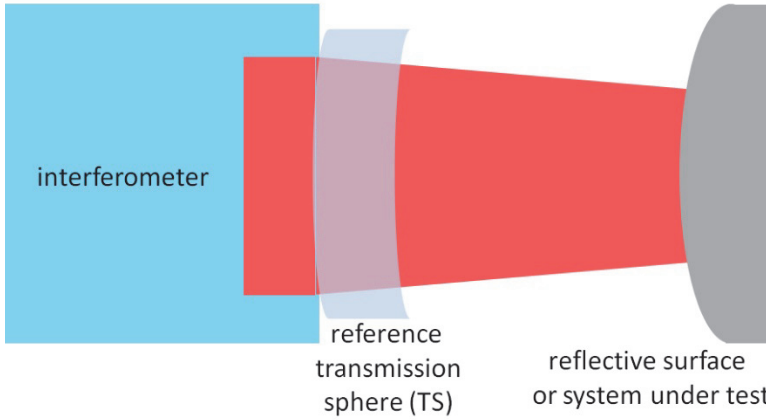


Figure 3-22 *This setup could be used to measure the surface figure or RWFE of a reflective optical system. This setup would be used to measure convex mirror surfaces or the RWFE of optical systems that diverge a beam upon reflection.*

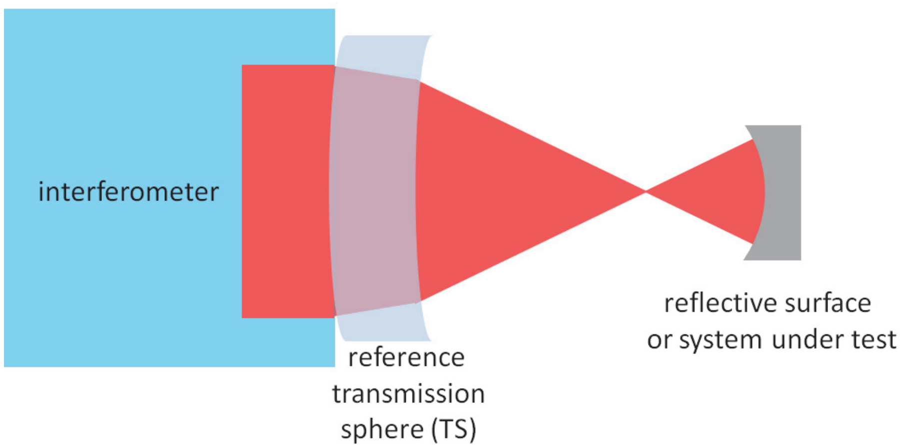


Figure 3-23 *This setup could also be used to measure the surface figure or RWFE of a reflective optical system. This setup would be used to measure concave mirror surfaces or the RWFE of optical systems that converge a beam upon reflection.*

To measure the TWFE of a generic transmissive optical system that operates with collimated output (such as a window, prism, beamsplitter, or telescope), the setup shown in Figure 3-24 can be used.

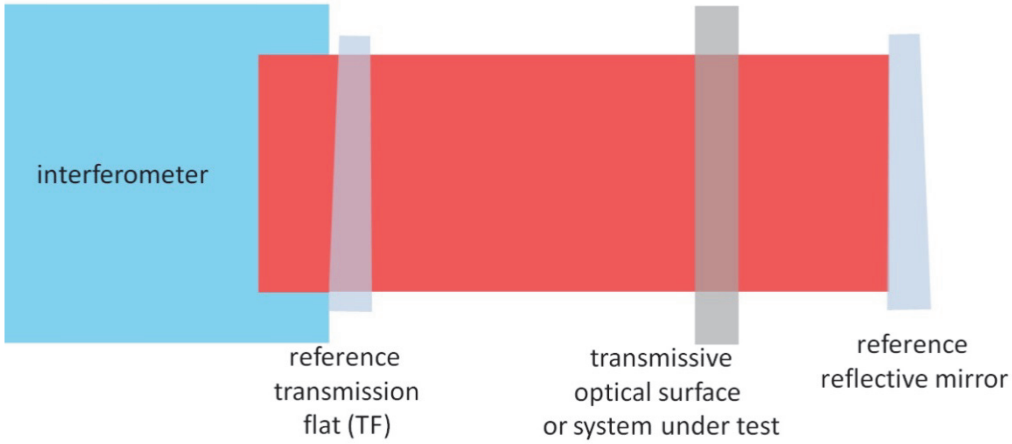


Figure 3-24 *This setup could be used to measure the TWFE of a transmissive optical system.*

An example of a transmissive optical system that may be tested in the configuration of Figure 3-24 is shown in Figure 3-25, where the generic transmissive optical system is replaced with a right-angle prism. This test measures the performance of three optical surfaces of the prism system: transmission through the two side surfaces and reflection at the hypotenuse surface. In addition, the bulk of the optical element is tested within the clear aperture.

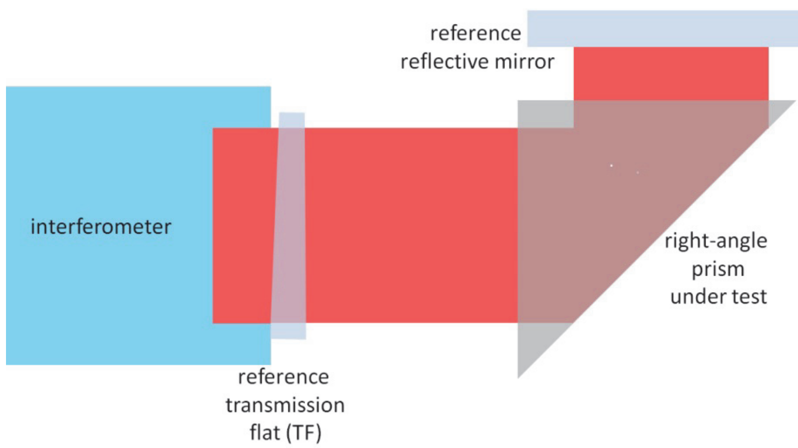


Figure 3-25 *This setup is an example of an application of the setup shown in Figure 3-24. In this figure, the generic transmissive optical system is replaced with a right-angle prism.*

Interferometry is critical for measurement of precision prisms, because it can provide further insight into a prism's performance beyond just its TWFE. Interferometers can measure beam deviation, $\Delta\theta$, due to the error, ε, in a prism's apex angle. Equation 3-16 may be used to calculate the error, ε, in the apex angle from the measured beam deviation $\Delta\theta$ (the deviation between the outgoing and incoming beams). In this equation, n is the refractive index of the prism. If this prism is measured in the configuration shown in Figure 3-26, the angle of the interferogram's tilt fringes, $\alpha_{\text{tilt fringes}}$, will yield the apex angle error, ε.

$$\epsilon = \frac{\Delta\theta}{2n} = \frac{\alpha_{tilt\,fringes}}{4n} \qquad (3\text{-}16)$$

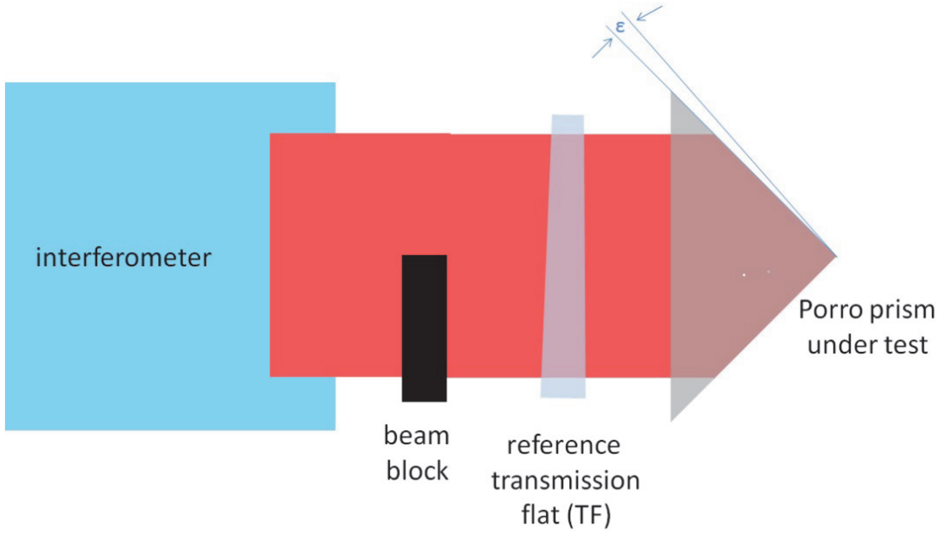


Figure 3-26 *This figure shows an interferometric test setup used to measure a prism's apex angle error in the Porro configuration via a Twyman-Green or Fizeau interferometer.*

Only a portion of optical systems operate with collimated input or output, so it is critical to understand how to measure the TWFE of a transmissive optical system with converging and diverging output. Figure 3-27 shows a setup that can be used to measure a converging optical system. Figure 3-28 shows an alternative that can be used to test a transmissive optical system with converging or diverging output.

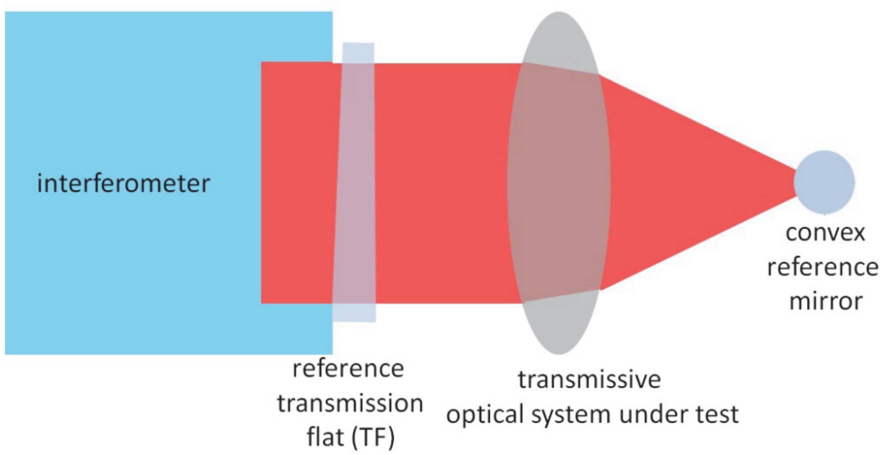


Figure 3-27 *This setup could be used to measure the TWFE of a transmissive optical system that converges a beam.*

