Introduction

Even though several thousand different optical components are listed in this catalog, performing a few simple calculations will usually determine the appropriate optics for an application or, at the very least, narrow the list of choices.

The process of solving virtually any optical engineering problem can be broken down into two main steps. First, paraxial calculations (first order) are made to determine critical parameters such as magnification, focal length(s), clear aperture (diameter), and object and image position. These paraxial calculations are covered in the next section of this chapter.

Second, actual components are chosen based on these paraxial values, and their actual performance is evaluated with special attention paid to the effects of aberrations. A truly rigorous performance analysis for all but the simplest optical systems generally requires computer ray tracing, but simple generalizations can be used, especially when the lens selection process is confined to a limited range of component shapes.

In practice, the second step may reveal conflicts with design constraints, such as component size, cost, or product availability. System parameters may therefore require modification.

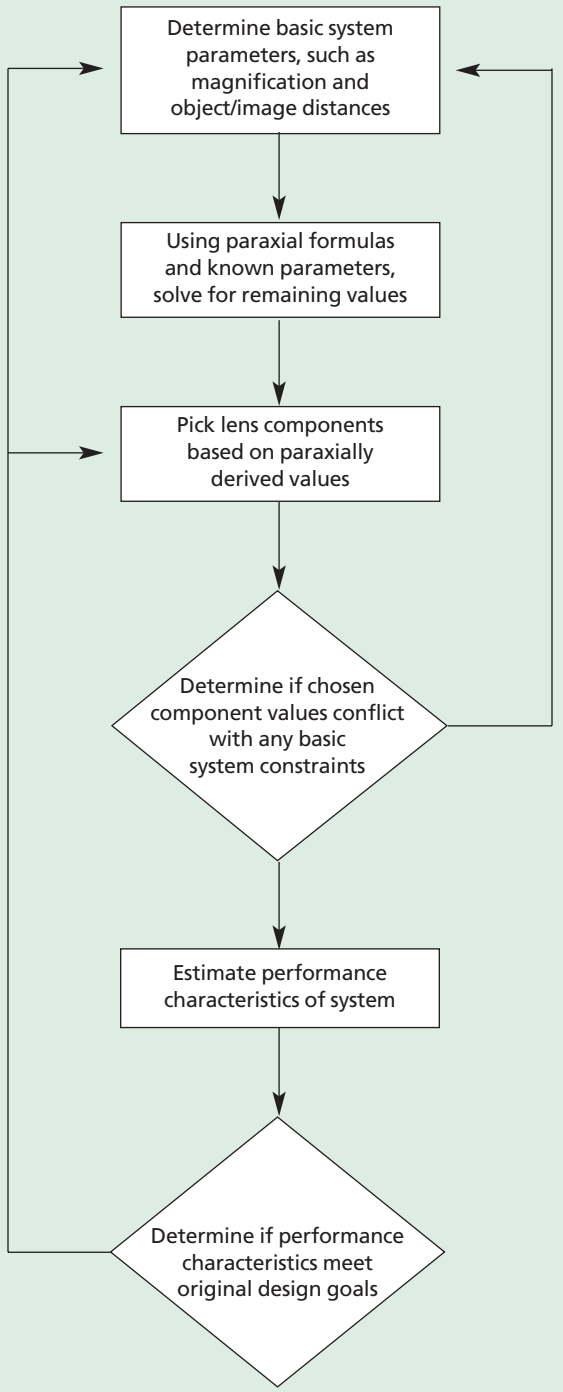
Because some of the terms used in this chapter may not be familiar to all readers, a glossary of terms is provided beginning on page 1.29.

Finally, it should be noted that the discussion in this chapter relates only to systems with uniform illumination; optical systems for Gaussian beams are covered in Chapter 2, *Gaussian Beam Optics*.

ENGINEERING SUPPORT

Melles Griot maintains a staff of knowledgeable, experienced applications engineers at each of our facilities worldwide. The information given in this chapter is sufficient to enable the user to select the most appropriate catalog lenses for the most commonly encountered applications. However, when additional optical engineering support is required, our applications engineers are available to provide assistance. Do not hesitate to contact us for help in product selection or to obtain more detailed specifications on Melles Griot products.

THE OPTICAL ENGINEERING PROCESS



Paraxial Formulas

SIGN CONVENTIONS

The validity of the paraxial lens formulas is dependent on adherence to the following sign conventions:

