

LAB 3: STOPS, PUPILS, VIGNETTING, AND F/#

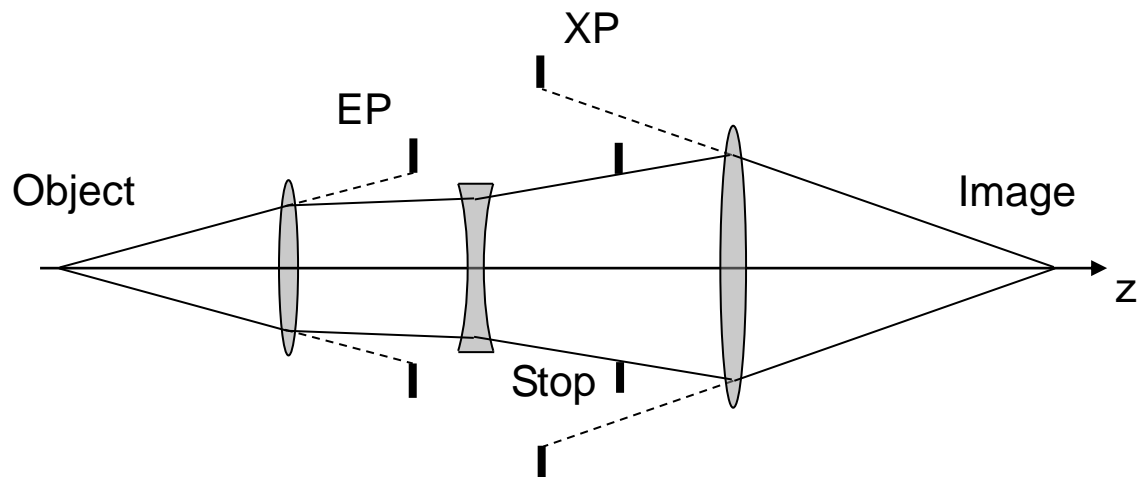
BACKGROUND

(from OPTI 201R & 202R class notes, Greivenkamp)

Stops and Pupils

The aperture stop is the aperture in the system that limits the bundle of light that propagates through the system from the axial object point. The stop can be one of the lens apertures or a separate aperture (iris diaphragm) placed in the system, however, the stop is always a physical or real surface. The beam of light that propagates through an axially symmetric system from an on-axis point is shaped like a spindle.

The entrance pupil (EP) is the image of the stop into object space, and the exit pupil (XP) is the image of the stop into image space. The pupils define the cones of light entering and exiting the optical system from any object point.



The EP is in the system object space, and the XP is in the system image space.

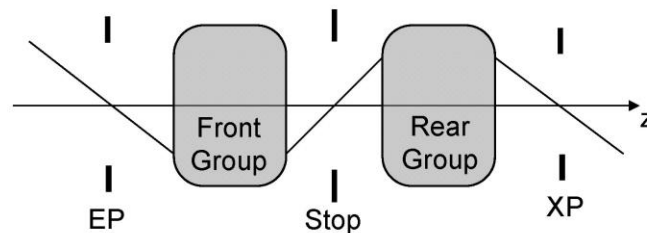
NOTE ("*Nofziger*"): In the diagram above, both the entrance pupil (EP) and the exit pupil (XP) are virtual pupils. The on-axis point-source object emits rays into a full hemisphere. The spindle (cone) of rays that passes unobstructed through this optical system is defined by the outer rays (shown by the solid lines). Note that:

- The aperture stop ("Stop") limits the size of the bundle of rays that passes through the optical system.
- Therefore, the outer limiting rays touch the edge of the aperture stop.
- Rays that diverge from the (on-axis) object point fill the entire entrance pupil. (The EP defines the size of the bundle of rays that enter the optical system.)
- Rays that diverge from the (on-axis) object point fill the entire entrance pupil.

Pupil Positions by Paraxial Raytrace

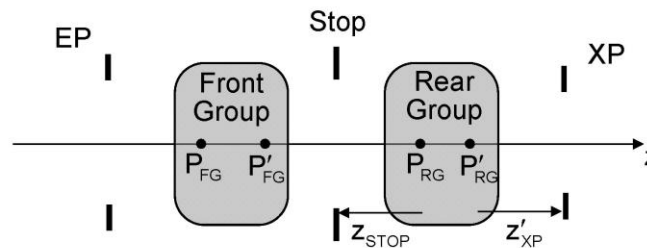
The stop is a real object for the formation of both the entrance and exit pupil.