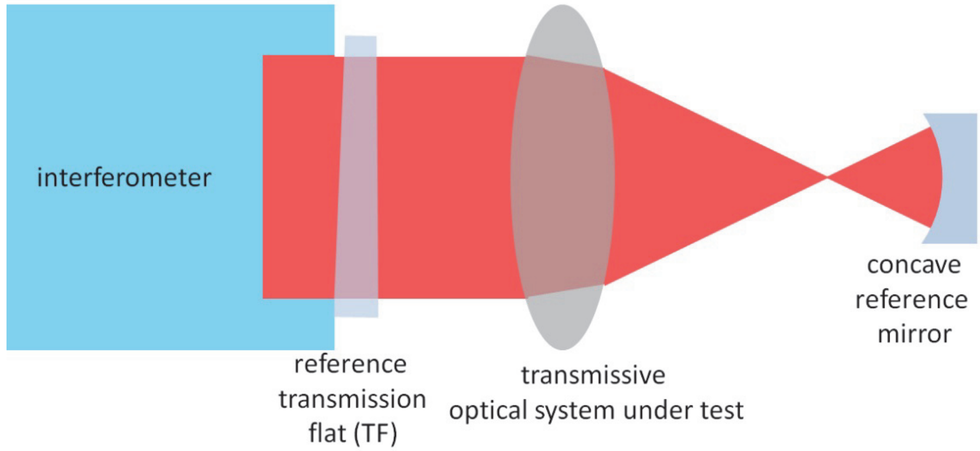


Figure 3-28 *This setup could also be used to measure the TWFE of a transmissive optical system that converges or diverges a beam.*

All of the above interferometer setups create interference by reflecting a wavefront of light at normal incidence, back **along the same path** into the interferometer. The reference optics are said to be located at the *null position* in these test setups. However, any interferometer setups that accomplish this by focusing light near a reference surface (as in Figures 3-22, 3-23, 3-27, and 3-28) are subject to a problem: according to the law of reflection, interference can also be created by reflecting the wavefront of light back along the path the light is taking. This effect is seen when the reference mirror is positioned as illustrated in Figure 3-29, which is known as the cat's-eye position (or cat's-eye focus).

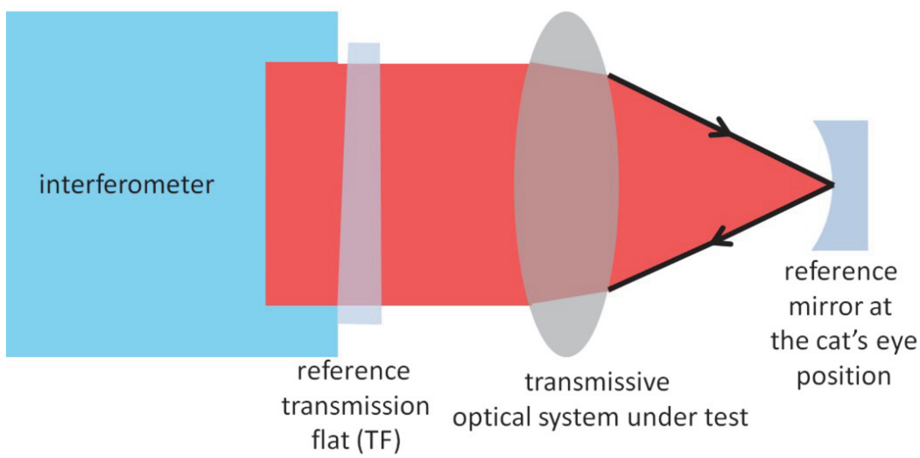


Figure 3-29 *Illustrated here is the light path taken when a reference optic is located at the cat's-eye position. Interference will occur from this configuration, and it must be understood so that it can be used or avoided during interferometric testing.*

In most applications of interferometric testing like those shown above, the technician should take care to know and avoid the cat's-eye position. However, the cat's-eye position can actually be a very useful position because it precisely locates a surface at the focus of the interferometer. In particular, the cat's-eye position of Figure 3-29 is used in combination with the proper null position of Figure 3-28 to measure the radius of curvature of the concave reference mirror shown. A long, straight rail, known as a radius slide, is used to measure the displacement of the optic being tested—this displacement equals its radius of curvature.

Autostigmatic Testing of Aspheres

As an alternative to tests with null optics or CGHs, the technician can use a standard interferometer to test aspheric surfaces by employing autostigmatic testing techniques. Figure 3-30 shows the test setup for a paraboloidal mirror, which has foci at the focal point shown and at optical infinity. Therefore, the reference mirror used is flat.

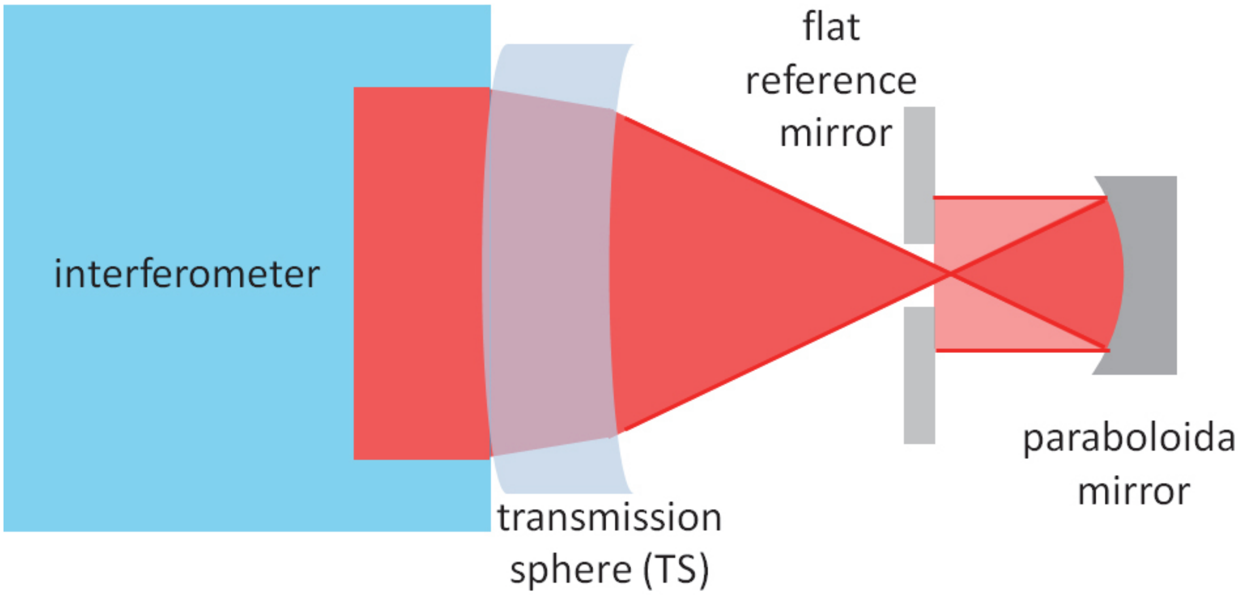


Figure 3-30 *Illustrated here is the light path taken when a flat reference mirror is used to test a paraboloidal surface.*

Figure 3-31 shows the test setup for an ellipsoidal mirror. Because an ellipsoidal mirror has foci at the two focal points shown, the curved reference mirror must be located with its focus at the second focal point of the ellipsoid being tested.

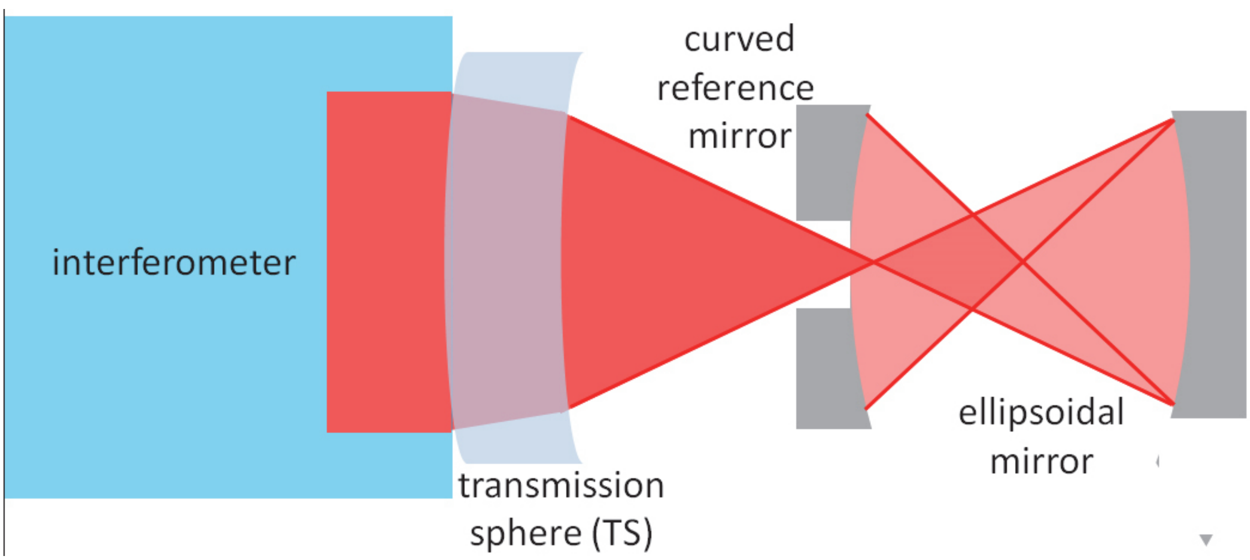


Figure 3-31 *Illustrated here is the light path taken when a curved reference mirror is used to test a ellipsoidal surface.*

Figure 3-32 shows the test setup for a hyperboloidal mirror, which has foci at the two focal points shown: one real and one virtual. The transmission sphere must create a focus at the real focal point of the hyperboloid being tested.

