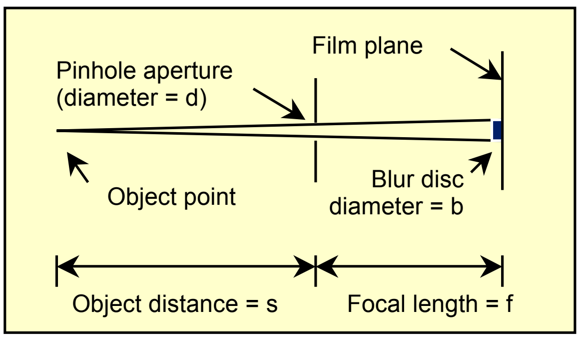
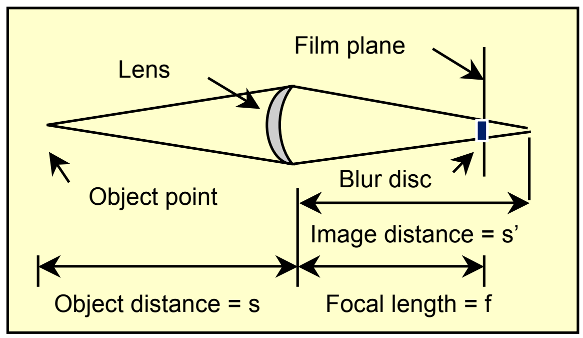
Optimum Pinhole Camera Design

A pinhole camera forms images on film by using a very small aperture in place of a photographic lens. Its extremely small aperture and simple geometry give it extraordinary depth of field. A pinhole lens gives sharper average focus over extreme changes in object distance, although an ordinary lens gives a sharper image for objects within its more limited focus range.

An conventional photographic lens collects rays through a relatively large aperture, and converges them to a point of focus on the film. Depth of focus is limited by the fact that object points at widely different distances are cannot be brought to the same focal distance. Focus is maintained only with modest variations in object distance, because lens-to-image distance increases as object distance decreases, particularly at short distances. A pinhole lens has a greater depth of field, because it creates focus simply by limiting the diameter of the aperture, and not by converging rays of a broad ray bundle. Figure 1 illustrates these effects, for a camera focussed at infinity and viewing a point on a nearby object.



(a) Pinhole



(b) Conventional

Figure 1. Camera Image Formation

For a conventional camera, the point of best focus is determined by setting an equal blur for near and far objects at the nearest and furthest distances in the scene. This range of focus typically is marked on the lens focusing ring, and depends on f-number. The "in-focus" range of the lens is maximized by setting the lens to the *hyperfocal distance,* which is the nearest focus for which objects at infinity have an acceptable blur.

For a pinhole camera, virtually all points are in the same focus, which is determined by aperture size. Best focus is achieved by choosing an optimum aperture diameter, which depends upon the object distance and focal length. If the aperture is too small, blurring increases due to diffraction effects. If the aperture is too large, blurring increases due to geometric effects. However, the optimum size can be determined by a simple formula, which now will be derived.

Geometric blur of a pinhole lens was shown in Figure 1a. Light rays emanating from a point on the object are limited by the small aperture to a very narrow cone, which gives rise to a uniform blur circle on the film. This blur is made smaller by making the aperture smaller, which is the reason why it becomes a pinhole. The exact diameter of this geometric blur (b_G) depends upon aperture diameter (d), image distance (f), and object distance (s), and is given by the equation:

$$b_G = d \bullet \left(\frac{s+f}{s} \right) = d \bullet (1+M),$$

where M is the magnification, equal to (f/s)

