



Negative Control

Sharpness and Depth of Field

How human vision dictates negative resolution

by Ralph W. Lambrecht



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If your camera is precisely aligned and the lens is focused at a specific subject distance, then all objects at precisely this distance are in focus, and strictly speaking, everything else is out of focus. In practice, however, our eyes have a limited optical resolution, and therefore, objects reasonably close to the focus plane will also appear perfectly sharp in the final print. This creates a zone of still acceptable focus surrounding the focus plane, and objects within this zone are considered to be in focus, while those outside are out of focus. This zone is called the depth of field.

Limits of Human Vision and Normal Viewing Distance

The limits of human vision differ substantially with the shape and pattern of the object being observed. The eye's capability to recognize a single line is astonishing. A dark human hair is easily distinguished against a well-illuminated white background at a distance of 10 m (30 feet) or more. This calculates to a visual angle of about 1 arc second ($0^{\circ}00'01''$). The eye's capability to recognize a single point is less impressive. The smallest object size, clearly and consistently visible to most people, calculates to a visual angle of about 1 minute of arc ($0^{\circ}01'00''$).

Neither of these two tests realistically represents the task of observing a photograph, where visual quality is not limited by the ability of the eye to detect individual image elements but to resolve fine detail. Several line patterns are used in ergonomic studies to support an objective measure for the resolving power of the human eye. With these patterns, resolving power is measured as the capacity of the eye to discriminate closely spaced lines as separate and distinct line images (see fig.1a).

A commonly agreed result of these studies is that the minimum visual angle, at which a line is perceived within a pattern of three bars, separated by spaces of

equal width, is about 1 minute of arc (0°01'00"). Beyond these studies, empirical test have shown that common detail and distinct texture is still visible down to about 20 seconds of arc (0°00'20"), a value that must be considered for critical observation. Finally, factors such as image contrast and ambient illumination, significantly influence the minimum visual angle. Fig.1a-c help to find your personal limits, but for the rest of this book, the minimum visual angle of the middle-aged human eye is assumed to be between 20 seconds and 1 minute of arc, which is the range from critical to standard observation, respectively.

Of course, a minimum visual angle does not tell much about the best optical resolution of photographic detail, unless we are aware of the minimum viewing distance to the photograph. Physiological limitations place comfortable near distance vision at about 250 mm, and a most critical viewer might be as close as his or her eyes will focus, investigating all areas of the photograph. Aside from photographic competition judges, this is probably the exception, but at this distance, standard human vision resolves 7 lp/mm (line pairs per millimeter), and critical observation reveals detail down to 20 lp/mm, which is still well within the resolution limit of photographic paper.

In order to keep depth-of-field scales independent of print size, lens and camera manufacturers make the reasonable assumption that for uncropped prints 8x10 inches or larger, the normal viewing distance is about equal to the print diagonal. For an 8x10 print and the standard minimum visual angle of 1 minute of arc, this calculates to a minimum viewing distance of 325 mm and a resolving power of 0.1 mm or 5 lp/mm. In other words, at this distance and under normal viewing conditions, the human eye cannot separate print detail smaller than 0.2 mm.

To make an 8x10 inch print from an entire 35 mm negative requires about an 8.5x enlargement. Therefore, negative detail is 8.5x smaller than its respective print detail, and consequently, the maximum print detail of 0.2 mm has an equivalent maximum negative detail of 0.022 mm (see fig.2). Any 35 mm negative detail smaller than 0.022 mm cannot be resolved during print observation, and consequently, does not have to be in focus on the negative to appear sharp in the print.

Although, we have used the 8x10 print as an example, our assumption of a fixed relationship between viewing distance and print size is appropriate for all

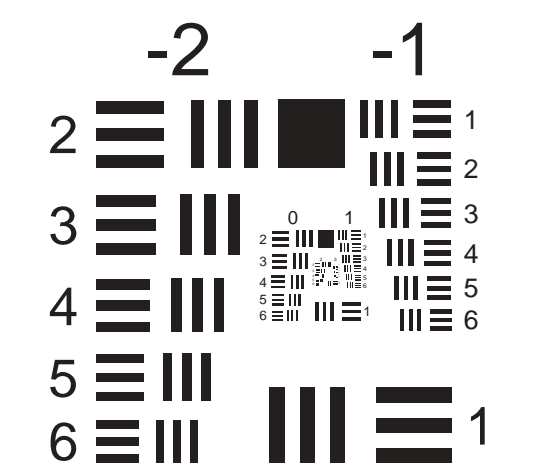


fig.1a The USAF/1951 test pattern is divided into groups with six elements each.