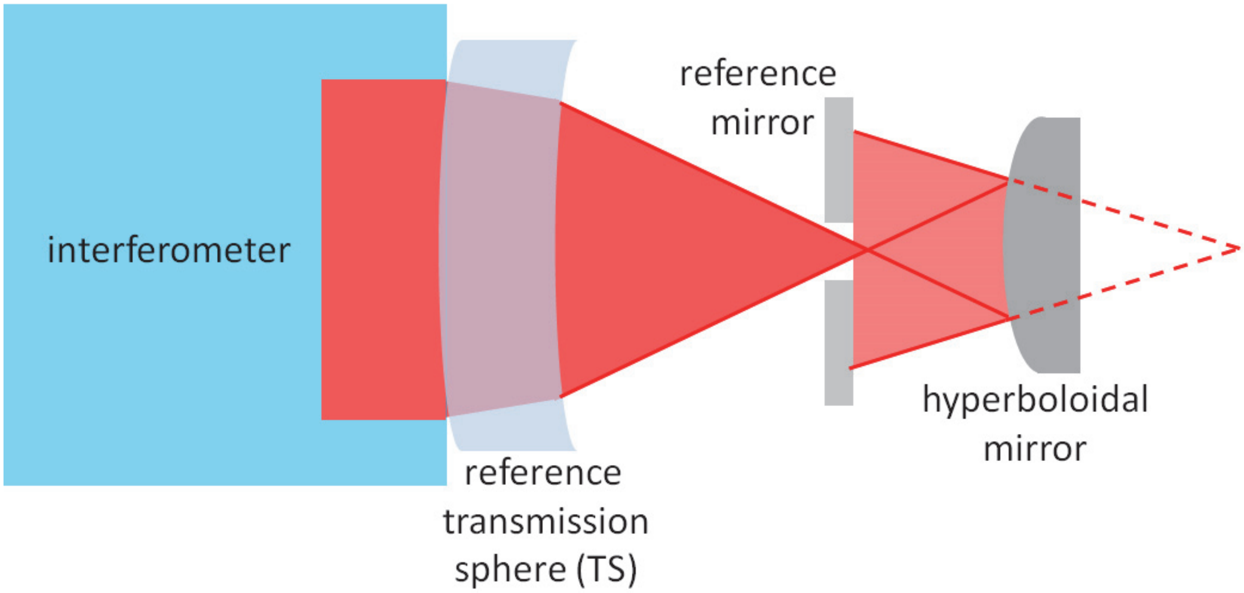


Figure 3-32 *Illustrated here is the light path taken when a reference transmission sphere is used to test a hyperboloidal surface.*

Commercial Interferometer Systems

At the time of this writing, two significant companies are making commercial interferometers for optical testing. Zygo Corporation (in Middlefield, Connecticut, USA) has been making interferometers since the 1970s. Analysis of Zygo interferometer output is accomplished by using its MetroPro interferogram-analysis software. An example of a typical MetroPro output window with an interferogram is shown in Figure 3-33 along with a screenshot from Zygo's newer MetroPro X software. The MetroPro screenshot (top) shows the high-frequency structure of a diamond-turned telescope mirror, and the MetroPro X screenshot (bottom) shows the wavefront of crystalline CO_2 laser optic.

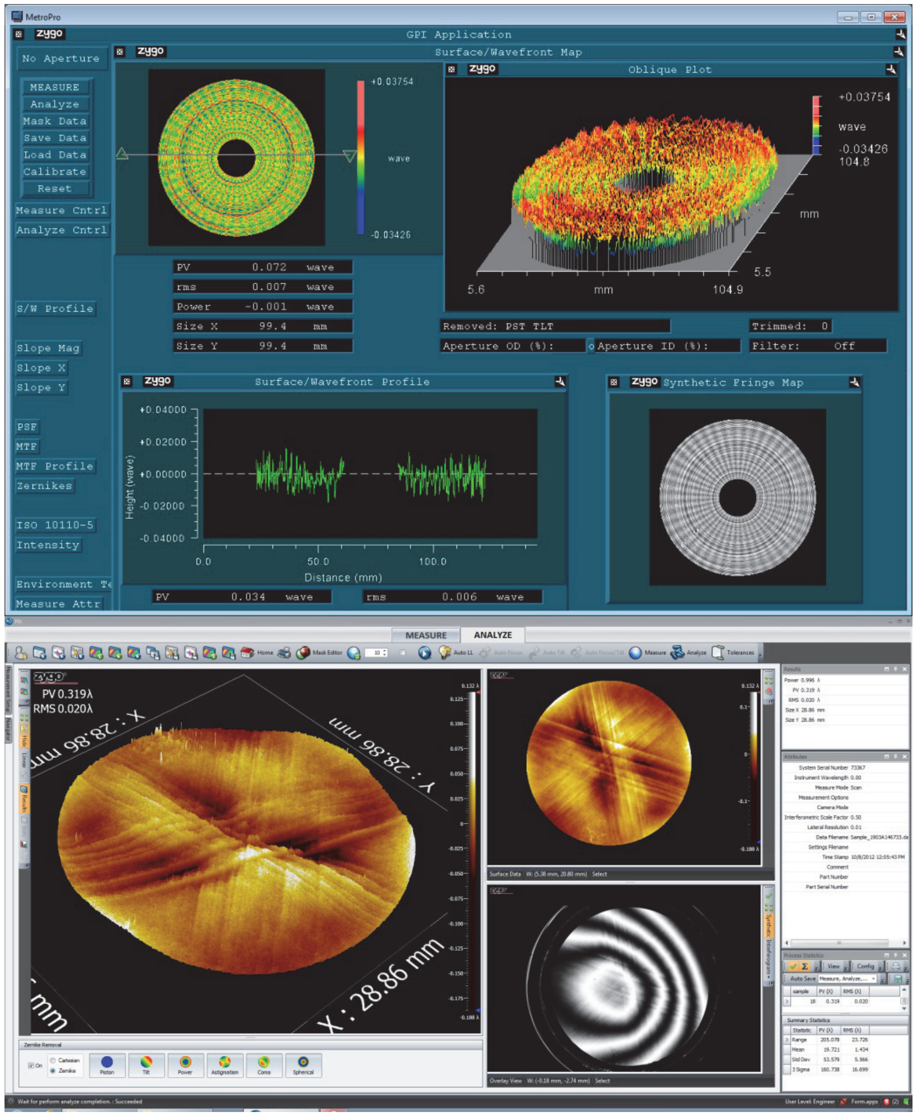


Figure 3-33 *These screenshots from Zygo's MetroPro software show a diamond-turned telescope mirror on the top (MetroPro 9) and a crystalline* CO_2 *laser optic on the bottom (MetroPro X). The raw (wrapped) fringe measurements can be seen in the lower right portions of both images.*

The company 4D Technology (in Tucson, Arizona, USA) has been making vibration-stabilized interferometers since the 1990s. Their 4Sight interferogram-analysis software, a screenshot of which is shown in Figure 3-34, performs the image processing necessary to enable dynamic interferometry.

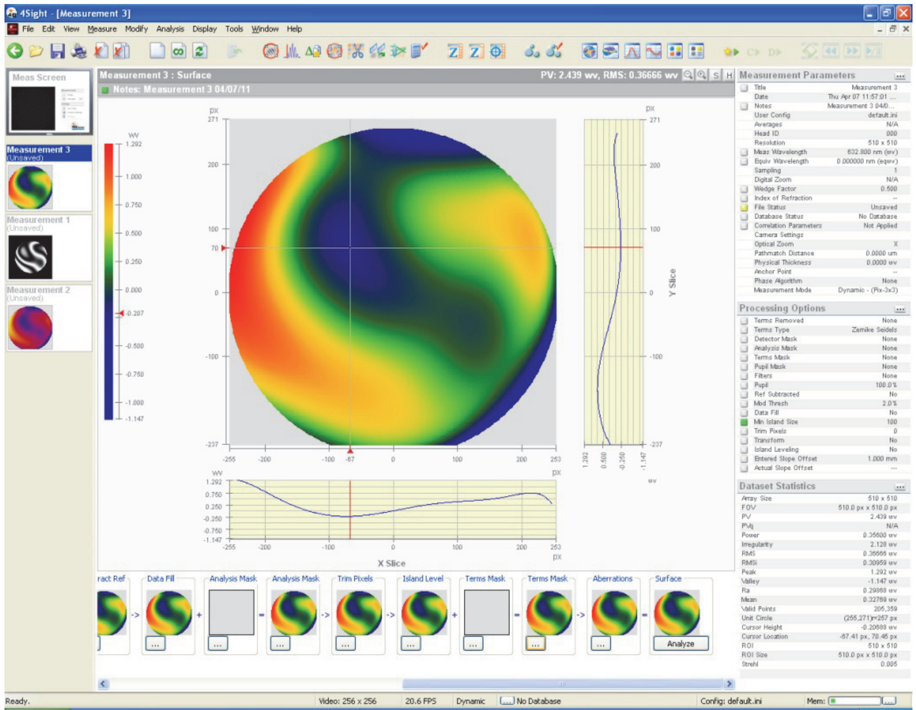


Figure 3-34 *This screenshot from 4D's 4Sight software shows an unwrapped interferogram and the wavefront metrics for this measurement. In fact, the raw (wrapped) fringe measurement can be seen in the smaller image on the left side of the screenshot.*

TRIOPTICS (Wedel, Germany, with offices in West Covina, California, USA) manufactures interferometers and a number of other practical optical metrology systems, including MTF-measurement systems. TRIOPTICS also owns the American company Davidson Optronics, a company that makes metrology tooling and references. Mahr (in Göttingen, Germany with offices in Providence, Rhode Island, USA) and PolyTec (in Waldbronn, Germany with offices in Irvine, California, USA) also make commercial interferometer systems for inspection of optical surfaces and wavefronts.

There are numerous other common and custom interferometer systems, the most historically notable of which are those made by Wyko Corporation, whose interferometer systems are currently maintained by 4D Technology. Their interferometers provided some of the first commercial systems with real-time image analysis capability.

Diffraction International (in Hopkins, Minnesota, USA) is an authority in CGH generation and interferometric testing with CGHs. They also make the Durango software package, which can be used to analyze interferograms.

Aberrations Observed during Interferometric Alignment

First-Order Aberrations

Interferograms reveal numerous details about the alignment of the optical system under test. Interferogram-analysis software breaks down an interferogram into the basic aberrations, usually by fitting a Zernike polynomial to the measured wavefront. The following discussion draws on Zernicke aberration theory to describe how each aberration might be used during the tedious process of optical alignment.

The *piston* term is simply a count of the total phase between the two wavefronts being compared: the waverfront from the reference surface and the wavefront from the optical system under test. This can be viewed as a uniform DC-offset for all points of an interferogram. It is usually neglected in optical wavefront measurements. When designing or measuring an optical system, piston is seldom specified (requested in the procurement specifications) or reported by the precision optics test technician.

The wavefront of the optical system under test may be tilted about a horizontal or vertical axis with respect to the reference surface. This aberration is known as *tilt*, and it will be decomposed into x-tilt and y-tilt terms. A tilt about the y- or vertical axis, which results in axial displacements of the wavefront along the x-axis, is called "x-tilt"; a tilt about the x- or horizontal axis, which results in axial displacements of the wavefront along the y-axis, is called "y-tilt." (Tilt about a horizontal axis may be called "tip.")

During an optical alignment, tilt may be deliberately introduced to help diagnose higher-order aberrations. It should be correctable by physically tilting the optical system under test. It is considered a first-order aberration because it may be removed by a straightforward mechanical alignment.

Similarly, the wavefront of the optical system under test may be displaced along the optical axis with respect to the reference surface. This aberration manifests as *defocus* (also known simply as *focus*). Like tilt, this first-order aberration can be corrected by a mechanical translation of the optical system under test along the optical axis. It may be introduced during alignment to help observe higher-order aberrations. Moving an optical system under test through its focus is an excellent way to observe astigmatism, and defocus can be used to balance symmetric aberrations such as spherical aberration.

