Chapter

6

Stops and Apertures

6.1 Introduction

In every optical system, there are apertures (or stops) which limit the passage of energy through the system. These apertures are the clear diameters of the lenses and diaphragms in the system. One of these apertures will determine the diameter of the cone of energy which the system will accept from an axial point on the object. This is termed the *aperture stop,* and its size determines the illumination (irradiance) at the image. Another stop may limit the size or angular extent of the object which the system will image. This is called the *field stop.* The importance of these stops to the photometry (radiometry) and performance of the system cannot be overemphasized.

The elements of an inexpensive camera system are sketched in Fig. 6.1 and illustrate both aperture and field stops in their most basic forms. The diaphragm in front of the lens limits the diameter of the bundle of rays that the system can accept and is thus the aperture stop. The mask adjacent to the film determines the angular field coverage of the system and is quite apparently the field stop of the camera.

Not all systems are as obvious as this, however, and we will now consider more complex arrangements. Because the theory of stops is readily explained by the use of a concrete example, the following discussions will be with reference to Fig. 6.2, which is a highly exaggerated sketch of a telescopic system focused on an object at a finite distance. The system shown consists of an objective lens, erector lens, eyelens, and two internal diaphragms. The objective forms an inverted image of the object. This image is then reimaged at the first focal

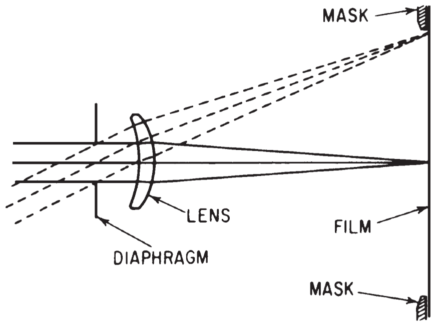

Figure 6.1 The elements of a simple box camera illustrate the functions of elementary aperture and field stops (the diaphragm and mask, respectively).

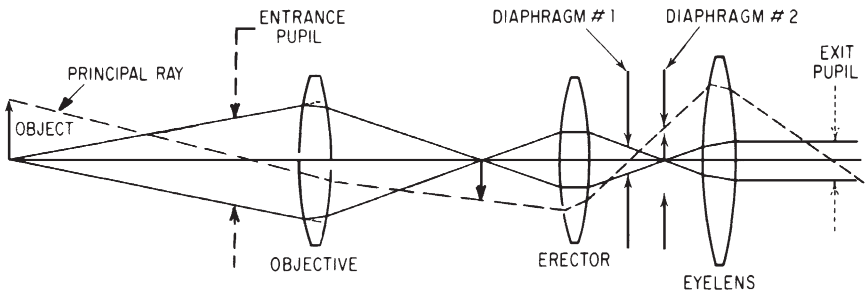

Figure 6.2 Schematic sketch of an optical system to illustrate the relationships between pupils, stops, and fields.

point of the eyelens by the erector lens, so that the eyelens forms the final image of the object at infinity.

6.2 The Aperture Stop and Pupils

By following the path of the axial rays (designated by solid lines) in Fig. 6.2, it can be seen that diaphragm #1 is the aperture of the system which limits the size of the axial cone of energy from the object. All of the other elements of the system are large enough to accept a bigger cone. Thus, diaphragm #1 is the aperture stop of the system.

The oblique ray through the center of the aperture stop is called the *principal,* or *chief, ray,* and is shown in the figure as a dashed line. The *entrance* and *exit pupils* of the system are the images of the aperture stop in object and image space, respectively. That is, the entrance pupil is the image of the aperture stop as it would be seen if viewed from the axial point on the object; the exit pupil is the aperture stop image as it would be seen if viewed from the final image plane (in this case, at an infinite distance). In the system of Fig. 6.2, the entrance pupil lies near the objective lens and the exit pupil lies to the right of the eyelens.

