How to Optimize the Sharpness of Your Photographic Prints: Part II - Practical Limits to Sharpness in Photography and a Useful Chart to Deteremine the Optimal f-stop.

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Abstract: In the first of this series of two articles the ability of the human eye to resolve closely spaced details was discussed as was the level of detail that is needed in a negative to result in resolvable detail in a photographic print. Here we continue that discussion and discuss f-stop choices to maximize sharpness and we present useful charts that can be used in the field to make sensible, even optimal, f-stop selections.

Introduction

In the first article of this two-part series we discussed the ability of the normal (typical) human eye to see as separate, i.e. *resolve*, two closely spaced details. We noted that this depends importantly on the physical separation of the two objects and on the distance from them to the eye. We found that these defined the visual angle and for visual angles greater than about 1/60 degree the typical eye could resolve those small details. We saw that the 1/60 degree originated in the anatomy of the eye and in the laws of physics. We also discussed the relationship between the resolution needed on a negative and that needed on a photograph, viewing distance included.

Here in the second article we will explore the translation of these facts into practical advice that can be used in the field to maximize the sharpness of a photographic print. In particular, when one wants to photograph a scene the depth of field may be narrow (e.g. you focus narrowly on the eyes in a portrait situation), or it may be wide (e.g. to render into acceptable focus a range of distances in a landscape scene) and its value and the point of sharp focus will determine what distances from the camera are in acceptable focus on the negative.

Suppose you are in the field and you want to photograph a scene. Just to be definite, let's take a specific example. Let's assume that the scene is a landscape and there is a fencepost, say, 20 feet from you and there is a tree 50 feet from you. And, just to make the example complete, lets assume that you wish the images of the fencepost and the tree to each be as sharp on film as you can make them, and you don't care too much about the sharpness of anything else closer or further away in the scene. We will presume that the focal plane is vertical, with no tilts or swings. We ask two questions:

(1) which aperture (f-stop) will be best to ensure that a certain *range of distances* in the scene (from the fence post to the tree) will be rendered in *optimally sharp focus*? We might also ask a second question, (2) which range of apertures is available to us so that this range of distances in the scene will be *acceptably* in focus? There is a precise answer to the first question, and to answer the second question we need to know what level of resolution will be acceptable to us in the final print. To answer this second question we will utilize the information from the first article. (There is a third question that may come to mind. Once you determine an optimal aperture or range of apertures, where in the scene do you focus to actually expose the film? The answer: one third of the way from the fencepost to the tree. In general the focus point should be one third of the way into the scene between the two objects of interest.) We will now address our two questions.

Optimal sharpness

Now, one can focus on the post and one can separately focus on the tree. When doing so, if we are using a view camera, we notice that the position of the ground glass relative to the lens changes as the point of focus in the scene is changed. So, the ground glass must be moved some distance further from the lens as the focus point switches from the further tree to the closer fencepost. If one makes note of this *change in the lens to ground glass distance*, one can readily determine the *optimal aperture* that will provide the optimal focus for everything between the fencepost and the tree in the scene. And, one can readily determine what *range of apertures* will result in acceptable focus, but this latter question depends on what resolution one wants in the final print.

Since one is first asking for the optimal aperture, one is really asking what aperture gives the *best* resolution for the situation at hand. Using the equations from the physics of light (optics), it is possible to write down an equation for the resolution in terms of any given aperture and any given change in the distance between the lens and the ground glass when you focus separately on any two objects (e.g. our fencepost and our tree). The equation used combines two effects that limit sharpness. One is the blurring effect that comes from the reduced depth of field that results from large finite aperture size; only one distance from the lens is in perfect focus on the negative, other distances are increasingly out of focus the larger the aperture. The other is the blurring effect caused by the physical constraints produced by diffraction caused by the aperture itself. The former is most significant for large aperture openings; the latter is most significant for small aperture openings (i.e. high f-stop values). Sparing all of the mathematical details, the result is given in figure 1 as a set of curves for several specific sets of changes in the distance between the lens and the ground glass from 0.5 mm to 10 mm as one might find for a range of different situations. We will next discuss this figure in some detail.