As an example, tilt fringes in a Michelson interferometer can be used to calculate the displacement of one side of a mirror by the relationship shown in Equation 3-16 using the schematic of Figure 3-35. In this figure, the red lines represent a wavefront reflected from the reference and the test mirrors in the Michelson, and the variable N indicates the number of linear tilt fringes observed. The OPD is twice the distance Δd.

$$\Delta\boldsymbol{\phi} = \frac{2\pi}{\lambda}\ \boldsymbol{OPD} = 2\boldsymbol{\pi}\mathrm{N} \Rightarrow \qquad (3\text{-}17)$$

$$\mathrm{N} = \frac{\mathrm{OPD}}{\lambda} = \frac{2\cdot\Delta\mathrm{d}}{\lambda}$$

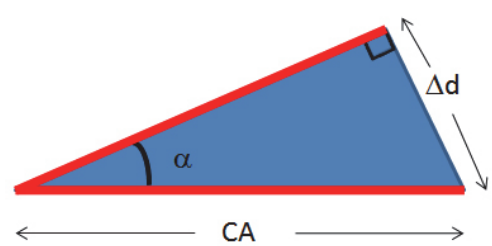


Figure 3-35 *The bold lines represent the position of a mirror in a Michelson interferometer before and after it is tilted by distance Δd to angle α. CA is the clear aperture of the beam on the tilted mirror.*

Third-Order Aberrations

This section concisely describes common occurrences of third-order aberrations and recommends simple methods by which to improve wavefront quality when these aberrations occur. The most straightforward methods involve compensating for these aberrations using a first-order aberration (focus or tilt).

Spherical aberration (SA) is often observed in large-aperture spherical optical systems. In fact, it is the spherical nature of the optical surfaces that causes this aberration. This aberration is known as an "on-axis aberration" because of its fourth-order dependency on only the radial coordinate in the aperture stop, ρ, in the wavefront polynomial. Therefore, this aberration can be reduced by *stopping down* the optical system: decreasing the radial size of the pupil. This is typical in camera systems with an adjustable aperture stop, as is common in single-lens reflex (SLR) cameras. However, this reduction in SA comes at the cost of less light through the optical system due to the smaller aperture stop. (Conversely, this is the reason why it's harder to see clearly in dim lighting—the aperture stop of your eye, the pupil, is open wide, giving rise to significant SA and other aberrations.) SA may also appear when the clear apertures of optical elements in a multi-element optical system are larger than required. For this reason, it is important to properly size clear apertures.

Spherical aberration can be compensated by the first-order aberration *defocus*. When viewed at the effective focal length, the point-spread function (PSF) of a system with SA is quite large, but it can be slightly defocused to a smaller spot (PSF). If an image is formed (a detector is placed) in this defocus plane, this defocus improves the overall wavefront quality. A comparison of the PSF for pure SA is shown in the left of Figure 3-36 , while the right image shows a defocused version of the same optical wavefront.

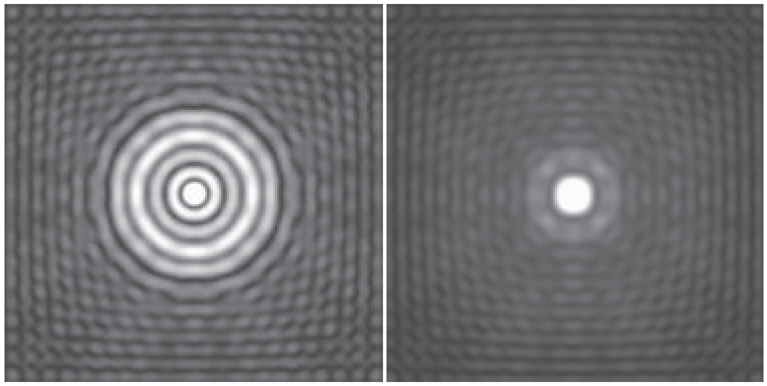
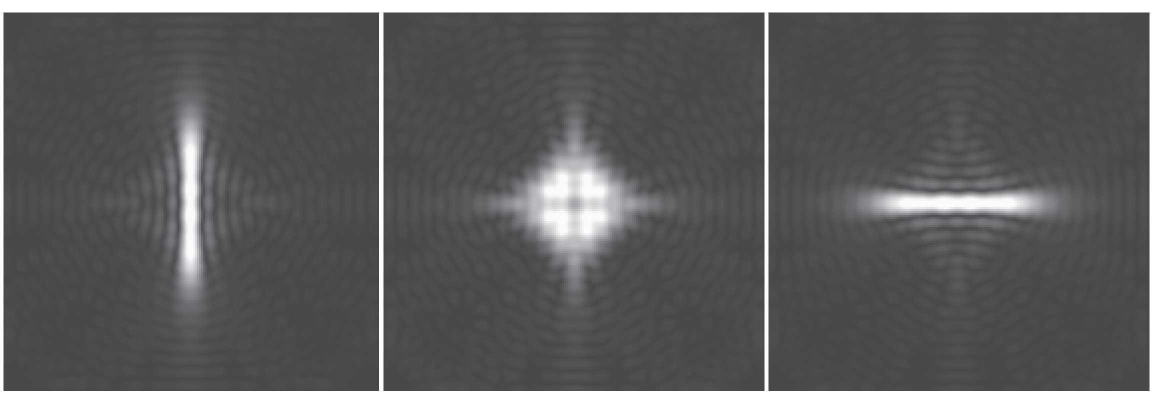


Figure 3-36 *The spots formed by an optical system with spherical aberration (left) that is compensated by defocus (right).*

Coma is a third-order aberration that may be seen in misaligned optical systems that operate off-axis. Like spherical aberration, coma depends on the radial coordinate in the aperture stop, ρ, but its dependence is slightly weaker: it depends on the third-order of ρ. Therefore, coma can also be improved by stopping down an optical system at the cost of less throughput. Coma also depends on the object height, *h*, (equivalently, the off-axis field angle) of the wavefront polynomial, making it an off-axis aberration. Larger off-axis field angles means more coma will be present.

Coma's presence may be an indication that an element of an optical system is tilted or decentered. For instance, coma is common in telescopes when the optical axes of the primary and secondary mirrors are misaligned in tilt or decenter.

Astigmatism is another third-order aberration that is particularly prevalent in misaligned off-axis optical systems. Like coma, astigmatism depends on the object height, *h*, and the radial coordinate, ρ, of the wavefront polynomial, but it depends on the square of both. Therefore, keeping an aperture stop and object size (field angle) smaller will reduce the astigmatism. Because astigmatism also depends on the square of the cosine of the ray's angle in the aperture stop, two focal "lines" form in an astigmatic optical system, as described in Module 1 of *Metrology of Optical Systems*. When adding defocus to move from the tangential focal line to the saggital focal line, the *circle of least confusion* can be observed, as shown in the Figure 3-37. This defocus plane gives the best concentration of energy in the PSF that can be created for an astigmatic optical system.



Figures 3-37 *As the astigmatic optical system is defocused from the tangential (left) to the saggital (right) focal line, the circle of least confusion can be observed.*

Higher-Order and Mount-Induced Aberrations

In principle, the Zernike polynomial can be expanded to infinite terms to describe an optical wavefront, and each term will represent a higher-order wavefront aberration. In some situations, prominent shapes or features will appear in an interferogram that can be described by Zernike terms. These aberrations may indicate the way that the optics are mechanically mounted. For example, a common mounting technique is the three-point mount, which can lead to a higher-order aberration called *trefoil* (too often incorrectly spelled "trefoil"). Figure 3-38 shows an interferogram with significant trefoil. The points at which one or more optical components are mounted are likely to be oriented along the contour lines of the interferogram. Such a mount-induced aberration is particularly evident when working with optics with high aspect ratios (a small thickness divided by a relatively large diameter) and when the mounting hardware was not designed for the particular optic. Three-point self-centering lens mounts are subject to this aberration, as are three-point mirror mounts without appropriate flexures.

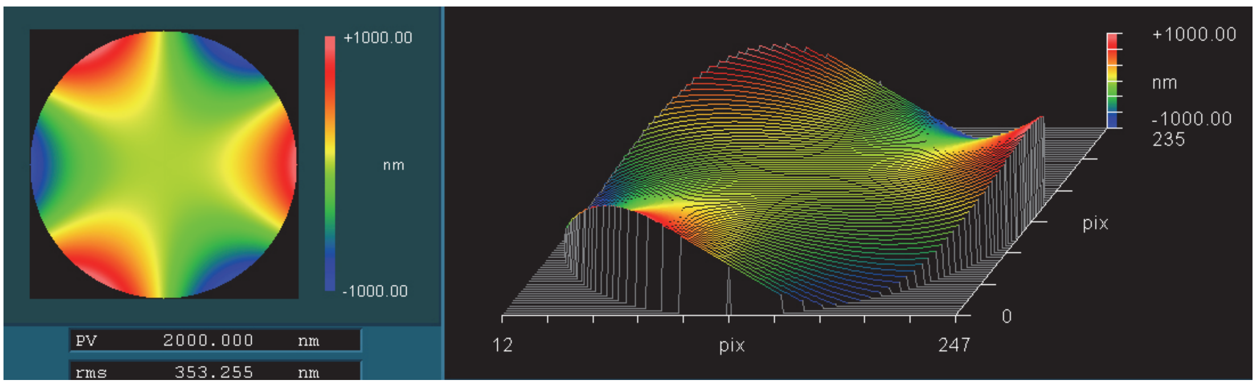


Figure 3-38 *This interferogram is indicative of a three-point mounting aberration.*

Four-point mounts may result in a higher-order aberration known as *clover*, six-point mounts may result in *hexafoil*, and more complex mounting configurations can create aberrations that do not have specific names in the Zernike polynomial expansion.

Due to the symmetric nature of the Zernike polynomial equation (which is used because of the circularly symmetric nature of optical systems), there is a practical limit to the number of its useable terms: most applications of interferometry use up to 36 terms. Because of this symmetry, asymmetrical wavefront errors cannot be mathematically described, even by a combination of Zernike terms. For example, common wavefront errors induced by surface roughness and high-frequency periodic surface structure cannot be fit to a Zernike polynomial or any mathematical function that is intended to describe a smoothly varying surface. For this reason, these aberrations are deemed residual aberrations and quantified differently from Zernike aberrations. Regardless of the description of the aberration, it is essential to perform tests so that aberrations manufactured into optics can be quantified and discerned from aberrations that are induced on optics by their mounts, gravity conditions, or the environment.

Measurement Artifacts

Reference optics used in a double-pass optical test are intended to return a beam along the exact same path as its incident beam; the ideal reflected beam retraces the path of the incident beam after reflection from an ideal reference optic. However, if the optical system or component under test aberrates the incident wavefront (which it will, since this why it is being tested), the ideal reference optic no longer matches the aberrated optical wavefront, so that upon reflection back through the optical system, the exact same path is not exactly retraced, leading to *retrace error*. Retrace error is common in optical testing, but it is seldom discussed in the literature. It can be mitigated by ensuring that all optical apertures are appropriately filled, including the incident wavefront and the wavefront reflected back into the optical system by the reference optic. Often, slowing the optical speed of the reference optic (longer radii) will decrease the retrace error. Regardless, it is critical to verify the error in a measurement with respect to expectations from theory, design, and the manufacturer's metrology.