The pupil locations can be found by tracing a paraxial ray starting at the center of the aperture stop. The ray is traced through the group of elements behind the stop and reverse traced through the group of elements in front of the stop. The intersections of this ray with the axis in object and image space determine the locations of the entrance and exit pupils. Both pupils are often virtual and are found using virtual extensions of the object space and image space rays.



Pupil Positions by Gaussian Imagery

The pupil locations and sizes can also be found using Gaussian imagery. Imaging the stop through the rear group of elements to find the XP is straightforward:

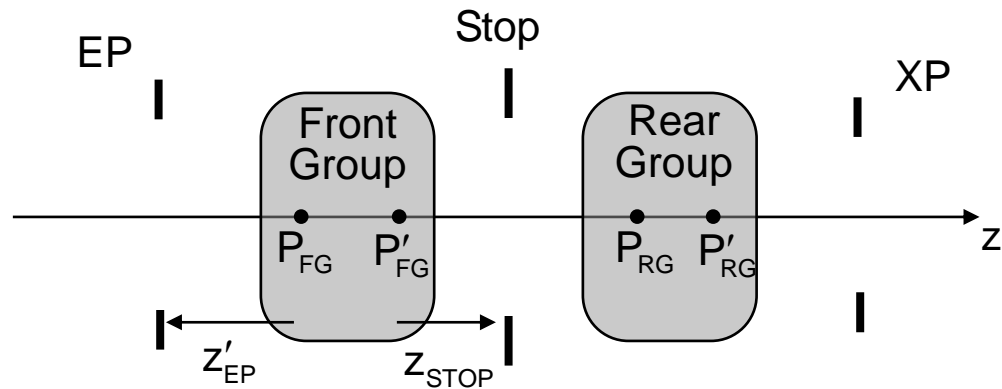


For the XP:
$$\frac{1}{z'_{XP}} = \frac{1}{z_{STOP}} + \frac{1}{f_{RG}} \quad (\text{in air})$$

$$m_{XP} = \frac{z'_{XP}}{z_{STOP}} \quad D_{XP} = |m_{XP}| D_{STOP}$$

Pupil Positions by Gaussian Imagery

Flipping the paper over is effective but awkward. The proper way to determine the EP location is to remember that the light from the real stop propagates from right to left to form the EP, and to assign a negative index to this imagery (just as is done after a reflection). The object and image distances are measured from the principal plane of the front group that is in the same optical space as the object (stop) or image (pupil). The stop (or object) position is measured relative to P'_{FG} , and the EP (or image) position is measured relative to P_{FG} .



For the EP:

$$\frac{n'}{z'_{EP}} = \frac{n}{z_{STOP}} + \frac{1}{f_{FG}} \quad n = n' = -1 \quad (\text{in air})$$

$$\frac{-1}{z'_{EP}} = \frac{-1}{z_{STOP}} + \frac{1}{f_{FG}} \quad m_{EP} = \frac{z'_{EP} / n'}{z_{STOP} / n} = \frac{z'_{EP}}{z_{STOP}} \quad D_{EP} = |m_{EP}| D_{STOP}$$

Experiment 3-1: Example System—(Stop and Pupils)

Assemble the following optical system which was presented as an in-class example. Use the ThorLabs “Cage System” to hold the lenses on top of the nodal slide. Use the microscope (NOT a ruler) to locate the 2 lenses and the stop:

Example System

Two thin lenses with a stop halfway between:

$$f_1 = 100\text{ mm}$$

$$f_2 = 75\text{ mm}$$

$$t = 50\text{ mm}$$

Stop at 25 mm / 25 mm

Stop Diameter = 20 mm

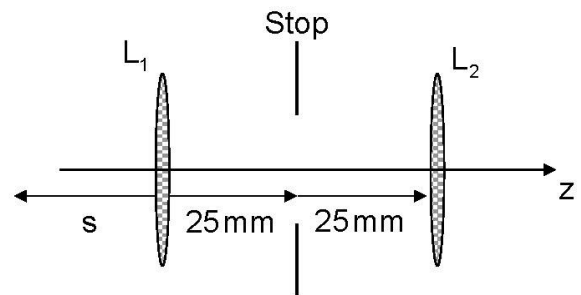
$$\text{Stop Radius} = a_{STOP} = 10\text{ mm}$$

Object Height = 10 mm

Two Positions:

$$s_A = -100\text{ mm} \quad (\text{from } L_1)$$

$$s_B = -50\text{ mm} \quad (\text{from } L_1)$$



- NOTE:**
- The 2 lenses are pre-mounted in the lens holders.
 - Each lens is a plano-convex lens.
 - Lens center thicknesses: $t_c(L1) = 4.6\text{ mm}$; $t_c(L2) = 5.1\text{ mm}$
 - The Aperture Stop is held fixed to the post on the nodal slide.
 - Lenses L1 and L2 need to be positioned somewhere along the 2 minirails.
 - The final layout has the 2 curved surfaces facing each other.