Notice that the initial and final intersections of the dashed principal ray with the axis locate the pupils, and that the diameter of the axial cone of rays at the pupils indicates the pupil diameters. It can be seen that, for any point on the object, the amount of radiation accepted by, and emitted from, the system is determined by the size and location of the pupils.

6.3 The Field Stop

By following the path of the principal ray in Fig. 6.2, it can be seen that another principal ray starting from a point in the object which is farther from the axis would be prevented from passing through the system by diaphragm #2. Thus, diaphragm #2 is the field stop of this system. The images of the field stop in object and image space are called the *entrance* and *exit windows,* respectively. In the system of Fig. 6.2, the entrance window is coincident with the object and the exit window is at infinity (which is coincident with the image). Note that the windows of a system do not coincide with the object and image unless the field stop lies in the plane of a real image formed by the system.

The angular field of view is determined by the size of the field stop, and is the angle which the entrance or exit window subtends from the entrance or exit pupil, respectively. The angular field in object space is frequently different from that in image space. (Alternate definition: the angular field of view is the angle subtended by the object or image from the first or second nodal point of the system, respectively. Thus, for nontelescopic systems in air, object and image field angles are equal according to this definition. Note that this definition cannot be applied to an afocal system, which has no nodal or principal points.)

6.4 Vignetting

The optical system of Fig. 6.2 was deliberately chosen as an ideal case in which the roles played by the various elements of the system are definite and clear-cut. This is not usually the situation in real optical systems, since the diaphragms and lens apertures often play dual roles.

Consider the system shown in Fig. 6.3, consisting of two positive lenses, A and B. For the axial bundle of rays, the situation is clear; the aperture stop is the clear aperture of lens A, the entrance pupil is at A, and the exit pupil is the image, formed by lens B, of the diameter of lens A.

Some distance off the axis, however, the situation is markedly different. The cone of energy accepted from point D is limited on its lower edge by the lower rim of lens A and on its upper edge by the upper rim of lens B. The size of the accepted cone of energy from point D is

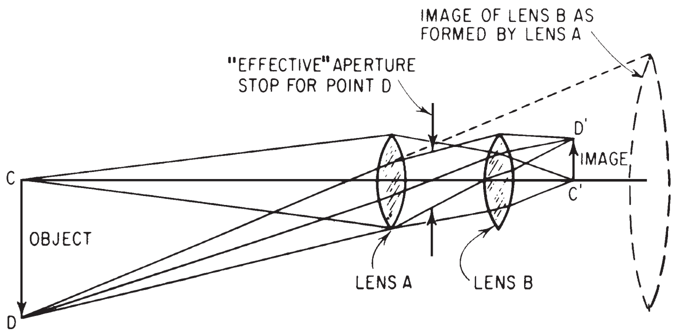

Figure 6.3 Vignetting in a system of separated components. The cone of rays from point *D* is limited by the lower rim of lens *A* and the upper rim of *B,* and is smaller than the cone accepted from point *C.* Note that the upper ray from *D* just passes through the image of lens *B* which is formed by lens *A.*

less than it would be if the diameter of lens *A* were the only limiting agency. This effect is called *vignetting,* and it causes a reduction in the illumination at the image point *D′*. It is apparent that for some object point still farther from the axis than point *D,* no energy at all would pass through the system; thus there is no field stop per se in this system as shown.

The appearance of the system when viewed from point *D* is shown in Fig. 6.4. The entrance pupil has become the common area of two circles, one the clear diameter of lens *A,* and the other the diameter of lens *B* as imaged by lens *A.* The dashed lines in Fig. 6.3 indicate the location and size of this image of *B,* and the arrows indicate the "effective" aperture stop which has a size, shape, and position completely different than that for the axial case.

In a photographic lens with an adjustable iris diaphragm, its location should be such that when stopped down to a small diameter, its clear aperture is centered in the vignetted oblique beam.