Other Applications of Interferometry

Displacement-Measuring Interferometers (DMIs) and Laser Tracker Systems

Another important optical alignment tool that relies on interferometry is the displacement-measuring interferometer. These systems are the basis of the general-purpose interferometers used to measure linear differences in position, or *displacements*. In fact, displacement-measuring interferometers (DMIs) are used to measure the difference between the focus of an optical element and the cat's eye focus of the interferometer, thereby giving the radius of the surface, as described above.

Rather than just measuring linear displacements, DMIs can be partnered with a precision gimbal that accurately articulates an interferometer's laser beam in azimuth and elevation. This system, known as a laser tracker, can measure a three-dimensional point cloud of locations on an object. This valuable technology is used for precision optical alignment and can measure location accurately to less than 25 micrometers. Such a system may be used by the aerospace industry to align a telescope sensor, or it may be used by the entertainment industry to map a remote movie set that will later take the generated point cloud to remake the distant scene.

Interferometric Sensors

Because interferometry is such a sensitive science that can be used to measure wavefront changes to fractions of nanometers, interferometers are heavily employed in the field of sensing. Strain sensors are often based on interferometric devices: a small strain can be detected interferometrically by measuring an optical path difference as strain is applied. Sagnac interferometers are commonly used for rotational measurements, since they are the basis of modern optical gyroscope technology. In fact, sensitive interferometers have even been used to sense ocean tides and gravitational waves. The applications of this sensitive science are limitless.

Holographic Interferometry

A hologram is a volumetric interferogram it stores the phase information as well as the transverse fringes of a traditional interferogram. The fringes stored within two similar but independent holograms can be made to interfere by using a unique and powerful technique: When viewing an object under coherent illumination, a hologram can be recorded using holographic film. If that object is displaced in any way, a second hologram can be recorded that will interfere with the first. The displacement will be tracked as fringes. Technically, these are

Moiré fringes that result from superposition of the holographic fringe information stored in the film.

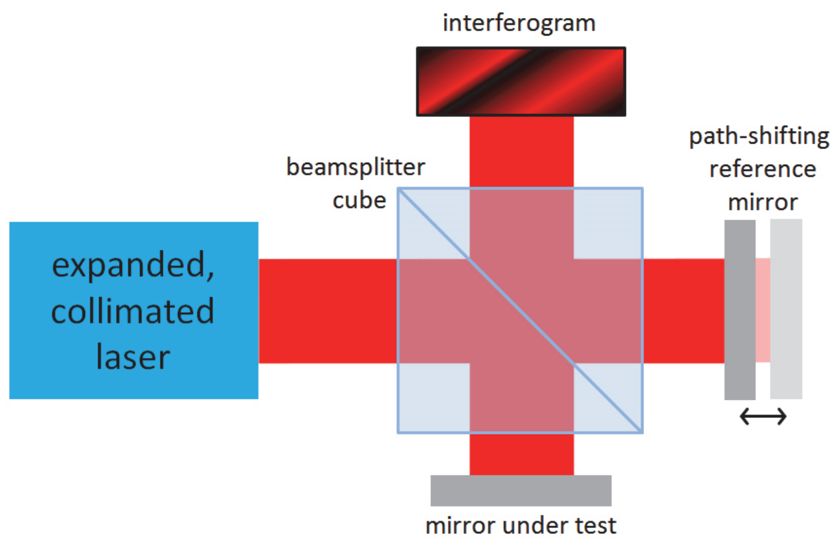
This powerful metrology technique is used to assess the structural modes of large objects that undergo minor dynamic disturbances, such as airplane engines and wings, and to measure small displacements of dynamic mechanical parts.

LABORATORIES

Laboratory 3-A
The Michelson Interferometer

Theory

The Michelson interferometer is a basic system used to test optical systems and elements. See Figure 3-14 for its typical configuration. These systems may be constructed using a laser with any one of the three beamsplitters (cube, wedged plate, pellicle) and two flat mirrors. Interference patterns will result depending on the quality of the optics used to make the system and the alignment achieved. The goal of this lab is to construct a Michelson interferometer, as shown in the figure below, using each of these three beamsplitters to understand the nuances associated with each variation of the optical system.



Furthermore, the tilt of a flat mirror should be calibrated and compared to the result of Figure 3-35, and the translation of a mirror should be calibrated as the mirror is translated along the beampath.

When the interferometer is well-aligned using the laser source, the laser can be replaced by an LED or even a white-light source. This interferometer setup will be used to measure the coherence length of these lower-coherence-length sources.

Equipment

- Low-power long-coherence-length laser, mounted
- Spatial-filter mount for microscope objective and pinhole
- Microscope objective to collimate the beam to a diameter >40 mm
- A well-corrected positive lens, focal length 20 to 200 mm, clear aperture >40 mm
- One flat mirror mounted in a tip-tilt mount

- One flat mirror mounted in a tip-tilt mount atop a translation stage with its axis along the incident beam path
- Cube beamsplitter (non-polarizing), mounted
- Wedged plate beamsplitter, mounted
- Wedged plate compensator window, mounted
- Pellicle beamsplitter (optional), mounted

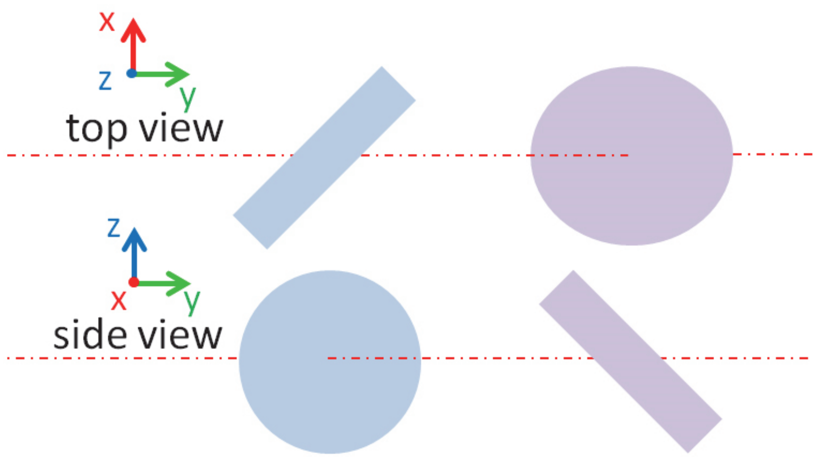
Procedure

1. Construct a point source using the laser, spatial-filter mount, microscope objective, and pinhole. Alternatively, a fiber laser with single mode output might be used.
2. Collimate the point source using a well-corrected positive lens.
3. Align the interferometer shown in the figure above and calibrate the fringe motion obtained by tilting one of the mirrors.
4. Document the interferometer alignment and fringe motion associated with this beamsplitter. That is, measure the nanometers of fringe motion per angular motion of the tip-tilt mount and linear motion of the translation stage.
5. Replace the cube beamsplitter with a wedged plate beamsplitter and include a wedged plate compensator window. Re-align the interferometer.
6. Document the interferometer alignment and fringe motion associated with this wedge beamsplitter. That is, measure the nanometers of fringe motion per angular motion of the tip-tilt mount and linear motion of the translation stage.
7. Replace the cube beamsplitter with a pellicle beamsplitter and re-align the interferometer.
8. Document the interferometer alignment and fringe motion associated with this pellicle beamsplitter. That is, measure the nanometers of fringe motion per angular motion of the tip-tilt mount and linear motion of the translation stage.
9. Using the beamsplitter of your choice, replace the laser source with an LED source. Tilt and translate the mirrors until interference fringes are obtained.
10. Translate one mirror until fringes can no longer be observed, and then translate the mirror back to measure to each end of the interference—this distance is the LED's coherence length.
11. If time allows, repeat this coherence-length-measurement experiment with a while-light source.

Laboratory 3-B
Astigmatism Compensation by Tilted Window

Theory

Astigmatism is easily introduced to any optical setup by inserting a flat window. It is for this reason that a plate beamsplitter is undesirable in an interferometer. This effect can be problematic, but it may be compensated by inserting an identical flat window at a compound angle. If the first window is oriented at an angle of incidence of 45° with respect to the beam's direction, rotated about a horizontal line, then the second window should be oriented at an angle of incidence of 45° with respect to the beam's direction, rotated about a vertical line, as shown in the figure below.



Equipment

- Michelson interferometer
- Two identical windows

Procedure

1. Locate just one window in the path of the Michelson interferometer and measure the aberration, noting the significant astigmatism. (This can be done simply by using a plate as the beamsplitter.)
2. Add the second window in the beam path and observe the improvement to the aberrations measured. Document how angles of incidence changes the aberrations measured.

Laboratory 3-C
Etalon Basics

Theory

A Fabry-Perot interferometer or etalon, as shown in Figure 3-17, is tedious to align because the spacing required between the two surfaces is small, and the orientation must be parallel for high-quality results. A collimated, expanded laser beam or a diffuse, extended source can be used as the input. Create a Fabry-Perot interferometer using each type of source and study the results.

Equipment

- Low-power laser, mounted, spatially filtered, and collimated
- Diffuse, uniform source, such as a white screen illuminated from the back or side by a bright white light
- Two collimating lenses
- Focusing lens
- Observation screen or camera
- Translation stage on which to mount the windows
- Two windows, with one side each to be coated as a partial reflector, if possible

  (If it is not coated, the reflectivity will be about 4%.)

Procedure

1. Collimate the laser using a well-corrected positive lens located at a focal length from a spatial filter.
2. Mount the two windows of the etalon in close proximity, a few millimeters apart, one atop a translation stage.
3. Mount the focusing lens after the etalon, one focal length away from the observation screen.
4. Observe the Fabry-Perot fringes and document the results of varying system parameters such as the separation of the etalon surfaces.
5. Repeat the experiment with the extended source by collimating its output using a well-corrected positive lens located at a focal length from the source.

Problem Exercises and Questions

57. Define the important terms of interferometry: interferogram, wavefront error, surface figure error, coherence, and fringe visibility.

58. Calculate the visibility for two beams with irradiance values.
    $E1 = E2 = 20$ W/mm².

59. Calculate the visibility for two beams with irradiance values.
    $E1 = 20$ W/mm² and $E2 = 10$ W/mm².

60. Plot the irradiance, $E_{interference}$, of a two-beam interference pattern as a function of phase shift, $\Delta\varphi$, using one beam with irradiance $E1 = E2 = 20$ W/mm².

61. Plot the irradiance, $E_{interference}$, of a two-beam interference pattern as a function of phase shift, $\Delta\varphi$, using one beam with irradiance $E1 = 20$ W/mm² and $E2 = 10$ W/mm².