- (0) Position the microscope so its post is "bottomed-out" in the collet holder. This establishes the height for all of the following alignments:
- (1) Remove lens L2 from the ThorLabs mini rails. Focus the microscope on the Aperture Stop. Adjust the height of the Aperture Stop to center it in the crosshairs of the microscope.

- (2) Use the microscope to position the Aperture Stop over the axis of rotation of the nodal slide (i.e. translate the Aperture Stop until its image in the microscope is stationary with rotation of the nodal slide).
- (3) Use the microscope / translation stage to measure the diameter of the Aperture Stop.
- (4) Using the microscope as an optical “ruler,” position the curved surface of lens L2 to be 25 mm from the Aperture Stop. (HINT: Take the thickness of lens L2 into account.)
- (5) Using the microscope as an optical “ruler,” position the curved surface of lens L1 to be 25 mm from the Aperture Stop. (HINT: Take the thickness of lens L1 into account.)
- (6) Remove the microscope from the optical rail. Rotate the nodal slide so lens L1 is facing the light source. Flood the Aperture Stop with light (using the desk lamp). Look into the system visually (from image space) and observe the exit pupil (XP).

Q1 Does the XP appear larger, smaller, or the same size as the Stop?

- (7) Focus the microscope on the XP.
- (8) Use the microscope / translation stage to measure the diameter of the XP.

Q2 Calculate m_{XP} from your measured values.

- (9) Use the microscope / translation stage as an optical ruler to measure z'_{XP} .

Q3 Compare your measured values of m_{XP} and z'_{XP} to the values calculated in the example problem above.

- (10) Refocus the microscope on the XP and turn on the light source. Put a piece of scotch tape over the Stop.

Q4 Observe the XP. What do you see and why?

- (11) Turn the system around on the nodal slide and repeat these steps for the entrance pupil, EP.

Q5 Does the EP appear larger, smaller, or the same size as the Stop?

Q6 Calculate m_{EP} .

- Q7** Compare your measured values of m_{EP} and z'_{EP} to the values calculated in the example problem above.
- (12) Refocus the microscope on the EP and turn on the light source. Put a piece of scotch tape over the Stop.
- Q8** Observe the EP. What do you see and why?

Experiment 3-2: Vignetting

(from OPTI 201R & 202R class notes, Greivenkamp)

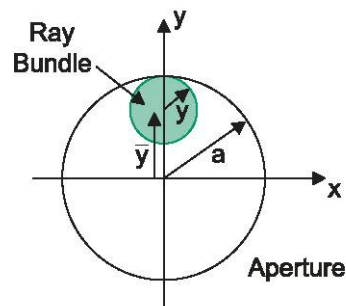
"For an off-axis object point, the beam of light through the system is shaped like a spindle of skew cone-shaped sections as long as no aperture other than the stop limits the beam. If the beam is intercepted by one or more additional apertures, vignetting occurs. The top and or bottom of the beam is clipped, and the beam of light propagating through the system no longer has a circular profile."

(from the Field Guide to Geometrical Optics, Greivenkamp)

"While the stop alone defines the axial ray bundle, vignetting occurs when other apertures in the system, such as a lens clear aperture, block all or part of an off-axis ray bundle."

- Unvignetted beam

"No vignetting occurs when all of the apertures pass the entire ray bundle from the object point. Each aperture radius a must equal or exceed the maximum height of the ray bundle at the aperture:



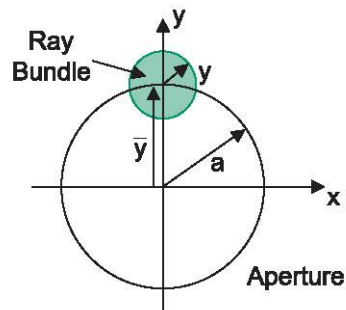
Unvignetted:

$$a \geq |y| + |\bar{y}|$$

By definition, vignetting cannot occur at the aperture stop or at a pupil."
(Therefore, the ray bundle from the on-axis object point is never vignetted.)