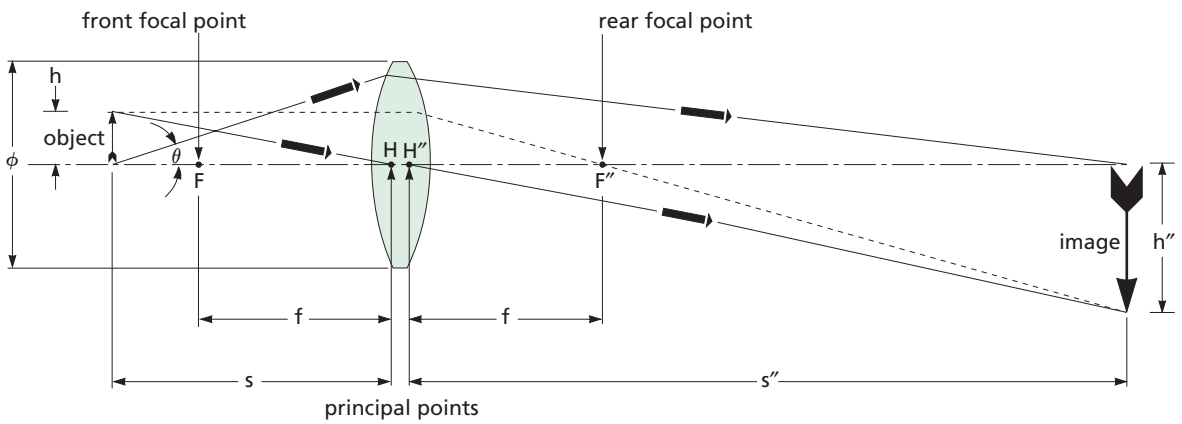
For lenses: (refer to figure 1.1)

- s is + for object to left of H (the first principal point)
- s is – for object to right of H
- s″ is + for image to right of H″ (the second principal point)
- s″ is – for image to left of H″
- m is + for an inverted image
- m is – for an upright image

For mirrors:

- f is + for convex (diverging) mirrors
- f is – for concave (converging) mirrors
- s is + for object to left of H
- s is – for object to right of H
- s″ is – for image to right of H″
- s″ is + for image to left of H″
- m is + for an inverted image
- m is – for an upright image

When using the thin-lens approximation, simply refer to the left and right of the lens.



Note location of object and image relative to front and rear focal points.

ϕ = lens diameter

m = s″/s = h″/h = magnification or conjugate ratio, said to be infinite if either s″ or s is infinite

θ = arcsin (ϕ/2s)

h = object height

h″ = image height

s = object distance, positive for object (whether real or virtual) to the left of principal point H

s″ = image distance (s and s″ are collectively called conjugate distances, with object and image in conjugate planes), positive for image (whether real or virtual) to the right of the principal point H″

f = effective focal length (EFL) which may be positive (as shown) or negative. f represents both FH and H″F″, assuming lens to be surrounded by medium of index 1.0

Figure 1.1 **Sign conventions**

Typically, the first step in optical problem solving is to select a system focal length based on constraints such as magnification or conjugate distances (object and image distance). The relationship among focal length, object position, and image position is given by

$$\frac{1}{f} = \frac{1}{s} + \frac{1}{s''} . \qquad (1.1)$$

This formula is referenced to figure 1.1 and the sign conventions given on page 1.3.

By definition, magnification is the ratio of image size to object size or

$$m = \frac{s''}{s} = \frac{h''}{h}. \qquad (1.2)$$

This relationship can be used to recast the first formula into the following forms:

$$f = m\frac{(s + s'')}{(m + 1)^2} \qquad (1.3)$$

$$f = \frac{sm}{m + 1} \qquad (1.4)$$

$$f = \frac{s + s''}{m + 2 + \frac{1}{m}} \qquad (1.5)$$

$$s\ (m + 1) = s + s'' \qquad (1.6)$$

where $(s + s'')$ is the approximate object-to-image distance.

With a real lens of finite thickness, the image distance, object distance, and focal length are all referenced to the principal points, not to the physical center of the lens. By neglecting the distance between the lens' principal points, known as the hiatus, $s + s''$ becomes the object-to-image distance. This simplification, called the thin-lens approximation, can speed up calculation when dealing with simple optical systems.

Example 1: Object outside Focal Point

A 1-mm-high object is placed on the optical axis, 200 mm left of the left principal point of a 01 LDX 103 (f = 50 mm). Where is the image formed, and what is the magnification? (See figure 1.2.)

$$\frac{1}{s''} = \frac{1}{f} - \frac{1}{s}$$

$$\frac{1}{s''} = \frac{1}{50} - \frac{1}{200}$$

$$s'' = 66.7 \text{ mm}$$

$$m = \frac{s''}{s} = \frac{66.7}{200} = 0.33$$

(or real image is 0.33 mm high and inverted).

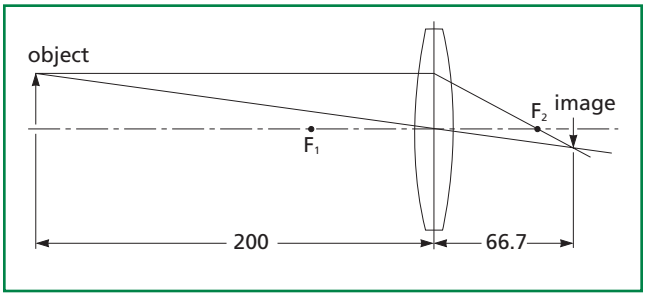


Figure 1.2 **Example 1** (f = 50 mm, s = 200 mm, s″ = 66.7 mm)

Example 2: Object inside Focal Point

The same object is placed 30 mm left of the left principal point of the same lens. Where is the image formed, and what is the magnification? (See figure 1.3.)

$$\frac{1}{s''} = \frac{1}{50} - \frac{1}{30}$$

$$s'' = -75 \text{ mm}$$

$$m = \frac{s''}{s} = \frac{-75}{30} = -2.5$$

(or virtual image is 2.5 mm high and upright).