62. What is the OPD between an air path and the path through a 9-mm-thick window with a refractive index of $\mathbf{n_{window}} = 1.52$?

63. What is the phase shift, $\Delta\varphi$, between the path through a 22.114-mm-thick window with a refractive index of $\mathbf{n_{window}} = 1.662$ and a 22.115-mm-thick window with a refractive index of $\mathbf{n_{window}} = 1.661$ at a wavelength of 840 nm?

64. The phase difference through a 4-mm-thick window is measured to be 200 radians. What is the refractive index difference if the wavelength used is 632.8 nm?

65. Which aspect of an interferometric test determines the ultimate possible accuracy of the measurement?

66. Which of the following reference optic(s) may to be used in an interferometric test of a positive lens system? Explain how (each of) your selection(s) would be aligned and applied for this test.

    (A) an F/4 reference sphere after collimated interferometer

    (B) a precision ball bearing

    (C) a precision concave reference mirror

67. List the types of aspheres.

68. The conic constant on an optical drawing is $k = -3$. What type of asphere is this?

69. The conic constant on an optical drawing is $k = -1$. What type of asphere is this?

70. What are the distances to the foci of a paraboloid if its best-fit spherical radius, $R = -150$ mm ?

71. What are the distances to the foci of an ellipsoid if its best-fit spherical radius, $R = 150$ mm and its conic constant, $k = -2.5$?

72. List two methods used to format a test beam.

73. List at least three terms used to describe a surface's form.

74. Explain fringe unwrapping.

75. What scale factor should be used when interferometrically testing a complex lens system a normal incidence in double pass?

76. There are 12 fringes across an interferogram in a Michelson interferometer that uses a 632.8 nm laser. What is the OPD between the two arms of the interferometer?

Advanced Problem Exercises and Questions

77. What is the radius of the optical surface tested using Newton's rings in 546.07 nm light if the radial distance to the ninth ring is 11.158 mm?

78. Calculate the beam deviation through a BK-7 plate beamsplitter that is 8 mm thick and composed of plate parallel surfaces if the incident light strikes the first surface at an AOI of 45°.

79. There are 27 tilt fringes across an interferogram in a Michelson interferometer that uses a 632.8 nm laser. With this interferometer, you are testing a mirror with a clear aperture of 25 mm. To what angle was the mirror tilted?

80. An interferogram is fit with a 36-term Zernike polynomial. The lowest point is 39 nm below the mean, and the highest point is 16 nm above the mean. The standard deviation of the residual data is 3.7 nm. What is the PVr for this data set?

81. An ISO 10110 drawing has the specification **3/—RMSi < 0.33**.
Is a mirror with a RMS error of 100 nm acceptable if it is tested in single reflection (single pass) with a 632.8 nm laser?

82. What is the full width at half maximum (FWHM) ($\Delta\lambda$) for a Fabry-Perot interferometer, in terms of the system's parameters (n, r, d, λ)?

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GLOSSARY

- *Abbe number* defines the dispersion of a transmissive optical material, typically at three wavelengths within the transmission spectrum of the material
- *Absorption* is the conversion of light to another form of energy, such as heat, sound, or radiation.
- *Absorptivity* is the general spectral property that describes how a material absorbs light at each wavelength.
- *Absorptance* is the specific property of how a particular material sample absorbs light. For example, you can state, "For wavelengths around 1 µm, the *absorptivity* of aluminum coatings are higher than a dielectric coating," and "At 1.064 µm, I measured the *absorptance* of aluminum-coated mirror, serial number 19, to be 500 ppm, which was 300 times the *absorptance* of the dielectric-coated mirror, serial number 11."
- *Aberrations* are deformations to a wavefront of light that occur when the light interacts with an optical surface. Any aberrations are deviations from an ideal wavefront.
- *Absolute* measurements are made without a reference, and not dependent on anything else.
- *Accuracy* is the closeness of a measured value to a desired, nominal value.
- *Adhesive and bonding materials* are liquids that are used to join two materials together permanently. Some adhesives may be optically transmissive to join two glasses together, others may be used to join precision optics to their mechanical mounts.
- *Afocal* telescopes have collimated input and output, imaging an object at positive infinity to an image at negative infinity.
- *Albedo* is a ratio of the total light scattered to the total light incident on a material.
- *Amorphous materials* have their atoms or molecules arranged in a random manner, without structure.
- *Analyzer* (or *analyzing polarizer*) is a polarizer that is located after light of a known polarization interacts with an optical material. Its purpose is to analyze the changes in the polarization state relative to the known polarization prior to the interaction with the optical material.
- *Aspheres* are departures from spherical surfaces that are mathematically created by taking a conic section, whereby a cone is cut, and the resulting cross section is revolved around its axis to form a particular three-dimensional surface. Four different types of shapes can be formed, including a sphere, an ellipsoid, a paraboloid and a hyperboloid. Shaping optical surfaces with aspheres can improve the image quality of an optical system.
- *Attenuation* is the process of diminishing the power of an optical signal, typically due to absorption.
- *Autocollimating alignment telescope* (or *autocollimator*) is a telescope with a narrow field of view used to perform precision optical alignments and angle measurements.

- *Average* or *mean* is the typical, expected value of a data set or measurement. Arithmetically, it equals the sum of all measurements divided by the number of measurements.
- *Bevels* (see *chamfers*)
- *Bi-directional reflectance distribution function (BRDF)* represents the amount of light that is scattered to all angles backward, into the hemisphere towards the source
- *Bi-directional transmittance distribution function (BTDF)* represents the amount of light that is scattered to all angles forward, into the hemisphere away from the source
- *Birefringence* is the phenomenon that occurs because some optical materials have a refractive index that depends on the direction light interacts with the material. It is common for crystalline and plastic optics.
- *Blanks* are precision optical substrates that have not yet undergone any precision optical machining.
- *Bolometers* are resistors that change their resistance value with temperature.
- *Brittleness* is a material property associated with easy fracture under stress without significant strain (deformation).
- *Bubbles* are trapped pockets of air within the bulk structure of a glass optical element.
- *Calibration* describes the process of comparing measurements made by a system or tool to a known, accurate standard, and then applying the appropriate correction values to ensure that future measurements are made relative to the standard.
- *Calipers* are hand tools used to measure distance or length.
- *Calorimetry* is the measurement of temperature, usually associated with precision absorption measurements.
- *Center thickness* is the thickness along the physical center of an optical element; it is not necessarily along the optical axis of the element.
- *Centration* is the process of ensuring that the physical center of an on-axis optical element coincides with its optical axis, spacing all edges equally from the optic's vertex.
- *Chamfers* or *bevels* are features cut into the edges of precision optics to make them less sharp and safer to handle. They are typically cut at 45° to the optical surface so that they form a thin, flat edge around the optic. The size of a chamfer or bevel is typically measured from the edge of the optic inward, not along the length of the chamfer face.
- *Chemical vapor deposition* (CVD) involves the formation of a bulk ceramic structure by causing a chemical reaction between atoms or molecules to take place within a vacuum chamber, and then allowing the resulting compound to deposit down onto a substrate until a solid material forms.
- *Cleanliness classes* define the standards for how clean a *cleanroom* must be when working with precision optics.
- *Cleanliness levels* define the standards for how clean an optical surface must be.

- *Cleanrooms* are special rooms from which air particles are removed continuously by creating a positive pressure from ceiling to floor with respect to the outside world, effectively blowing contaminating particles outside at all times. Cleanrooms are required for handling, cleaning, coating, and assessment of precision optics. Small workbench areas that are clean may be called *clean hoods* or *flowbenches.*
- *Cleanroom supplies* include all equipment required to work in a cleanroom without introducing external contaminants and particles that come off the human body. (To contrast with personal protective equipment that is intended to keep the human body safe from the cleanroom laboratory chemicals.) Equipment including cleanroom suits (aka "bunny suits"), smocks, finger cots, gloves, masks, hair nets, beard covers, and shoe booties are all cleanroom supplies.
- *Clear aperture* or *effective diameter*, denoted $\varnothing_e$ per the ISO 10110 optical drawing standard, is the region of the optical surface that interacts with light. It is always smaller in extent than the physical diameter or surface area of the part.
- *Cleavage* is a property that describes how crystals can be sheared apart along their crystal planes.
- *Coefficient of thermal expansion (CTE)* describes how a material changes size with temperature.
- *Collimated light* travels in a straight line, neither diverging nor converging.
- *Computer numeric control (CNC) milling machines* are advanced multiple-axis (usually three or five) cutting machines that take raw, three-dimensional mechanical drawing files from the optical or optomechanical designer, and use a computer program to control a cutting tool that shapes a raw optical blank into its *near-net shape* prior to optical finishing.
- *Conic constants* mathematically represent aspherical surfaces' departure from a sphere. Conic constants, k, for aspheric optical surfaces are as follows, $k < -1$ are for hyperboloids, $k = -1$ for paraboloids, $-1 < k < 0$ for ellipsoids rotated about their major axis, $k = 0$ for spheres, and $k > 0$ for ellipsoids rotated about their minor axis.
- *Coordinate-measuring machines (CMMs)* are used to measure precisely the features of a mechanical part or precision optic using an encoded multiple-axis (usually three or more) stage and a calibrated sapphire (or ruby) ball tip. The stage is made of a large frame of precision rails within which the CMM can measure the dimensions of parts. The sapphire tip contacts the part being measured from multiple directions, and the points of contact are used to map the dimensions of part's surface.
- *Coring machines* are used to cut the central portion out of a precision optical blank to create annular optics. They operate in a manner similar to *lathes*.
- *Crystal* materials are made of atoms or molecules that are arranged in an ordered manner. Materials can be caused to *crystallize* by forming them slowly and deliberately, particularly by using a host layer to start the crystallization process. *Monocrystalline* materials consist of one uniform crystalline pattern throughout the bulk of the material, while *polycrystalline* materials are comprised of multiple monocrystalline regions with different orientations throughout the bulk, separated by *grain boundaries*.