Example A

Let us determine the pupils, windows, and fields of an optical system of the type shown in Fig. 6.2, assuming the lenses to be "thin lenses." The elements of the system are as follows:

Objective	clear aperture = 2.3 in effective focal length = 10 in
Erector	clear aperture = 1.7 in effective focal length = 2 in
Eyelens:	clear aperture = 1.3 in effective focal length = 1 in

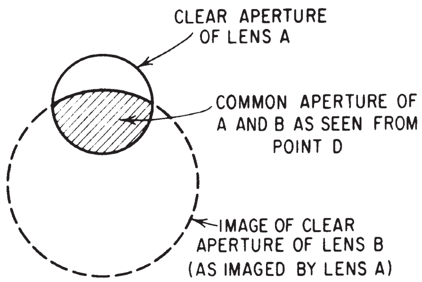

Figure 6.4 The apertures of the optical system of Fig. 6.3 as they are seen from point *D*.

Diaphragm #1: clear aperture = 0.25 in

Diaphragm #2: clear aperture = 0.7 in

Distance, object to objective: 50 in

Distance, objective to erector: 16.5 in

Distance, erector to eyelens: 5 in

Distance, erector to diaphragm #1: 2.38 in

Distance, erector to diaphragm #2: 4 in

We begin the analysis by tracing a paraxial ray from the object point on the axis, using the thin lens raytracing equations (2.41 and 2.42) of Chap. 2. We insert two zero-power elements in the system to represent the diaphragms, so that we can determine the ray heights at the diaphragms. We assume a nominal ray height of +1.0 at the objective lens, giving $u_1 = [1.0/(-50.) = +0.02$. The calculation is shown in the table of Fig. 6.5, lines 3 and 4.

To determine which element of the system limits the diameter of the axial cone of rays, we add to our tabulation lines 5 and 6, showing the clear aperture of each element (*CA*) and the ratio of the clear aperture to the height that the axial ray strikes the element (*CA*/*y*).The element for which this ratio is the smallest, in this case diaphragm #1, is the aperture stop. Because of the linear nature of the paraxial equations, we can get the *y* and *u* values for any other axial ray by multiplying each entry in lines 3 and 4 by the same constant. If we use for the constant the value of $\frac{1}{2}$ *CA*/*y* for diaphragm #1 (0.9645), we will get the data for a ray which just passes through the rim of diaphragm #1. This ray data is shown in lines 7 and 8 of the table. A comparison of the new *y* values of line 7 with the clear apertures of line 5 indicates that the ray will pass through all the other elements with room to spare.

To determine the locations of the pupils, we trace a ray through the center of the aperture stop (diaphragm #1) in each direction. The data of such a ray is shown in lines 9 and 10 of the table. We then determine the axial intersections of this ray in object and image space and find that the (apparent) entrance pupil is located 0.1631/0.02474 =

	Object plane		Objective lens		Erector lens		Diaphragm #1		Diaphragm #2		Eyelens	
1. $\phi = 1/f$			+ 0.1		+ 0.5		0.0		0.0		+ 1.0	
2. d		+ 50.0		+ 16.5		+ 2.38		+ 1.62		1.0		
3. y	0.0		+ 1.0		− 0.32		− 0.1296		0.0		+ 0.8	
4. u		+ 0.02		− 0.08		+ 0.08		+ 0.08		+ 0.8		0.0
5. CA			+ 2.3		+ 1.7		+ 0.25		+ 0.7		+ 1.3	
6. CA/y			+ 2.3		+ 5.31		+ 1.929		Infinity		+ 16.25	
7. $y_o = 0.9645y$	0.0		+ 0.9645		− 0.3086		− 0.125		0.0		+ 0.07716	
8. $u_o = 0.9645u$		+ 0.01929		− 0.07716		+ 0.07716		+ 0.07716		+ 0.07716		0.0
9. y_p	+ 1.4		+ 0.1631		− 0.5142		0.0		+ 0.35		+ 0.5660	
10. u_p		− 0.02474		− 0.04105		+ 0.21605		+ 0.21605		+ 0.21605		− 0.35
11. $y_p + y_o$			+ 1.1276		− 0.8228		− 0.125		+ 0.35		+ 0.6432	
12. $y_p - y_o$			− 0.8013		− 0.2056		+ 0.125		+ 0.35		+ 0.4889	

Figure 6.5 Tabulation of the raytrace data for Example A.