- Partially-vignetted beam

A second vignetting condition is defined when an aperture passes about half of the ray bundle from an object point:



Half vignetted:

$$a = |\bar{y}|$$

and

$$a \geq |y|$$

- Fully Vignetted

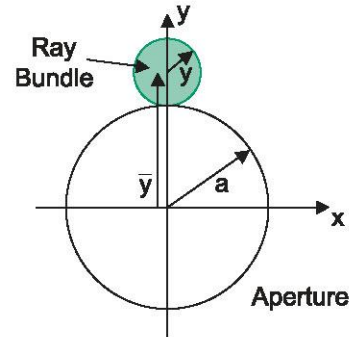
"The maximum FOV supported by the system occurs when an aperture completely blocks the ray bundle from the object point:"

Fully vignetted:

$$\alpha \leq |\bar{y}| - |y|$$

and

$$\alpha \geq |y|$$



"The vignetting conditions are used in two different manners:

- For a given set of apertures, the FOV that the system will support with a prescribed amount of vignetting can be determined. A different chief ray defines each FOV.
- For a given FOV and vignetting condition, the required aperture diameters can be determined.

A system with vignetting will have an image that has full irradiance or brightness out to a radius corresponding to the unvignetted FOV limit. The irradiance will then begin to fall off, going to about half at the half-vignetted FOV, and decreasing to zero at the fully vignetted FOV. This fully vignetted FOV is the absolute maximum possible."

Explore vignetting vs. object location for the optical system used above. Image a point source at infinity (i.e. auto-collimate the point source) and flood the optical system with collimated rays. Use the iris diaphragm (in front of lens L1) to limit the on-axis beam diameter so that it just fills the Aperture Stop.

Q9 Where is the aperture stop for this system?

Q10 Where is the entrance pupil for this system?

(1) Explore vignetting vs. off-axis object angle (chief ray angle \bar{u}), by rotating the optical system about the Entrance Pupil (NOT the Aperture Stop).

Q11 Describe your findings.

Q12 What aperture causes \approx half vignetting to occur?

Q13 What aperture causes full vignetting to occur?

Experiment 3-3: Real Instruments—(Stop and Pupils)

Use the setup provided to study the stop and pupils associated with one of the telescopes in a pair of binoculars.

NOTE:

- The aperture stop is the outer edge of the objective lens.
- Therefore, the entrance pupil EP is co-located with the stop.
- The exit pupil is real, and is located behind the eyelens.
- The eye relief is defined as the distance from the last vertex of the eye lens to the exit pupil. It is a distance, usually quoted in mm.

- (1) Use a ruler to measure the diameter of the stop, in mm.
- (2) Position a piece of plain white paper up against the front of the objective lens. Flood it with light from the desk lamp. This fills the aperture stop (and also the entrance pupil) with light.
- (3) Look at (i.e. focus on) the exit pupil visually, with just your eye.

Q14 Describe what you see.

- (4) Look through the microscope and focus it on the exit pupil.
- (5) Use the microscope / translation stage to measure the diameter of the XP.

Q15 Compare to the expected value of 5 mm (for these particular binoculars).

- (6) Use the microscope as an optical ruler to measure the eye relief, the distance from the XP to the rear vertex.

Q16 What is your measured value for the eye relief, in mm?

- (7) Observe the exit pupil in the following optical instruments (all used visually). In each instrument, the aperture stop is the first optical element that the light encounters in the system.

For each instrument, flood the aperture stop with diffuse white light using the piece of paper and the desk lamp. Use the clear ruler to measure the diameter of the XP:

- the spotting scope
- the Newtonian reflecting telescope
- the microscope you've been using!

Experiment 3-4: F-Number

The concept of F-number, or F/#, is defined for a lens or mirror, and is usually quoted as an optical specification for that component. For an object at infinity, a (positive/negative) lens produces an image located at its (rear/front) focal point, and the F/# of the lens is defined as:

$$(F/\#)_{\infty} \equiv \left| \frac{\text{focal length}}{\text{lens diameter}} \right|$$

This is the lens F/# quoted in an optical catalog. Keep in mind this is true only if the beam fills the full opening, or **aperture**, of the lens.

If the aperture is limited in size ("stopped down"), or if the object is not at infinity (the image is no longer at the focal point), then the *beams* in object or image space may be described by an F/#, often called the "working" F/# of the lens.

$$F/\# \text{ of beam} = \text{working } F/\# = (F/\#)_w \equiv \frac{L}{D}$$

where L is the distance from an arbitrary plane perpendicular to the beam to the beam's point of divergence or convergence, and D is the beam diameter in the plane. It is a measure of how fast a beam is converging or diverging. The smaller the F/#, the faster the beam converges or diverges. A beam that is collimated has an F/# approaching infinity.

The following examples in Fig. 2.1 should help clarify the concept. In all examples, distances are measured in mm.

- (1) Use the 100mm focal length lens (KBX064) and a diffuse pinhole source to investigate the concept of F/#. The lens diameter is 25 mm.