elements	groups					
	-2	-1	0	1	2	3
1	6.88	3.44	1.72	0.86	0.43	0.21
2	6.13	3.06	1.53	0.77	0.38	0.19
3	5.46	2.73	1.36	0.68	0.34	0.17
4	4.86	2.43	1.22	0.61	0.30	0.15
5	4.33	2.17	1.08	0.54	0.27	0.14
6	3.86	1.93	0.96	0.48	0.24	0.12

fig.1b visual angle in arc minutes (at 1 m distance)

elements	groups					
	-2	-1	0	1	2	3
1	0.25	0.50	1.00	2.00	4.00	8.00
2	0.28	0.56	1.12	2.24	4.49	8.98
3	0.31	0.63	1.26	2.52	5.04	10.1
4	0.35	0.71	1.41	2.83	5.66	11.3
5	0.40	0.79	1.59	3.17	6.35	12.7
6	0.45	0.89	1.78	3.56	7.13	14.3

fig.1c test pattern resolution in lp/mm

fig.1a-c You can use the USAF/1951 test pattern to check your personal limits of vision. If applicable, conduct the tests using your prescribed corrective glasses.

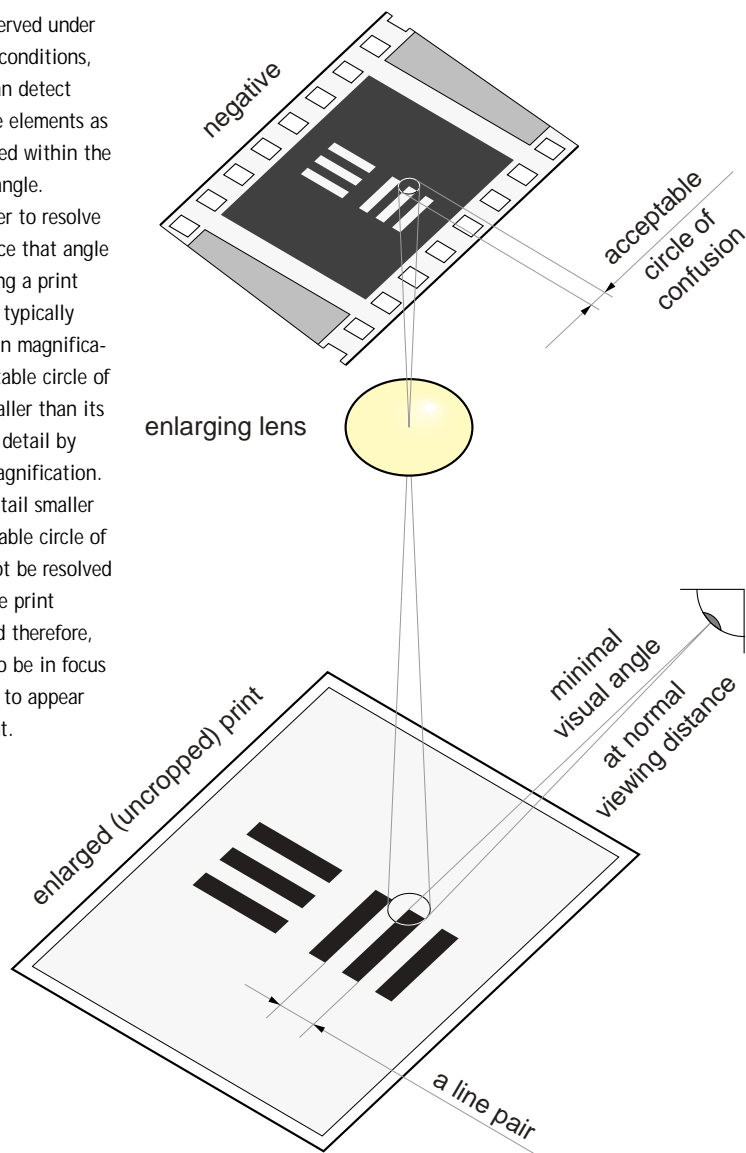
1.) Place fig.1a into a well lit area, and evaluate the test pattern from a distance of 1 m (40 inches). Find the group and element where you can still make out a line pattern, and fig.1b will reveal your minimum visual angle in arc minutes.