+6.594 in to the right of the objective lens (note that this differs from Fig. 6.2) and that the exit pupil is 0.566/0.35 = +1.617 in to the right of the eyelens.

The diameter of the pupils is found from the ray data of lines 7 and 8 by determining the ray height in the plane of the pupils. Thus, the diameter of the entrance pupil is $2(0.9645 + 0.01929 \times 6.594)$, or 2.183 in, and the diameter of the exit pupil is $2(0.07716 - 0.0 \times 1.617)$, or 0.154 in.

A comparison of the values of CA/y_p would indicate that diaphragm #2 is the field stop. (The ray data in lines 9 and 10 of Fig. 6.5 have already been adjusted so that y_p at diaphragm #2 is equal to half of its clear aperture, in a manner analogous to that by which lines 7 and 8 were derived from lines 3 and 4.) The field of view is given by the slope of the principal ray which just skims through the field stop. This is the ray of lines 9 and 10; the object field is ±0.02474 radians and the image field is ±0.35 radians. The linear size of the object field is twice the height at which this ray strikes the object plane, or 2.8 in.

A check for vignetting could be made by tracing rays from an object point at the edge of the field through the upper and power rims of the entrance pupil. Again, because of the linearity of the paraxial equations, we can avoid this labor, since the height of the upper rim ray at an element is given by $y_p + y_0$ and that of the lower rim ray by $y_p - y_0$. (The values of y_0 and y_p are taken from the ray trace data which has been adjusted, i.e., lines 7 and 9.) This data is tabulated in lines 11 and 12 and a comparison with the clear apertures of the elements indicates that these rays pass through the system without vignetting.

An alternate technique for determining the aperture stop is to calculate the size and position of the image of *each* diameter of the system as seen from the object, i.e., as imaged by all the elements ahead of (or to the left of) the diameter. Then the diameter whose image subtends the smallest angle from the object is the aperture stop. A scale drawing of the images is handy when this technique is used.

6.5 Glare Stops, Cold Stops, and Baffles

A glare stop is essentially an auxiliary diaphragm located at an image of the aperture stop for the purpose of blocking out stray radiation. Depending on the system application, a glare stop may be called a *Lyot stop,* or in an infrared system, a *cold stop.* Figure 6.6 shows an erecting telescope in which the primary aperture stop is at the objective lens. Energy from sources outside the desired field of view, passing through the objective and reflecting from an internal wall, shield, or supporting member, can create a glare which reduces the contrast of the image formed by the system. In a long wavelength infrared

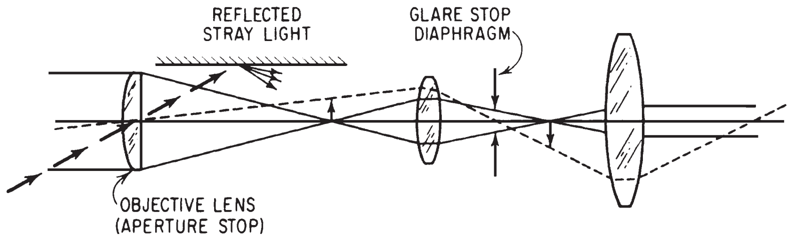

Figure 6.6 Stray light reflected from an inside wall of the telescope, is intercepted by the glare stop, which is located at the internal image of the objective lens.

system, the housing itself may be a source of unwanted thermal radiation. This radiation can be blocked out by an internal diaphragm which is an accurate image of the objective aperture. This stop is usually cooled and is located inside the evacuated detector Dewar. Since the stray radiation will appear to be coming from the wall, and thus from outside the objective aperture, it will be imaged on the opaque portion of the diaphragm. Another glare stop could conceivably be located at the exit pupil of this particular system, since it is real and accessible; however, it would make visual use of the instrument quite inconvenient.