In this case, the lens is being used as a magnifier, and the image can be viewed only back through the lens.

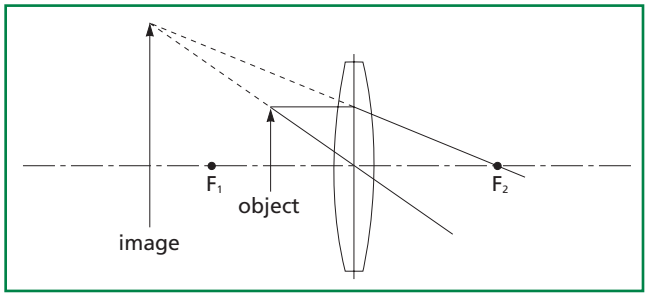


Figure 1.3 **Example 2** (f = 50 mm, s = 30 mm, s″ = −75 mm)

Example 3: Object at Focal Point

A 1-mm-high object is placed on the optical axis, 50 mm left of the first principal point of an 01 LDK 019 (f = 50 mm). Where is the image formed, and what is the magnification? (See figure 1.4.)

$$\frac{1}{s''} = \frac{1}{-50} - \frac{1}{50}$$

$$s'' = -25 \text{ mm}$$

$$m = \frac{s''}{s} = \frac{-25}{50} = -0.5$$

(or virtual image is 0.5 mm high and upright).

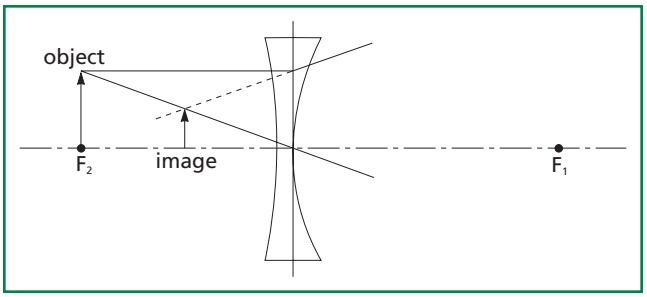


Figure 1.4 **Example 3** (f = −50 mm, s = 50 mm, s″ = −25 mm)

A simple graphical method can also be used to determine paraxial image location and magnification. This graphical approach relies on two simple properties of an optical system. First, a ray that enters the system parallel to the optical axis crosses the optical axis at the focal point. Second, a ray that enters the first principal point of the system exits the system from the second principal point parallel to its original direction (i.e., its exit angle with the optical axis is the same as its entrance angle). This method has been applied to the three previous examples illustrated in figures 1.2 through 1.4. Note that by using the thin-lens approximation, this second property reduces to the statement that a ray passing through the center of the lens is undeviated.

F-NUMBER AND NUMERICAL APERTURE

The paraxial calculations used to determine necessary element diameter are based on the concepts of focal ratio (f-number or f/#) and numerical aperture (NA). The f-number is the ratio of the focal length of the lens to its clear aperture (effective diameter).

$$\text{f-number} = \frac{f}{\phi}. \tag{1.7}$$

To visualize the f-number, consider a lens with a positive focal length illuminated uniformly with collimated light. The f-number defines the angle of the cone of light leaving the lens which ultimately forms the image. This is an important concept when the throughput or light-gathering power of an optical system is critical, such as when focusing light into a monochromator or projecting a high-power image.

The other term used commonly in defining this cone angle is numerical aperture. Numerical aperture is the sine of the angle made by the marginal ray with the optical axis. By referring to figure 1.5 and using simple trigonometry, it can be seen that

$$NA = \sin\theta = \frac{\phi}{2f} \tag{1.8}$$

or

$$NA = \frac{1}{2(\text{f-number})}. \tag{1.9}$$

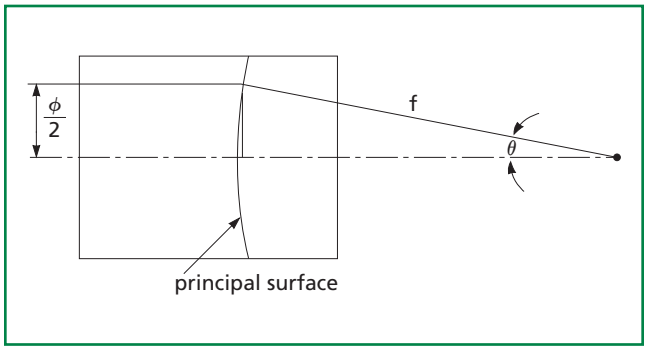


Figure 1.5 **F-number and numerical aperture**

Ray f-numbers can also be defined for any arbitrary ray if its conjugate distance and the diameter at which it intersects the principal surface of the optical system are known.

NOTE

Because the sign convention given previously is not used universally in all optics texts, the reader may notice differences in the paraxial formulas. However, results will be correct as long as a consistent set of formulas and sign conventions is used.