2.) Place fig.1a into a well lit area, and evaluate the test pattern from as close a distance as comfortable. Find the group and element where you can still make out a line pattern, and fig.1c will reveal your near-vision resolving power in line pairs per millimeter (lp/mm).

You can also use the USAF/1951 test pattern to check the performance of your photographic lenses.

3.) Mount camera and lens onto a tripod, and use a fine-grain film to take a photograph of fig.1a from a distance equal to a known multiple of the focal length (25 - 100x). Consider the use of a cable release and flash photography to reduce camera-shake as much as possible. Inspect the negative with a loupe and find the group and element where you can still make out a line pattern. Identify the accompanying resolution of the test pattern in fig.1c, and multiply that value by the focal-length multiplier, used above, to find the actual lens resolution in line pairs per millimeter (lp/mm).

fig.2 If a print is observed under normal viewing conditions, human vision can detect individual image elements as small as perceived within the minimal visual angle. However, in order to resolve print detail, twice that angle is needed. Making a print from a negative typically requires a certain magnification. The acceptable circle of confusion is smaller than its respective print detail by this factor of magnification. Any negative detail smaller than the acceptable circle of confusion cannot be resolved during the above print observation, and therefore, does not have to be in focus on the negative to appear clear in the print.



print sizes. Any change to the negative magnification is mathematically compensated for by a change in viewing distance. This conveniently keeps the size of the minimum negative detail, for all full-negative enlargements of a given negative format, consistent.

Circle of Confusion

Imagine the following experiment. In a darkened room, point your camera and normal lens towards the lit bulb of a miniature flashlight placed as far away as possible. The pinpoint light is extremely small and

has practically no height or width. If you focus the lens on that light, it forms a tiny point on the view screen. However, if you focus slightly in front of, or behind, the light, it will change to a small blurry circle. If that blurry circle is smaller than the minimum negative detail, then it will still look like a point when enlarged for printing. The blurry circle is the 'circle of confusion'.

Except for the purpose of close inspection, we assumed that the minimum distance from which a print is viewed is about equal to the print diagonal. Consequently, every size negative has its own acceptable circle of confusion, because the same print could be made from different size negatives, but the resolution limit of our eyes is fixed. A small negative requires more magnification to produce the same size print than a large negative. Therefore, a small negative requires smaller negative detail and, consequently, a smaller circle of confusion. Assuming that the entire negative is printed to produce the print, fig.3 gives standard and critical dimensions for the acceptable circle of confusion for several negative formats.

film format	circle of confusion [mm]		other requirements for critical print observation	
	standard observation	critical observation	min negative resolution	max focus tolerance based on infinity depth of focus at f/11
	0° 01' 00"	0° 00' 20"	[lp/mm]	[mm]
24x36	0.022	0.007	134	±0.08
6x4.5	0.039	0.013	77	±0.14
6x6	0.042	0.014	72	±0.15
6x7	0.048	0.016	62	±0.18
6x9	0.052	0.017	58	±0.19
4x5	0.089	0.030	34	±0.33
5x7	0.112	0.037	27	±0.41
8x10	0.179	0.060	17	±0.66
11x14	0.252	0.084	12	±0.92

fig.3 The acceptable circle of confusion for standard and critical viewing conditions depends on the film format and the optical resolution limits of the human eye.

Depth of Field

The flashlight experiment clearly showed that there is a zone of still acceptable focus surrounding the focus plane, and its size depends on several variables in addition to the circle of confusion. The depth of field increases with subject distance and decreases with focal length. As a result, the longer the focal length or the closer the subject, the less depth of field. In macro photography, depth of field is often reduced to just a few millimeters. Short focal length lenses provide more depth of field than long focal length lenses from the same viewpoint, even when the negative is printed with a higher magnification to render the same scale print.