Diffraction blur in a pinhole camera is caused by a slight bending of light as it passes through the aperture, which spreads a perfect point image into a Fraunhofer diffraction ring pattern. Such diffraction rings are familiar to telescope users where great angular magnification makes even slight diffraction noticeable. Most of the energy is in this pattern lies in the central bright disc, which can be considered the blur diameter. In a pinhole camera, diffraction is noticeable because diffraction bending increases as the aperture becomes smaller. In addition, this bending is an angular effect, so blur also increases as the camera “focal length” or lens-to-image distance increases. The diameter of the diffraction blur (b_D) depends upon the wavelength of light (λ), the aperture size (d), and the image distance (f), and is given by the equation:

$$b_D = 2.44 \bullet \lambda \bullet \left(\frac{1}{d} \right) \bullet f$$

The total blur is given by the sum of these two components, b_G+b_D. Through calculus, the minimum of this sum is derived, as follows:

$$(1+M) = 2.44 \bullet \lambda \bullet f \bullet \left(\frac{1}{d} \right)^2, \text{ so}$$

$$d = \sqrt{\frac{2.44 \bullet \lambda \bullet f}{(1+M)}} \quad , \quad \text{where } M = \left(\frac{f}{s} \right) = \text{ magnification}$$

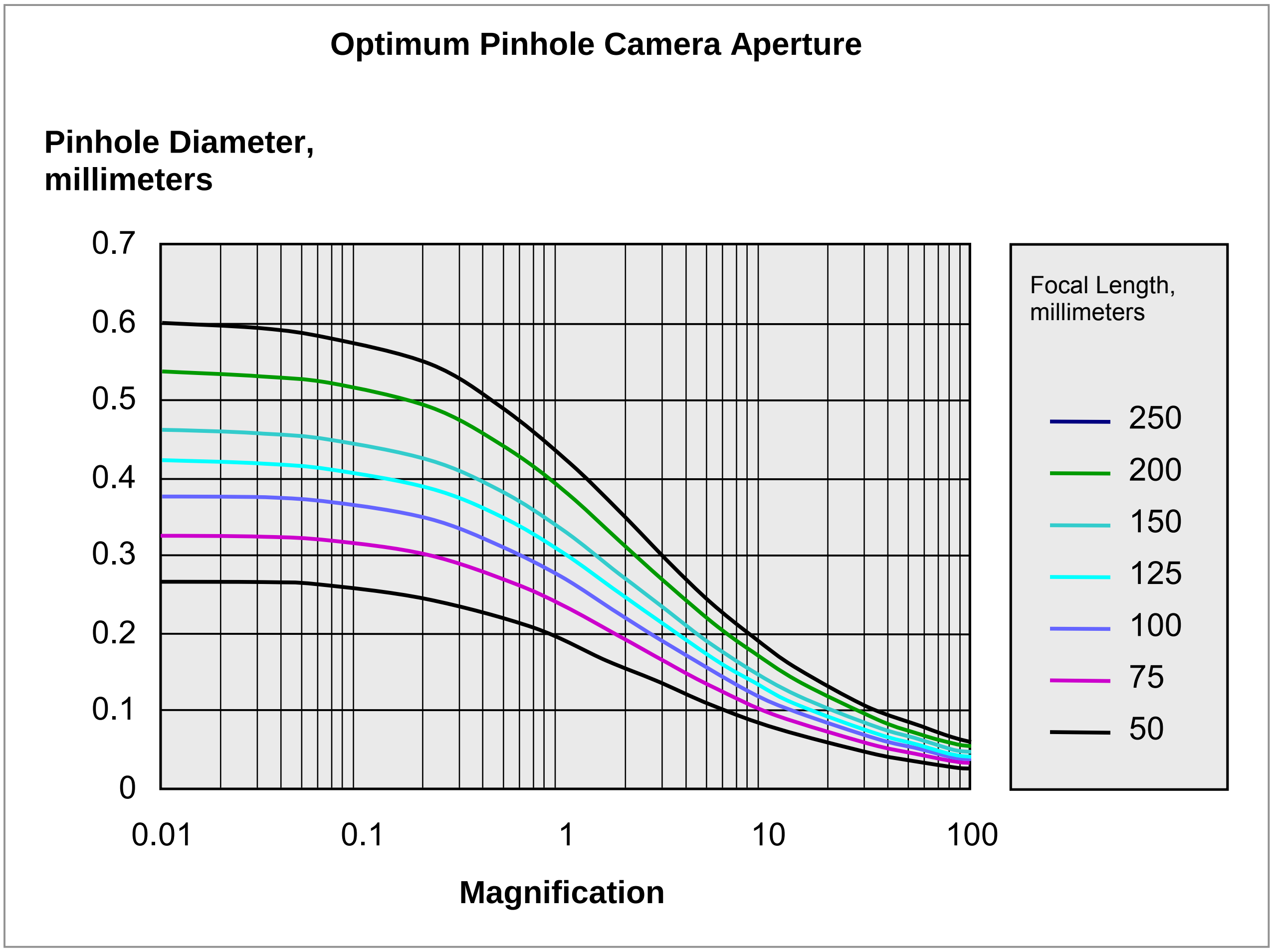
This equation defines the optimum pinhole aperture diameter for close-up work, as well as for more distant work. In using this equation, all distance measures (λ, f, d) must be in the same units (millimeters or inches, say). Note that the (1+M) term “disappears” at larger distances, so this equation simplifies to what is more often cited in the literature.