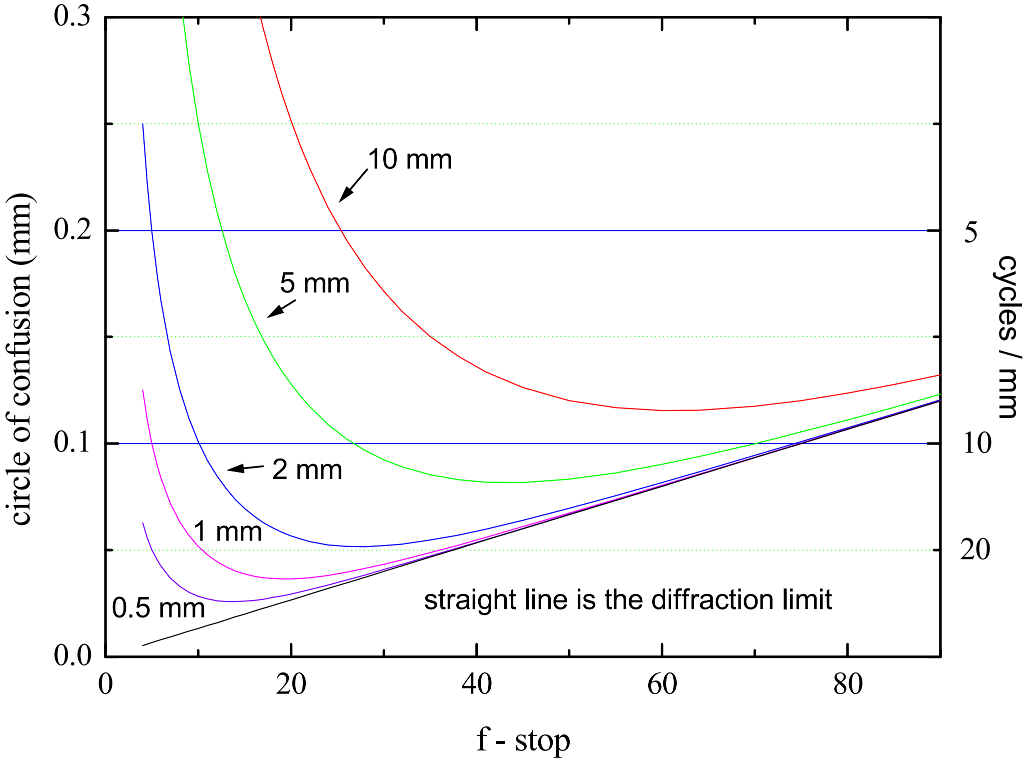

Figure 1: Circle of confusion (see text) vs. f-stop for several shifts in the position of the ground glass for near vs. far focus. The optimal f-stop is given by the location of the minimum in each curve. Also shown on the right axis is the number of *line pairs or cycles* per mm on the negative.

Each curve shown in figure 1 is computed for a different distance between the position of the ground glass for the near and far focus in a scene of interest. For a given curve, the circle of confusion produced on the *negative* can be read off the plot for any specific f-stop. The unit is the millimeter and, again, the vertical axis is labeled circle of confusion, which is traditional. The operational meaning of circle of confusion is this: if the circle of confusion is 0.1 mm, this means that ten lines per millimeter (each black line separated by an equal-width white gap) *on the negative* could be resolved as separate lines when viewed at a distance of ten inches from the negative. i.e. the lines are 0.1 millimeter apart and can be seen as separate. In the terminology of article I, there are 10 line pairs (10 black lines separated by 10 equally wide white spaces), or 10 cycles per mm. The concept of a line pair or cycle is very useful. For example, if a digital camera were to capture the image, the best that the camera could do would be to be able to capture one full cycle on two adjacent pixels, one receiving light, one not (see figure 2 in article I).

If the number is 0.2, then only 5 lines per millimeter (they are 0.2 mm apart) could be resolved on the negative. So, the definition of circle of confusion is the inverse of the number of line pairs (the black line and the white space) per millimeter that you have in mind. If a good normal eye were to view a contact print of the negative from a distance of ten inches, that good eye should readily be able to resolve five lines per millimeter and likely also resolve up to about ten lines per millimeter. So, one would need a circle of confusion of nearly 0.1 mm on the negative to ensure that a good eye will regard the negative or the contact print made from it as very sharp (when viewed from ten inches). You could generally get away with 0.2 mm, but some people would likely be able to detect a subtle lack of sharpness for the case of 0.2 mm.