- *Curvature* of an optical surface is the reciprocal of its radius of curvature. It has units of one over length.
- *Degreasers* are used to remove chemicals, such as greases, oils, paints, waxes, temporary epoxies, and pitches that are introduced during fabrication processes for handling and protection prior to final optical finishing and coating.
- *Detectors* generally describe a material, component, or system that senses light and converts it to an electrical signal.
- *Diameter, outer* describes the maximum physical extent of a circular part.
- *Diameter, inner* describes the maximum extent of the distance cored out of an annular part.
- *Diffraction limit* is the theoretical optimum performance limit for an optical system. If an optical system is said to be diffraction limited, its optics can no longer be improved in fabrication or alignment.
- *Diffraction* is the separation of light into its spectrum by transmission through or reflection off a structured surface.
- *Diffraction efficiency* is the ratio of the power of light diffracted into an order relative to the power of the incident light. The diffraction efficiency of a grating is controlled by the profile and shape of its grooves.
- *Digs* are pits within an optical surface or coating. They, along with scratches, describe the optical surface quality.
- *Discoloration* is a uniform non-clear color throughout the bulk of a material, due to uniform absorption of particular wavelengths throughout the entire material.
- *Dispersion* is the phenomenon that occurs because refractive index is a spectral quantity. Like diffraction, it may be used to separate an optical source into its spectrum.
- *Distance-measuring interferometers (DMIs)* are interferometers with lasers that are pointed by a two-axis gimbal system. DMIs operate by counting interferometric *fringes* to determine the distance from the tracker to the target. The beam is returned to the DMI using precision retroreflectors.
- *Dopants* are impurities that are deliberately added to a material to alter its optical, electrical, or mechanical properties.
- *Ductility* is a material property associated with high elastic deformation under stress.
- *Durability* is an optical material or coating's ability to preserve its surface quality by resisting environmental conditions such as abrasion, adhesion, humidity, fog, or salt water.
- *Edge radii* are rounded features cut into the edges of a precision optic to make it less sharp and safer to handle. They are specified as a radial distance, measured from the edge of the optic inward.
- *Edge thickness* is the thickness of a precision optic at its outer edge. This thickness should be large enough to safely handle the optic. A machine that applies edges to a precision optical element may be called a *edging machine.*

- *Elastic deformation* occurs when stress is applied to and removed from a material, and it returns to its original shape.
- *Ellipsometry* is a polarization-based measurement technique used to determine the complex refractive index of an optical material, particularly thin films. *Ellipsometers* are instruments used to perform ellipsometry measurements.
- *Etchers/engravers/markers* are used to add text to the edges of precision optics to name and number the parts. Marks may be as simple as a felt-tipped marker, but are usually permanent features applied by acid etch or laser engraving.
- *Evaporation* is a thin-film coating technique by which a substrate is coated when the material to be deposited (the *evaporant*) is boiled thermally, as on a stove, or by using a high-energy beam of charged particles like electrons or ions. This method creates a gas of the evaporant that accumulates as a film on the substrate surface.
- *Exceptions* are deviations from optical drawing specifications made by the vendor of an optical element, and (usually) agreed upon with the customer prior to fabrication.
- *Fluorescence* is a form of luminescence that indicates material's ability to emit low-frequency (redder) light when higher-frequency (bluer) light is incident upon it. Glow-in-the-dark materials are common fluorescent materials.
- The *f-number* of an optical system is simply the ratio of its focal length to its clear aperture.
- *Focal length* is the distance from the principal plane of an optical system to the focal point.
- *Focal point* is the point at which light from optical infinity converges.
- *Fourier-transform infrared (FTIR) spectrometer* is an optical instrument used typically to measure the infrared radiometric properties (reflectivity or transmissivity) of a material.
- *Fracture toughness* is most specifically related to digs, a material's ability to resist cracks, chips, and other forms of fracture.
- *Fractures* are physical breaks in a material's structure.
- *Freeform* surfaces are surfaces of any form that can be freely described, usually by a complex mathematical equation.
- *Fringes* are formed when two beams interfere in an interferometer. They represent the relative phase of one beam relative to the other as dark and light bands.
- *Gauge blocks of thickness and angle* are calibrated references (of thickness or angle) that are used as references for distance and angle measurements. Thickness gauge blocks may also be called *parallels.*
- *Gauge of height, hole, and depth* are tools used to measure the size of a precision optic's features. They are either calibrated tools or measurements are made relative to a reference such as a granite slab.
- *Glass code* is a six-digit glass code concatenates the first three decimals of the refractive index with the first three significant figures of the Abbe number, both as measured at the helium d-line of 587.56 nm. For instance, if the refractive index of a material is 1.ABC and its Abbe number is XY.Z, the glass code is ABCXYZ.

- *Gloves and finger cots* are protective equipment designed to keep human contaminants off optical surfaces and to keep potentially hazardous cleanroom chemicals off the user. Either is required when handling precision optics. Gloves cover the entire hand up to the wrist, while finger cots are rolled over each finger individually. They are typically made of latex or nitrile.
- *Goniometers* are two- or three-axis rotation stages designed to rotate about a point on the optical surface of a part.
- *Grain boundaries* are the regions between two monocrystalline regions within a polycrystalline material. If they are present in optical materials, they act as scattering sites.
- *Granite slab workbenches* are flat reference surfaces used for gauge-based height and depth measurements. They are often used to measure optical surfaces because they hold their extremely flat form over temperature and time.
- *Grinders* are coarse cutting materials used to shape a precision optic after it has been cut to near-net shape, prior to polishing. The material-removal mechanisms are often similar to, but coarser than those used in polishing systems.
- *Handling materials* are any items that come in contact with precision optics throughout their fabrication process. Handling materials should always be cleaner than the precision optic at each stage of the process. Materials for handling finished, coated optics must be cleaner than the specified requirement for the optic itself.
- *Hardness* is a material's ability to withstand pressure (force per area) without changing form.
- *Inclusions* are defects to the crystal matrix that forms the optic, usually caused by grain boundaries or impurities.
- *Impurities* are undesirable materials that happen to enter an optical material during its manufacture.
- *Inspection hoods* are dark enclosures that are used to inspect the surface quality and coating quality of a precision optic. They are made typically from a blackened box and a single large-area, uniform, narrowband (usually green) illumination source to facilitate the inspection.
- *Integrating spheres* are optical instruments used to illuminate uniformly the input plane of an optical system. These devices create the most uniform possible light source.
- An *interference pattern* (or *interferogram*) is the distribution of interferometric fringes over a detector. They are indicative of the optical aberrations or the wavefront error of an optical system.
- *Interferometry* is the science of causing two (or more) beams of light to superpose and create fringes based on the relationship of the phases of the beams of light. An *interferometer* is an essential measurement tool for evaluation and quality assurance of optical materials.
- *Internal stress* is residual force per area within the bulk of a material. Stresses are often relieved by fabrication processes such as annealing.
- *Laser trackers* measure the point locations of retroreflector targets in a three-dimensional volume. A laser from a distance-measuring interferometer (DMI) is pointed by a two-axis

gimbal system. The DMI counts fringes to determine the distance from the tracker to the targets as well as the azimuth and elevation angles of the tracker head via high-resolution angle encoders. Laser trackers are often referred to as optical or frameless coordinate-measurement machines (CMMs).

- *Lathes* are machining tools that rotate the part as it contacts a sharp tip. They may be used for cutting, grinding, or edging precision optics, among many other machining operations.
- *Linear polarizers* are optical devices that output linear polarized light when light transmits through them. They often function by absorbing light of one linear polarization while transmitting the other.
- *Loupes* (or Jewelers' loupes) are magnifying lenses with short working distances giving magnification values nominally ranging from 3x to 100x.
- *Luminescence* is a material's ability to emit light due to an external stimulus, such as an electrical signal or ultraviolet radiation.
- *Micrometers* are hand tools used to measure the thickness of a material.
- *Microscopes* are instruments used to magnify and view tiny objects. When working with precision optics, they are often used to view internal and surface flaws.
- *Mid-spatial frequency (MSF) error* is the value of an MTF curve in the middle, for spatial frequencies of moderate value. It is important because some residual material characteristics caused by optical fabrication techniques can suppress the spatial resolution of optical systems for these moderate spatial frequencies.
- *Mills* are machines used to make precision cuts in bulk materials. Unless operated by computer (see *CNC mills*), they are controlled by hand using calibrated stages and dials. They typically use a hardened steel or diamond-tipped tool to cut metal or glass to shape. *Water-jet milling* is also common for cutting optical substrates. *Bridgeport mills* are often used to refer to milling machines with their tool's rotation axis oriented vertically, with a translation stage for the part beneath it (like a drill press).
- *Modulation transfer function (MTF)* represents an optical system's ability to resolve spatial frequencies in the images it forms.
- *Monochromator* is an optical instrument that outputs narrow spectral bands of light by spatially filtering a broadband source. It is used to send individual colors onto a material during a radiometric measurement.
- *Mounting materials* are required to hold precision optical elements during grinding and polishing. These materials may include plaster, pitch, or wax, among other temporary bonding materials.
- *Near-net shape* or *raw machined blank* describes the state of a precision optic after it has been cut from a large blank piece of raw material, prior to final finishing (by grinding and polishing).
- *Nominal specifications* are the values written on a manufacturing drawing about which a tolerance will be specified. The closeness of a measured value to the nominal value gives its accuracy.

- *Non-volatile residue (NVR)* is material that remains on a surface and cannot be removed by thermal techniques such as evaporation. Often, a large amount of NVR can be cleaned, but there will always be some NVR lingering on an optical surface—this defines the cleanliness level of an optical surface.
- *Numerical aperture* of an optical system is defined as the reciprocal of twice its f-number. For an optical fiber, it equals the cosine of the critical angle times the refractive index of the fiber core.
- *Optical density* refers to the absorbance of an optical material as a base-ten logarithmic ratio of the incident to transmitted irradiance. The optical density of a material therefore is given as integers that represent the transmission of a material as factors of ten: a material with an optical density of 5 transmits ten times less light per wavelength than a material with an optical density of 4, which transmits ten times less light per wavelength than a material with an optical density of 3, etc.
- *Optical flat* describes the concept of a surface being so flat that it may be used as a reference for flatness measurements. Typically, optical flats are specified to have peak-to-valley reflected wavefront error on the order of tens of nanometers.
- *Optical infinity* describes the concept of an object being significantly distant from the optical system so that additional distance will not alter the imaging performance of the optical system. For most optical systems, an object distance of tens of meters approximates optical infinity.
- *Optical surface* describes the surface of a material that is designed to interact with light.
- *Parallels* (see *Gauge blocks of thickness and angle*)
- *Peak-to-valley* describes a measured parameter's maximum (peak) plus minimum (valley) excursion.
- *Personal protective equipment (PPE)* is any clothing worn to protect the user from the chemicals with which they work (to contrast with the equipment that protects optical hardware from human contaminants). PPE may include goggles, gloves, smocks, aprons, face masks, and booties.
- *Photoelastic effect* is a technique by which stress birefringence is observed in stressed materials by placing them into a polariscope, between two crossed polarizers, to reveal colors that represent their internal stress distribution.
- *Pitch* or *polyurethane pads* are viscoelastic (dense, springy) materials that are shaped to the desired form of the precision optic. An abrasive slurry is located between the optical material being processed and the pitch or pad, and the pitch or pad is moved over the optic (or *vice versa*) to polish the optical material into its desired shape.
- *Plastic deformation* occurs when stress is applied to and removed from a material, and it distorts and does not return to its original shape.
- *Polarimetry* is the science of measuring the polarization of light; p*olarimeters* or *polariscopes* are systems that measures light's polarization as it transmits through an optical material.