For f in millimeters, and for visible light, f =0.0006 millimeters, the equation is simplified and made easy to use.

$$d = 0.038 \bullet \sqrt{\frac{f}{(1+M)}}$$

This is the Prober-Wellman equation.

The figure below plots this equation for a typical range of f and M values for distant and close-up work. Separate curves for each focal length are color-coded as shown by the legend. (For those viewing a black-and-white copy, the sequence of the curves is the same in the graph as the focal lengths in the legend, with the longest focal length being at the top of the sequence.)



Aperture diameter is rather constant for small magnifications, when the object distance (s) is much larger than the image distance (f). However, as the object moves closer, the aperture size must be decreased to realize the best focus.

With an optimum aperture, a pinhole camera can realize one of its strongest points – the ability to take extreme close-up photos of small objects, with an unusually large depth of focus. The image remains consistently clear over a full range of depth of the object, and even into a distant background. An ordinary lens gives sharper focus at one distance, but becomes extremely blurred for close-up objects that have some depth.

A well-designed pinhole camera, at any magnification or focal length, also will give pictures that are virtually distortionless, which is particularly useful for wide-angle and close-up work.

Values for different wavelengths of light

The Prober-Wellman formula gives largest acceptable pinhole size, and the lowest f-stop pinhole for close-up and macro pictures. Table below has values for different color temperatures for different light sources, corrected values for removing round off errors, and values for direct values of pinholes in inches.

Color	Wavelength	Value for X	Value for X
	In millimeters	Pinhole in millimeters	Pinhole in inches
Infrared	0.00075	0.04278	0.001684
Red	0.00065	0.03982	0.001568
Daylight	0.00056	0.03696	0.001455
Green	0.00055	0.03663	0.001442
Blue	0.00045	0.03314	0.001305

Prober-Wellman Formula with expanded for color temperature and pinhole diameters in metric or imperial.

To find the pinhole for close-ups and macro pictures

For close-ups and macro picture pinhole sizes.

Pinhole size = X * SQRT[camera's focal length in millimeters / (magnifaction+1)]

When subject at infinity [magnification equals zero]

Pinhole size = X * SQRT[camera's focal length in millimeters]

Note! Smaller pinhole than formula size is an acceptable pinhole size for the picture, but the higher f/stop may be a handicap in taking the picture. For ½ diameter of the preferred size +2 more stops of light are required.

To find f-stop of camera

f-stop = camera's focal length in millimeters / pinhole diameter in millimeters

or

f-stop = camera's focal length in inches / pinhole diameter in inches

To find the distance and view area for PinPLUS cameras

Distance subject to pinhole = (1 / Magnification) * camera's focal length in inches)

Horizontal view window = (1 / Magnification) * film's horizontal length in inches)

Vertical view window= (1 / Magnification) * film's vertical length in inches)