So, for example, the range of distances in a scene that you wish to have in focus might be such that the ground glass does not move much as you focus on the near and far points (as would be the case if you were on a mountain top and you were to photograph a distant scene with nothing very close to the camera). For such a situation your focus range might move the ground glass 0.5 mm or even less. In such case, you would refer to the curve labeled 0.5 mm and note that the f-stop that corresponds to the best resolution (the low point on the curve labeled by 0.5 mm) is roughly f/14. The minimum in the curve gives the best, i.e. the optimal, f-stop for that situation. If the range of distances for a different situation resulted in a greater motion of the ground glass, we would be on a different specific curve. So, for example, suppose that in the situation of the fencepost and the tree we found that focusing on each of them separately resulted in a shift of the ground glass to lens distance by 5 mm. In that case, we would use the curve labeled 5 mm and determine that the optimal f-stop for that case would be roughly f/43. Note here that this f-stop would result in a circle of confusion of about 0.08 mm, and we could be confident that on a contact print from the negative both the fencepost and the tree would appear sharp to anyone with good normal vision who viewed it from a distance of ten inches. Whether a larger print would be sharp or not will depend on the amount of enlargement that you plan to do and also would depend on how far away from the print the viewer will stand. We will discuss these aspects related to the print in more detail shortly.

If the case at hand resulted in a shift of the ground glass by, say 3 mm, we would imagine a curve between the 2 mm case and the 5 mm case and get an approximate value for the optimal f-stop. A plot of the location of the circle of confusion value for the minimum for each of the curves in figure 1 (and many others that could be added to figure 1) for the complete range of ground glass to lens distances of shift is shown as a continuous curve in figure 2. This figure gives the optimal value of the f-stop for any change in position of the ground glass relative to the lens as you focus on one object of interest and then the other. We can see again from figure 2 that if the ground glass moved about 0.5 mm, the optimal f-stop is about f/14 and if the ground glass moved 5 mm, then the optimal f-stop is about f/43. And, to take a different case, if the ground glass moved a distance of 4 mm, the optimal f-stop would be about f/39. It is useful to note in passing here that the actual focus point (i.e. behind the closest object, one third of the distance between the two objects) is also at the midpoint of the shift in the lens to the ground glass distance. This is useful to remember when there is no convenient object part way into the scene to focus on.

It is important to note here that these results are the theoretical results for a perfect optical system. They ignore imperfections that may be present, e.g. in the lens. They properly account for diffraction effects but they do not account for aberrations that may be present. For example, some lenses have aberrations that limit optical performance when the lens is opened wide. So, if for your situation figure 1 or 2 would lead you to believe that f/10 might be optimal, it might be that your lens has significant aberrations when it is that wide open. So, while the theoretical curves are very valuable, especially when they yield a result that is in the midrange of the apertures available for your lens, they must be used with a bit of caution, especially for low f-numbers, and not blindly accepted without thought.