Q17 What is the $(F/\#)_{\infty}$ of the lens?

- (2) Place the lens 200mm from the object. Calculate what the image distance should be and from that, calculate what the working F/# should be in image space. Measure the actual working F/# of the beam in image space. Note the image brightness.

Q18 Calculate where the lens should be placed to produce a working F/# of 16 in image space.

- (3) Place the lens there and measure the actual working F/# of the beam in image space.

Q19 What happened to the image brightness?

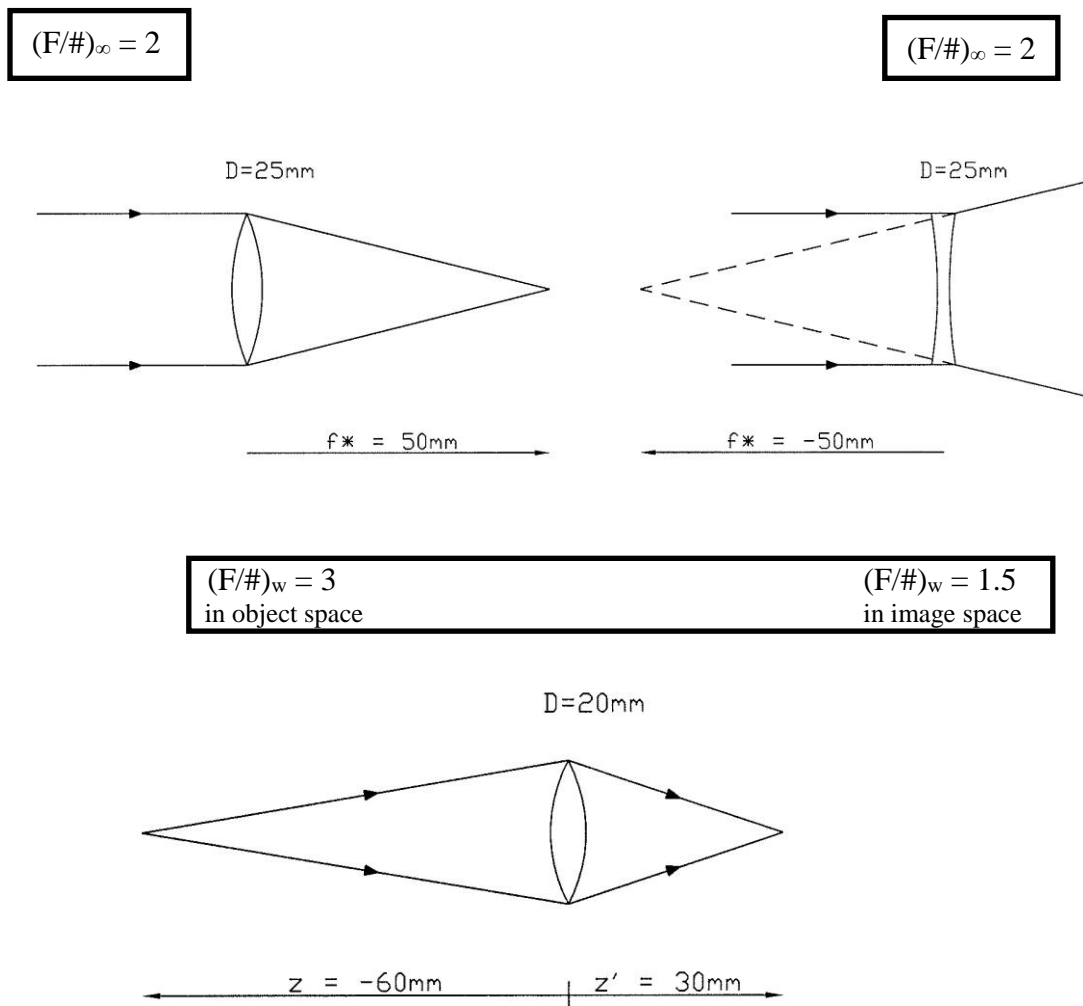


Figure 3.1. The concept of F-Number: $(F/\#)_\infty$ and $(F/\#)_w$.

Numerical Aperture

Note the value of Numerical aperture marked on the side of the 10X microscope objective lens.

- Q20** Calculate the full-angle (in degrees) of the cone of light that is accepted into this objective lens.
- Q21** What is the Numerical aperture of the lens used to focus light in a Blu-Ray DVD player? (*surf the internet to find the answer*)
- Q22** Calculate the full-angle (in degrees) of the cone of light that is accepted into the lens in a Blu-Ray DVD player.