The last, significant variable for the depth of field is the lens aperture. Fig.4a-b show how the circle of confusion makes depth of field possible and how the zone increases as the aperture is reduced. In fig.4a, a large aperture limits the depth of field to a relatively small zone. The image circle of a far point is larger than the circle of confusion, and therefore, the point is out of focus. In fig.4b, a smaller lens opening permits only light, which is close to the center of the optical axis, to reach the film. As a result, the image is dimmer, but depth of field is increased.

Closing the aperture by a few stops makes for a significant increase in depth of field, which quickly approaches infinity at minimum lens apertures. The tiny aperture of a pinhole camera, often smaller than $f/256$, produces images approaching infinite depth of field.

Quality small and medium format lenses have engraved depth-of-field scales, and an example of how to use them is given in 'Above Malham Cove'. In my experience, many of these scales use a rather optimistic circle of confusion, which provide only a mediocre depth of field. If you have more stringent requirements, then you may want to calculate a personalized depth-of-field table. The equations to calculate the front (df) and rear (dr) limits are:

$$df = \frac{u \cdot f^2}{f^2 + c \cdot N \cdot (u - f)}$$

$$dr = \frac{u \cdot f^2}{f^2 - c \cdot N \cdot (u - f)}$$

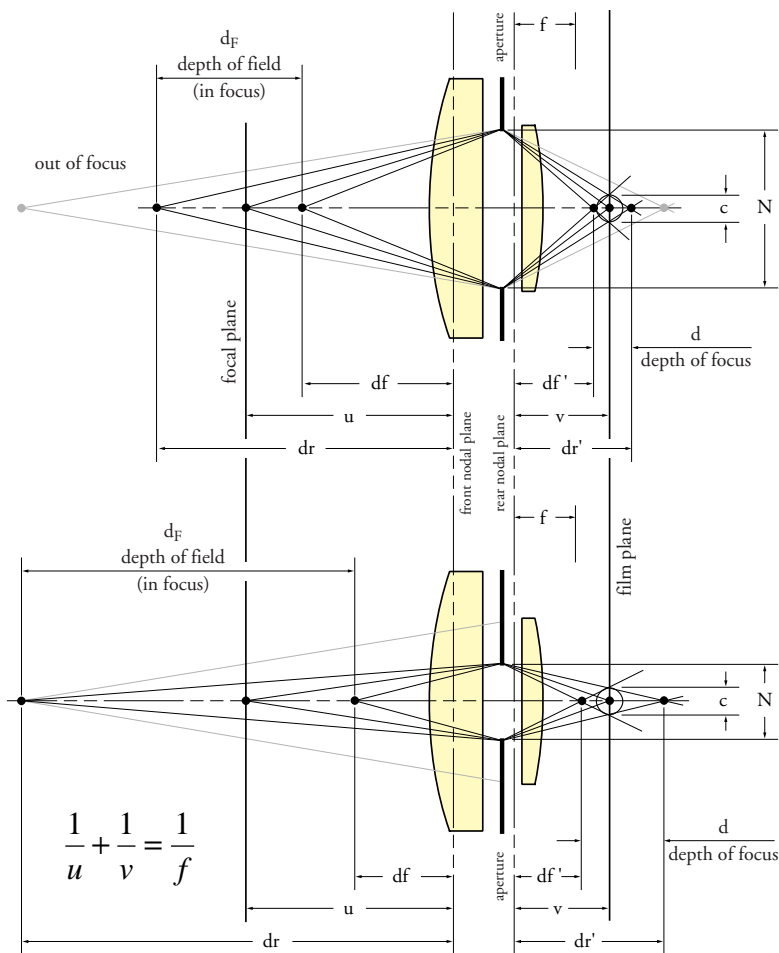
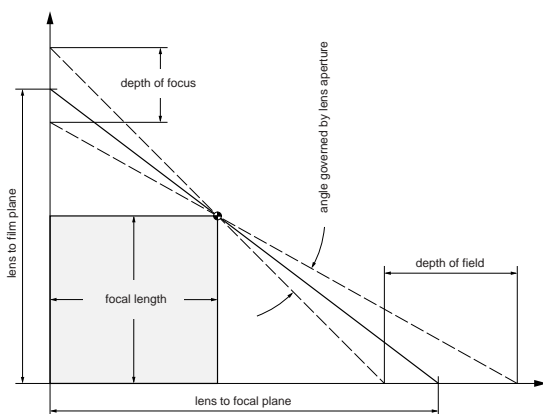


fig.4a-b A smaller lens opening permits only light, which is close to the center of the optical axis, to reach the film. As a result, the image is dimmer, but depth of field is increased.