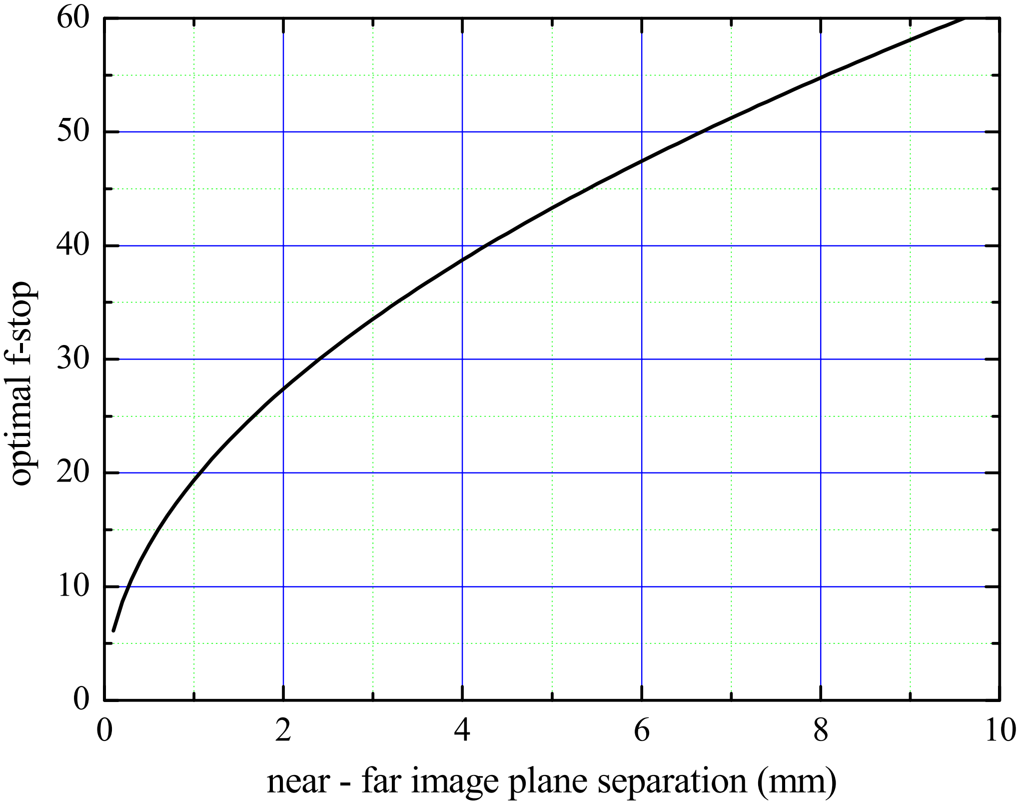

Figure 2: Optimal value of the f-stop as a function of the shift in the ground glass to lens distance for the near vs. far focus.

If we look at figure 1 we notice that while there is an optimal f-stop for a given near-far film plane separation, the plot also allows us to determine the *range* of f-stop values that yield a circle of confusion that is at least as good as a value we select. This sounds complicated, but an example will make it clear. In figure 3 we have reproduced figure 1, with a few additional lines. Suppose that we are interested in a scene for which the near focus vs. far focus ground glass shift in position is found to be 1 mm. We are then restricted to be on the 1 mm curve. If for our eventual final photograph we need a circle of confusion on the negative that is 0.05 mm or better (and we will see how to deal with determining this shortly), we note that there is a range of f-stops that will deliver this resolution or better. So, f/20 is about the best, but note that any f-stop between about f/10 and f/37 will result in a circle of confusion of 0.05 mm or better. This is shown directly on figure 3 by means of the horizontal dashed line, which emphasizes the 0.05 value of the circle of confusion, and by the two vertical lines that denote the f-stop values where the 1 mm curve meets the 0.05 mm circle of confusion line.

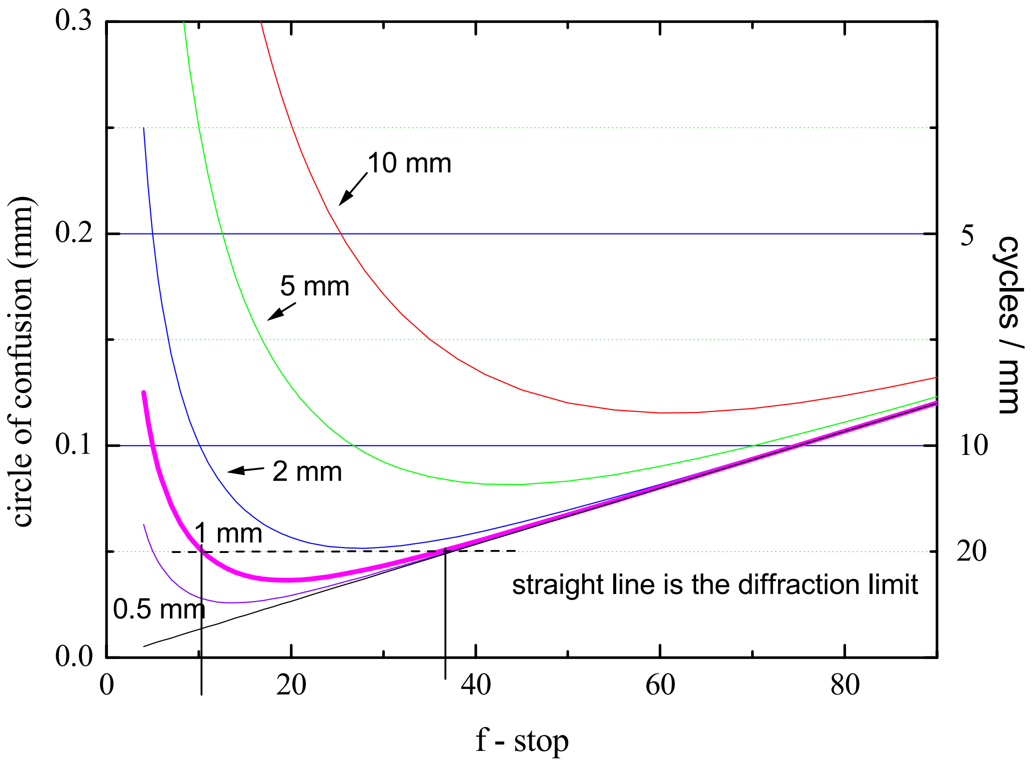

Figure 3: Example showing a range of f-stop values that result in a circle of confusion or 0.05 mm or better for the case of a 1 mm shift in the lens to ground glass distance.