In most systems the aperture stop is located at or very near the objective lens. This location gives the smallest possible diameter for the objective, and since the objective is usually the most expensive component (per inch of diameter), minimizing its diameter makes good economic sense. In addition, there are often aberration considerations which make this a desirable location. However, there are some systems, such as scanners, where the need to minimize the size and weight of the scanner mirror makes it necessary to put the stop or pupil at the scanner mirror rather than at the objective. This causes the objective to be larger, more costly, and more difficult to design.

In an analogous manner, field stops could be placed at both internal images to further reduce stray radiation. The principle here is straightforward. Once the primary field and aperture stops of a system are determined, auxiliary stops may be located at images of the primary stops to cut out glare. If the glare stops are accurately located and are the same size as the images of the primary stops (or slightly larger), they do not reduce the field or illumination, nor do they introduce vignetting.

Baffles are often used to reduce the amount of radiation that is reflected from walls, etc., in a system. Figure 6.7 shows a simple radiometer consisting of a collector lens and a detector in a housing. Assume that radiation from a powerful source (such as the sun) outside the field of view reflects from the inner walls of the mount onto the detector and obscures the measurement of radiation from the desired target, as shown in the upper half of the sketch. Under these conditions, there is no possibility of using an internal glare stop (since there is no internal image of the entrance pupil) and the internal walls of the mount must be baffled as shown in the lower half of the sketch (although an eternal hood or sunshade could also be used if circumstances permit).

The key to the efficient use of baffles is to arrange them so that no part of the detector can "see" a surface which is *directly* illuminated. The method of laying out a set of baffles is illustrated in Fig. 6.8. The dotted lines from the rim of the lens to the edge of the detector indicate the necessary clearance space, into which the baffles cannot intrude without obstructing part of the radiation from the desired field

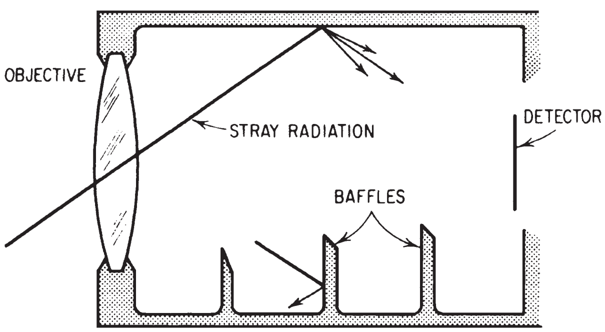

Figure 6.7 Stray (undesired) radiation from outside the useful field of this simple radiometer can be reflected from the inner walls of the housing and degrade the function of the system. Sharp-edged baffles, shown in the lower portion, trap this radiation and prevent the detector from "seeing" a directly illuminated surface.

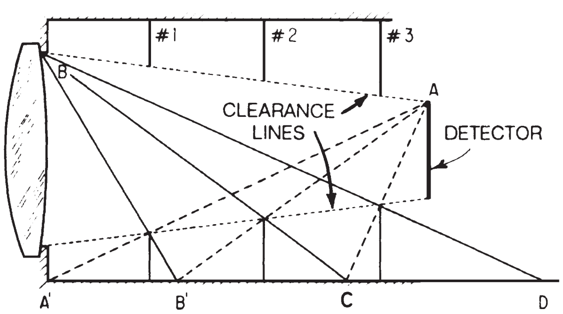

Figure 6.8 Construction for the systematic layout of baffles. Note that baffle #3 shields the wall back to point *D*; thus, all three baffles could be shifted forward somewhat, so that their coverages overlap.

of view. The dashed line AA' is a "line of sight" from the detector to the point on the wall where the extraneous radiation begins. The first baffle is erected to the intersection of AA' with the dotted clearance line. Solid line BB' indicates the path of stray light from the top of the lens to the wall. The area from Baffle #1 to B' is thus shadowed and "safe" for the detector to "see." The dashed line from B' to A is thus the safe line of sight, and baffle #2 at the intersection of AB' and the clearance line will prevent the detector from "seeing" the illuminated wall beyond B'. This procedure is repeated until the entire side wall is protected. Note that the inside edges of the baffles should be sharp and their surfaces rough and blackened.