where 'u' is the focusing distance and 'f' is the focal length, 'c' is the circle of confusion and 'N' is the aperture of the lens in f/stops. With the help of a spreadsheet and the equations provided, customized tables for many formats and lenses can be prepared and then kept in the camera bag for future assignments. When performing the computations, make sure to keep all units consistent, and convert very large and negative results to 'infinity'.



Depth of Focus

Similar to the zone of sharpness surrounding the focal plane, known as depth of field, there is an equivalent zone of sharpness surrounding the film plane, called the depth of focus (fig.4). As the film image is a scaled version of the subject in front of the camera, the depth of focus is a scaled version of the depth of field (fig.5). The front and rear limits of the depth of focus can be calculated from the depth of field as:

$$df' = \frac{f^2}{dr - f} \quad dr' = \frac{f^2}{df - f}$$

where 'f' is the focal length and 'dr' and 'df' are the depth of field behind and in front of the focal plane, respectively.

Depth of focus increases with the circle of confusion and magnification. It decreases with lens aperture and is at its minimum when the lens is focused at infinity. The total depth of focus 'd' is determined as follows:

$$d = 2 \cdot c \cdot N \cdot (1 + m)$$

where 'c' is the circle of confusion, 'N' is the aperture of the lens in f/stops and 'm' is the subject magnification, but the formula simplifies to:

$$d = 2 \cdot c \cdot N$$

for landscape photography or similar, where the lens is focused at or near infinity, and 'm' is small.

View camera lenses do not usually feature distance or depth-of-field markings. At first thought, this makes reaching the required depth of field through f/stop estimates impossible, or at least difficult and cumbersome. Nevertheless, since the depth of focus is directly related to the depth of field, this relationship can be used as a reliable alternative when operating a view camera.

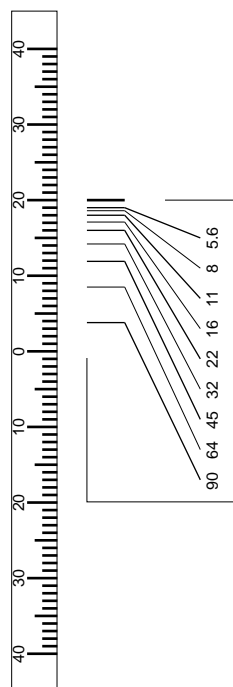
Fig.6a shows a depth-of-focus scale and gauge; fig.6b shows them in operation. Mount the 80 mm long scale to the monorail or the camera bed of your view camera. Focus the camera on the most distant point for which sharpness is required and mark the position of the focusing standard to the scale. Then focus on the

fig.5 (above) This illustration demonstrates the relationship between depth of field and depth of focus. Depth of focus increases with the circle of confusion and magnification. It decreases with lens aperture and is at its minimum when the lens is focused at infinity.

(based on an original by Harold M. Merklinger)

fig.6a (right) The depth-of-focus scale and gauge shown here are based on a circle of confusion applicable for 4x5 view cameras (0.089 mm). They can be used at any focal length. Make a copy of each for your personal use.

fig.6b (far right) A custom depth-of-focus scale and gauge was made using the depth-of-focus equation ($d=2 \cdot c \cdot N$). Mount the scale to the camera, and use the gauge to translate the distance between near and far focus into the required aperture. Then, move the focusing standard to the optimum focusing position, which is midway between the markings for near and far focus. This way, depth of field will be achieved between the near and far focal planes.



nearest point for which sharpness is required, mark its position and measure the distance.

Use the depth-of-focus gauge to translate the distance into the minimum aperture necessary, and slide the focusing standard to the optimum focusing position, located midway between the markings for near and far focus. The gauge can be used for any 4x5 camera and any focal length, because it is designed for infinity focus.