So, how do we decide on what circle of confusion to settle on? One way is to simply always pick the optimal aperture (if that gives an adequate shutter speed). But, for various reasons, we may need to deviate from that. How far can we go? The plots shown as figures 1 and 3 give the circle of confusion on the negative. If you are to create an enlargement and view the enlargement from the *same* 10 inch distance as you view the contact print (or negative), then you need a smaller circle of confusion in the original negative in order to preserve the desired level of sharpness in the final print. If you have a 4x5 negative with a circle of confusion, or separation of details, of 0.05 mm, and if you make a 8 x 10 print (a two times linear enlargement; 2 x 4 = 8), the separation of details in the print will expand (expanding the visual angle) and if viewed from the *same* distance as the contact print, the circle of confusion (i.e. separation of details) will be 0.1 mm (2 x 0.05 = 0.1) on the 8 x 10 print, still sharp. If you view the 8x10 print from twice as far away as the contact print, then as you move away the visual angle is reduced resulting in the double-distance-view 8 x 10 looking like the original-view-distance 4 x 5, with a separation of details of 0.05 mm.

To cite another example, suppose you have a 16 x 20 print and you want it to look sharp from a viewing distance of 20 inches. This is a 4 times enlargement from the original 4 x 5 and it is viewed from twice as far as our standard ten inches. If 0.1 mm detail separation (i.e. circle of confusion) is appropriate for a viewing distance of 10 inches, we can settle for 0.2 on the print for viewing from 20 inches. So, we need 0.2 on the print. The enlargement was by a factor of 4. Thus, to get 0.2 on the print with that enlargement, we need to have 0.05 on the negative. The example discussed in the context of figure 3 fits this criterion of 0.05 mm on the negative where we found a range of f-stop values that were acceptable.

It may be helpful to insert here some convenient numbers for the range of resolution that one might adhere to when making decisions in the field. So, for example, I generally use either 6x7 or 4x5 formats, and I always try to expose presuming I will make prints up to 11x14 from the 6x7 and 16x20 from the 4x5. Here I will show information for two viewing distances, 10 inches for those who like to get close, 20 for those who view from a larger distance. I tend to view 8 x 10 from a distance of about 10 inches, and 11 x 14 and 16 x 20 from about 20 inches, or a bit further away. I begin with the linear enlargement factor that each print size represents when enlarged from the given negative format.

Negative size =>	6 cm x 7 cm	4 in x 5 in	8 in x 10 in
Print Size			
8 x 10	3.39	2	1
11 x 14	4.66	2.75	1.38
16 x 20	6.77	4	2

Table 1: Linear enlargement factors to produce a given size print from a negative of various sizes. As an example, a full-frame 4 x 5 negative enlarged to a 16 x 20 print requires a linear enlargement factor of 4.

On the next page is a table (Table 2) of the values of the circle of confusion necessary on the *negative* to produce a sharp *print* of the given size when viewed from the given distance, using the criteria we have adopted. The number in Table 2 for the film format, print size and viewing distance that you prefer is the number to use with Figures 1, 2 or 3 to help you select the right f-stop. All entries are in millimeter units for direct use on the figures.

Negative size =>	6 cm x 7 cm	4 in x 5 in	8 in x 10 in
Print (viewed 10 in)			
8 x 10	0.030	0.05	0.10
11 x 14	0.021	0.036	0.072
16 x 20	0.015	0.025	0.05
Print (viewed 20 in)			
8 x 10	0.059	0.10	0.20
11 x 14	0.043	0.072	0.14
16 x 20	0.030	0.050	0.10

Table 2: Circle of confusion values required on a negative to produce a sharp print of a given size from the negative – using the 10 cycles/mm standard. The entries in the table all have mm units.