- *Polarization-dependent quantities* state that a particular property of an optical material changes with the polarization of the light that interacts with it.
- *Polishing* involves moving fine abrasives over the optical surface in a careful, repeatable manner to form the surface into the exact shape that was prescribed by an optical designer. The process of polishing is often called *finishing*.
- *Polishers* are machines used to polish optical surfaces. They are usually comprised of a rotating wheel made of pitch or a viscoelastic pad that is coated with a layer of abrasive slurry. *Planetary polishers* are polishers that have two nested stages of rotation. They consist of a large pitch or pad wheel that rotates beneath the circular optic. In turn, this circular optic rotates on its own within a ring that encloses it—this ring has a diameter of about half that of the large wheel. The result is a more uniform polish over time.
- *Porosity* is a surface defect where voids or holes remain in an optical surface, usually after coating.
- *Precision* is the deviation of many measurements from the average value measured. It is the spread about the value of the accuracy and the ability of a measurement to be reproduced consistently. A high-precision part will have a small spread about the mean measurement.
- *Principal plane* is the plane of effective refraction. For thin lenses, this is the center plane through the lens. For thick, compound lenses, it can be found by inputting collimated light, and tracing back the focused light in output space to where it meets the height of the collimated light.
- *Protective materials* are any items that are used to protect precision optics from contamination, tooling, and handling throughout their fabrication process. The protective materials should always be removable using a solvent or degreaser system. Materials used for protecting optics must might include plaster, pitch, wax, or paint.
- *Quantitative* measurements reveal a specific number, rather than a quality, about the value of a material property.
- *Radiometric properties* of a material relate how it transmits, reflects, absorbs, or emits light.
- *Radius of curvature* equals the distance from a spherical surface to its center point.
- *Radius slide* is a linear rail tool used with an interferometer to measure the radius of a surface or focal length of a lens or mirror.
- *References* are calibrated materials that may be flat, concave spherical, or convex spherical surfaces. They may be reflective or transmissive. In general, references are fabricated to standards that are at least ten times better than the surfaces to which they will be compared.
- *Reflection* is the process of light bouncing off a material.
- *Reflectivity* is the general spectral property that describes how a material reflects light at each wavelength.
- *Reflectance* is the specific property of how a particular material sample reflects light. For example, you can state, "For wavelengths less than 580 nm, the reflectivity of a gold-coated mirror is much lower than a silver-coated mirror," and "At 500 nm, I measured the

reflectance of gold-coated mirror serial number 9, to be 30% less than silver-coated mirror serial number 5."

- *Reflected wavefront error (RWFE)* is the deviation from an ideal wavefront after light reflects from a precision mirror.
- *Refraction* is the process of light bending as it moves from one optical material to another due to the difference in refractive index.
- *Refractive index* is the factor by which the speed of light is reduced in a material.
- *Refractometers* are instruments used to measure refractive indexes.
- *Relative* measurements are those made when the part being measured is compared to a reference material.
- *Resolution* is the minimum observable increment of a measurement.
- *Resolution targets* (see *Ronchi rulings*)
- *Reticles* are calibrated references that are superimposed in the image plane of optical instruments in order to calibrate the dimensions in the field of view and quantify a measurement.
- *Retroreflectors* (or *cornercubes*) are literally corners of coated glass cubes that operate by reflecting light back at the same angle of incidence in the opposite ("retro") direction. When retroreflecting, incident light bounces off all three sides of the cube before exiting the incident face traveling in the same direction. Some coating materials, such as 3M's Scotchlite (commonly seen coating street signs and running shoes), are retroreflective. Tiny spheres embedded in the coating act as an array of tiny retroreflectors.
- *Ronchi rulings* are alternating opaque and clear bands that form patterns with various spatial frequency. They are used to quantify the resolution of an optical system.
- *Root-mean square (RMS)* is a statistical measurement of the magnitude of a varying value. It is used commonly to quantify the error of an optical wavefront, since the phase of the wavefront is a varying value across the clear aperture of a precision optic.
- *Roughness* describes small, high-frequency deviations from flatness in an optical surface. Roughness indicates the material's surface finish.
- *Sag* is the departure of an optical surface from a planar surface.
- *Saws* are used to perform cuts to bulk glass, metal, and other optical materials. Common saws found in an optical shop include Miter (or "cut-off") saws as well as wire saws and band saws.
- *Scattering* occurs when light is diffusely reflected by a surface into multiple directions. Since most scattered light is no longer going in the specular direction, scattering is considered loss of energy.
- *Sclerometer* is a tool used to measure scratch resistance.
- *Scratches* are elongated cuts into an optical surface or coating. They, along with digs, describe the optical surface quality.
- *Scratch resistance* is a materials ability to withstand abrasive contact with other materials.

- *Scratch-dig references* are calibrated standards, made per the scratch-dig specifications of MIL-PRF-13830 and ISO 10110. They specify the quantity and character of the optical surface quality as a cosmetic reference.
- *Shadowgraph* is a technique used to assess the internal flaws of a material by shining diverging light through the material and casting a projection on a screen. The nature of the light's divergence will magnify flaws.
- *Shear plate interferometers* are used to test collimation. They produce straight-line fringes when a collimated beam passes through them, and curved fringes when transmitting a diverging or converging beam.
- *Single point diamond turning* (SPDT) uses a hard, sharp diamond tool embedded in a special CNC machine tool to cut a part to its final shape. This machine is a combination of a lathe and a mill—typically, they function by moving the part in a rotating chuck (mount) in three axes about a stationary diamond tip or by moving the diamond tip in three axes about the rotating part.
- *Sintering* is the process of forming a bulk material by crushing a powder of the material together under intense heat and pressure.
- *Slurries* (or abrasive slurries) are a mixture of abrasives and water that resides between the optical element being polished and the pitch that is shaped to form the optical surface; polishing gradually cuts down the optic to a smooth, high-quality surface finish.
- *Snell's Law* is the formula used to determine the angle to which light refracts when it moves from one material to another. It is dependent on the angle of incidence, angle of refraction, and the refractive indexes of the two materials.
- *Solvents* are chemicals designed to remove contaminants from the surface of a precision optical element. Common optical cleanroom solvents include isopropyl alcohol (isopropanol), methyl alcohol (methanol), acetone, and methyl ethyl ketone (MEK).
- *Sources* are any materials or systems that emit light.
- *Specifications* are values that fulfill the exact manufacturing requirements for a part.
- *Spectral attenuation coefficient* is the coefficient on the exponent of Beer-Lambert Law, given in units of inverse length. Essentially, it describes how much a material absorbs light as a function of the material's thickness.
- *Spectral quantities* state that a particular property of an optical material changes with the wavelength of the light that interacts with it.
- *Spectral signature* of a material is its characteristic reflection, transmission, absorption, or emission. This property is used to discern materials using spectroscopy.
- *Spectroscopy* (also *spectrometry*) is the measurement of the quantity of light at each wavelength before and after it interacts with an optical material.
- *Spectrophotometers* are tools used to measure radiometric properties of a material, such as reflectivity and transmissivity, in the visible portion of the spectrum.
- *Spectroradiometers* are tools used to measure radiometric properties of a material, such as reflectivity and transmissivity, in any portion of the spectrum, particularly in the infrared.

- *Specular reflection* occurs when incident light reflects from a surface in a uniform, predictable manner, as from a mirror surface. Only extremely flat or well-polished reflective surfaces reflect light in a specular manner.
- *Spherometer*s are used to measure the sag of an optical surface from a plane. Knowing the sag, the surface's radius may be calculated.
- *Sputtering* is a thin-film deposition process by which a substrate is coated when the material to be deposited (the target) is bombarded by a third material, called the *sputterant*. This method creates a fog of the coating material that accumulates as a film on the substrate surface.
- *Stereomicroscope* is a microscope with two eyepieces that provide an independent perspective of the object being viewed for both eyes, allowing a three-dimensional (stereo) image to form.
- *Storage materials* for precision optics must be cleaner than the cleanliness requirement precision optic itself. They must not contact or contaminate the optical surfaces, and they must not deteriorate over time or repeated use.
- *Strain* gives the amount of deformation of a material when a stress is applied.
- *Stray light* refers to any unexpected light in a system. It is often eliminated or controlled by baffles.
- *Stress* is an external force per cross-sectional area applied to a material.
- *Substrates* are the base material on which a coating is deposited.
- *Surface figure* is the detailed shape of an optical surface, like a topographical map with highs above and lows below the average surface shape.
- *Surface finish* gives the roughness of an optical surface.
- *Surface profilers* are instruments used to measure the roughness of an optical surface.
- *Surface quality* of an optical surface is given by the amount of scratches and digs in the surface.
- *Test plates* are references used to make relative measurements of the surface figure of precision optics.
- *Thermal shock* results in material damage when significant temperature changes are imposed on a material.
- *Tilt* refers to rotation of an optical element about a vertical axis. Generally, it includes tip in its definition, discerning as x-tilt (about a vertical axis) and y-tilt (about a horizontal axis).
- *Tip* refers to rotation of an optical element about a horizontal axis. More often, it is called y-tilt.
- *Tolerance* is the range of values allowed for a specification in order for the manufactured part to be acceptably within that specification.

- *Total indicated runout (TIR)* gives the deviation from the optical center of a precision optic. It is usually measured by placing a depth gauge at the edge of an optical element as that element is rotated about its vertex.
- *Total internal reflection (TIR)* is a phenomenon that causes complete reflection of light when it strikes a material of lower refractive index at angles greater than a critical angle.
- *Transmission* is the process of light passing through a material.
- *Transmissivity* is the general spectral property that describes how a material transmits light at each wavelength.
- *Transmittance* is the specific property of how a particular material sample transmits light. For example, you can state, "For wavelengths greater than 2.5 μm, the transmissivity of fused silica is higher than BK7," and "At 2.65 μm, I measured the transmittance of this fused silica window, serial number 2, to be three times that of BK7 window, serial number 15."
- *Transmitted wavefront error (TWFE)* is the deviation from an ideal wavefront after light transmits through a precision optical element or entire optical system.
- *Vertex* defines the center point on the surface of an optical element about which the optical element is symmetric in all directions. The radius of a spherical optical surface will pass through its center point and its vertex.
- *Wavefront* is a cross-section of a beam of light that gives the phase of the light at every point along that cross-section.
- *Waveplates* are devices that change the polarization of the light. Also called *phase retarders*.
- *Wedge* is a thickness deviation across the diameter of an optical element. Usually deliberately fabricated into optical windows.
- *Wipes or optical wipes* are soft, lint-free cloths, typically made of a synthetic material, used to package and handle precision optics.
- *Witness samples* are typically flat, 1"-diameter windows that are made of the same material, undergo similar processing, and have identical coatings as a precision optic. They are created to represent the optical properties of the precision optic while ensuring safety in handling the final (usually expensive) precision optic.
- *Wollaston prisms* are prism pairs that form basic polarimetric devices. After unpolarized incident light passes the prism pair, each polarization state is diverged to a different angle.