The cast and machined baffles shown in Fig. 6.7 are obviously expensive to fabricate. Less expensive alternatives include washers constrained between spacers, or stamped, cup-shaped washers which can be cemented or press-fitted into place. This type of baffling is not necessary in all cases. Frequently, internal scattering can be sufficiently reduced by scoring or threading the offending internal surfaces of the mount. In this way, the reflections are broken up and scattered, reducing the amount of reflection and destroying any glare images. The use of a flat black paint is also highly advisable, although care must be taken to be sure that the paint remains both matte and black at near-grazing angles of incidence and at the application wavelength. Sandblasting to roughen the surface and blackening (for aluminum, black anodizing works well) is a simple and usually effective treatment. Another treatment is the application of black "flocked" paper. This can be procured in rolls, cut to size, and cemented to the offending surfaces; this is especially useful for large internal surfaces and for laboratory equipment.

Specialized flat black paints are available for specific applications and wavelengths. In the absence of special paints, Floquil brand flat black model locomotive paint usually can be found at the local hobby shop and makes a pretty good general-purpose flat black. A specialized anodizing process, Martin Optical Black (or Martin Infrablack for the infrared) is extremely effective (<0.2 percent reflective) but is very fragile.

6.6 The Telecentric Stop

A telecentric system is one in which the entrance pupil and/or the exit pupil is located at infinity. A telecentric stop is an aperture stop which is located at a focal point of an optical system. It is widely utilized in optical systems designed for metrology (e.g., comparators and contour projectors and in microlithography) because it tends to reduce the measurement or position error caused by a slight defocusing of the system. Figure 6.9a shows a schematic telecentric system. Note that the dashed principal ray is parallel to the axis to the left of the lens. If this system is used to project an image of a scale (or some other object), it can be seen that a small defocusing displacement of the scale does not change the height on the scale at which the principal ray strikes, although it will, of course, blur the image. Contrast this with Fig. 6.9b where the stop is at the lens, and the defocusing causes a proportional error in the ray height. The telecentric stop is also used where it is desired to project the image of an object with depth (along the axis), since it yields less confusing images of the edges of such an object.

6.7 Apertures and Image Illumination—*f*-Number and Cosine-Fourth

f-Number

When a lens forms the image of an extended object, the amount of energy collected from a small area of the object is directly proportional to the area of the clear aperture, or entrance pupil, of the lens. At the image, the illumination (power per unit area) is inversely proportional to the image area over which this object is spread. Now the aperture area is proportional to the square of the pupil diameter, and the image area is proportional to the square of the image distance, or focal

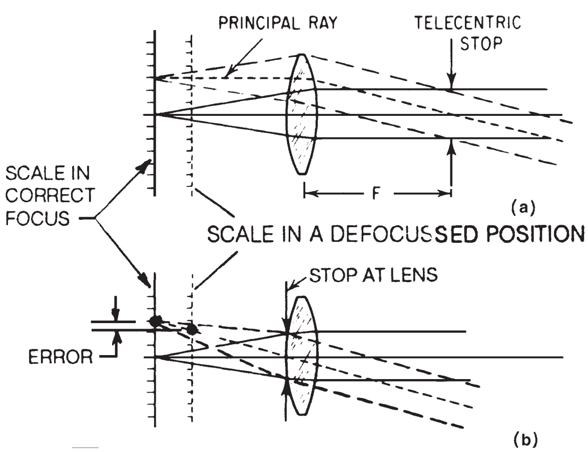

Figure 6.9 The telecentric stop is located at the focal point of the projection system shown, so that the principal ray is parallel to the axis at the object. When the object is slightly out of focus (dotted) there is no error in the size of the projected image as there is in the system with the stop at the lens, shown in the lower sketch.