These are quite stringent limits (we used 10 line pairs per millimeter for a viewing distance of 10 inches). If we were to adopt the less stringent limit of 5 cycles per millimeter (this would be consistent with the requirement for 20/20 vision at this distance) for a viewing distance of 10 inches (a number that is often adopted as the practical limit of routine casual human resolution) then we would simply *double* all of the values in table 2 just above, use those constraints on the figures and still be in very reasonable shape.

For my own work with a 4 x 5 I tend to use f-stop values in the range of f/22 and f/32 rather routinely. And, a glance at this table and figure 3 makes it clear that this is a very good choice for most landscape work. So, in a pinch, *if one remembers only that*, one will be well served. The table and figures also make clear that for flat field work (e.g. photographing a barn door with the film plane parallel to the door) it would be quite safe to go to f/11 – if your lens did not introduce aberrations at that large an opening.

It should be noted that what has been presented here (the plots) have been obtained from a mathematical treatment that is valid for situations other than close-ups. For close-ups other more complete equations need to be used. None the less, what is given here is valid over a broad range of situations and is even approximately OK for reasonably close situations. How close is a close-up? A reasonable figure of merit might be anything closer than a few times the focal length of the lens.

We should also point out here that the curves and the treatment that has been presented presume that one has ideal lenses, enlarger alignments, etc. We also presume that your ground glass and the film plane when the film is in your film holder in the camera occupy the same position in space (or that your medium format camera focuses properly). [Most folks take this for granted. I learned the hard way: for my 4x5 my film plane and the ground glass were not in the same location (by 0.019 inch), which resulted in negatives that were not perfectly in focus until the camera was fixed.] So, what you see in reality on your prints may be a bit less sharp than what you might expect here if, for example, your lenses have aberrations, your enlarger is not aligned, or anything else is out of proper adjustment.

Nothing beats looking at the final results and it would be worthwhile to do a few experiments with your system to check to see that you are getting what you expect. So, set up a camera, with several things in a scene, pick two objects at different distances from the lens, set the optimal f-stop, take the photograph, then expose more film using two f-stops on either side of optimal, etc. Then, make prints, make enlargements, and take a good look. So, do a bit of experimentation and take a careful look at the results. (Note: It is important to first check to see that the point that you focus on in the scene is actually the place that produces the sharpest image on the negative – some cameras are not perfect in this regard. For example, you might stand next to a picket fence and look along the fence. Focus on a particular slat (and mark it somehow) expose film and examine the negative. If the slat you focused on is not the sharpest on the negative (and you may have to make a print to be sure), your camera is slightly imperfect in manufacture like mine was and you need to keep the true focus point in mind for future work, or get the camera repaired.

Film Format

What has been written here is most useful to photographers who work with 4 x 5 and larger formats. But, it is valid for smaller formats as well and the 6 x 7 format has been listed in the tables. For 35 mm, the change in the distance between the film plane and the lens is rather narrow as one focuses on objects of interest at different distances from the lens, and for medium format in other than close-up situations it is also modest. But, a bit of thought and reference to figure 3 should make clear why it is that most normal lenses (e.g. 50 mm on a 35 mm camera, 80 mm on a 6x7 camera) generally only allow one to reach a f-stop of about f/22. And, it should be clear that the optimal situation for most images in those formats is obtained with f-stop values in the range of f/11 to f/22 or so. The narrow distance shift on focus for such formats for many situations restricts one to something like the 0.05 mm or the 1 mm curve in figure 1.

Other Work and References

The material (the plots) shown here was developed roughly a dozen years ago and available in various printed versions. Shortly thereafter some aspects of this material, in particular the selection of the optimal f/stop, were independently obtained by Paul Hansma and presented in a different but equivalent way in an article in Photo Techniques magazine in 1996 (Vol. 17, p.54). That article appears to have used lines instead of line pairs per mm, but there is agreement on optimal f-stop choices. There is also a more recent useful web site that incorporates some of Paul Hansma's material as well as that found in a number of other sources. That useful site is http://www.largeformatphotography.info/fstop.html#ref. Both of these references are worth a careful look, especially if you like a mathematical approach.

My primary references for these two articles were the very good books *Fundamentals of Optics* by Jenkins and White (3rd edition, 1957) and the Focal Press *Encyclopedia of Photography*. If you can find yourself a good clean copy of that Focal Press book with just about any publication date, grab it; most of the information in that book is timeless. Another very good book is *Applied Photographic Optics* by Sidney Ray (3rd edition, 2002), also by Focal Press. An excellent book on many details associated with the structure and function of the eye and the vision process is *Foundations of Vision* by Brian Wandell.