Limits of Diffraction

A beam of light is slightly bent when it passes near a solid object. The metal blades of the lens aperture exhibit this effect on the light on its way to the film, and it impedes optimum lens resolution. In practice, lens resolution is limited by two factors, diffraction and aberrations. The resolution limit due to aberrations depends on the lens construction and is reduced while stopping the lens down. A lens resolution of 80 to 100 lp/mm between $f/8$ and $f/11$ is typical for a quality small-format lens. However, diffraction limits the lens resolution 'r' to:

$$r = \frac{1}{1.22 \cdot \lambda \cdot N}$$

where ' λ ' is the wavelength of light and ' N ' is the aperture of the lens in f /stops. Fig.7 shows the diffraction limits for three wavelengths at 650 nm (infrared), 550 nm (the human eye's sensitivity peak) and 400 nm (ultraviolet). Diffraction increases, while aberrations are reduced, as the lens is stopped down. At $f/11$ or above, lens aberrations are significantly reduced, but diffraction starts to seriously limit lens resolution.

From fig.7, we see that a 35 mm lens cannot yield a print 'sharp beyond human detection'. However, stopping down to about $f/8$ will provide maximum lens performance and satisfying prints. A negative, made with a quality medium format lens at $f/8-11$, can be enlarged to a print standing up to the most critical observation with little room to spare, but it should not be stopped down beyond $f/16$ to avoid diffraction. A 4x5 lens performs best at about $f/11$, but can be stopped down to $f/32$, while still achieving critical resolution for a truly sharp print. Consider the limits of diffraction, while stopping down a lens, unless even front-to-back (un)sharpness is more important than localized image softness.

The above values are based on my equipment, materials and procedures. To determine the capabilities

of your system, prepare a set of negatives, depicting the USAF/1951 test pattern in fig.1a, at various lens aperture settings. Subsequently, determine your negative resolutions according to fig.1c, and use fig.3 to compare the results with the negative resolution required to support critical print observation.

Please note, it is futile to compute the depth of field using a circle of confusion smaller than the smallest 'blurry circle' created by the system. The minimum circle of confusion 'c' is calculated as:

$$c_{\min} = \frac{1}{r_{\max}}$$

where 'r' is the maximum negative resolution obtainable by the system. You cannot improve image quality beyond the limits imposed by the quality of the entire system.

Given a shake-free exposure, many medium- and large-format lens and aperture combination yield a negative resolution high enough to satisfy even the most critical observer. But, take a close look at 'Sharpness in the Darkroom' to make sure you transfer this sharpness from negative to print.

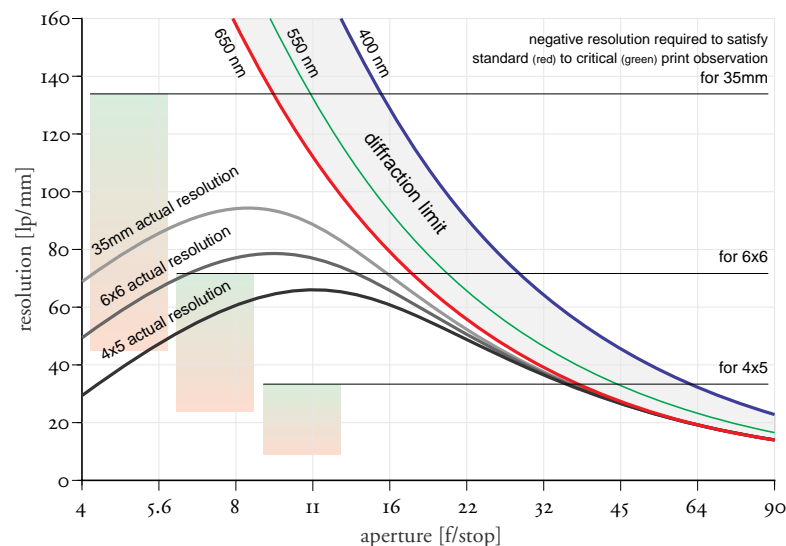


fig.7 Actual negative resolution is limited by lens aberrations and diffraction. While the lens is stopped down lens resolution first increases because aberrations are reduced, but then decreases because the limiting effect of diffraction increases. Eventually, diffraction is the only concern.