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The Author

Robert Hallock is Distinguished Professor in the Department of Physics at the University of Massachusetts, Amherst, where he has taught and done research for more than thirty years. He has been involved with photography for even longer, and for the past ten years has emphasized black and white photography with traditional archival darkroom techniques with image capture in 4 x 5 and 6 x 7 formats. He currently teaches a course on the physics of light, applications and perception, "*Seeing the Light*", with an emphasis on topics of relevance to students interested in Art and Photography.

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Appendix

Here we provide a bit of information that will help you to get a feeling for the shift in the position of the ground glass that will come from a change of focus from one object to another at a different distance from the camera. This depends on the specific distance for the two objects, but also on the focal length of the lens. This information will be of general use with reference to the use of figures 1 and 2, but it will also indirectly help to see the substantial effect different focal lengths have on the position of focus. In the table below, we show the position of the ground glass relative to the lens for a number of different lenses and for a number of different distances to the object in the scene. The first column is the distance from the object in the scene to the lens in feet. The second column is that same distance expressed in millimeters. The subsequent columns are the position of the ground glass relative to the position of the lens in millimeters for various focal length lenses (in mm). Note that for a lens focused on a far distance, the ground glass is at a distance from the lens equal to the focal length.

feet	mm	50	90	120	150	180	210	240	305
2	609.6	54.47	105.59	149.41	198.96	255.42	320.36	395.84	610.40
2.5	762	53.51	102.05	142.43	186.76	235.67	289.89	350.34	508.56
3	914.4	52.89	99.83	138.13	179.43	224.12	272.61	325.41	457.65
3.5	1066.8	52.46	98.29	135.21	174.54	216.54	261.47	309.67	427.11
4	1219.2	52.14	97.17	133.10	171.04	211.18	253.70	298.82	406.76
4.5	1371.6	51.89	96.32	131.51	168.42	207.19	247.96	290.90	392.22
5	1524	51.70	95.65	130.26	166.38	204.11	243.56	284.86	381.31
6	1828.8	51.41	94.66	128.43	163.40	199.65	237.24	276.25	366.05
7	2133.6	51.20	93.96	127.15	161.34	196.58	232.93	270.42	355.87
8	2438.4	51.05	93.45	126.21	159.83	194.35	229.79	266.20	348.60
9	2743.2	50.93	93.05	125.49	158.68	192.64	227.41	263.01	343.15
10	3048	50.83	92.74	124.92	157.76	191.30	225.54	260.51	338.91
12	3657.6	50.69	92.27	124.07	156.41	189.32	222.79	256.85	332.75
14	4267.2	50.59	91.94	123.47	155.46	187.93	220.87	254.30	328.48
16	4876.8	50.52	91.69	123.03	154.76	186.90	219.45	252.42	325.35
18	5486.4	50.46	91.50	122.68	154.22	186.11	218.36	250.98	322.95
20	6096	50.41	91.35	122.41	153.78	185.48	217.49	249.84	321.06
25	7620	50.33	91.08	121.92	153.01	184.35	215.95	247.80	317.72
30	9144	50.27	90.89	121.60	152.50	183.61	214.94	246.47	315.52
40	12192	50.21	90.67	121.19	151.87	182.70	213.68	244.82	312.83
50	15240	50.16	90.53	120.95	151.49	182.15	212.93	243.84	311.23
75	22860	50.11	90.36	120.63	150.99	181.43	211.95	242.55	309.12
100	30480	50.08	90.27	120.47	150.74	181.07	211.46	241.90	308.08
200	60960	50.04	90.13	120.24	150.37	180.53	210.73	240.95	306.53
500	152400	50.02	90.05	120.09	150.15	180.21	210.29	240.38	305.61
1000	304800	50.01	90.03	120.05	150.07	180.11	210.14	240.19	305.31
2000	609600	50.00	90.01	120.02	150.04	180.05	210.07	240.09	305.15
5000	1.524E6	50.00	90.01	120.01	150.01	180.02	210.03	240.04	305.06

Nothing beats experience gained in the field, but to demonstrate the utility of the table, let us take the example we cited earlier of the fence post and the tree, with the fence post 20 feet from the lens and the tree 50 feet from the lens. Now, we need to make the example specific to a particular focal length of lens. Let's take 210 mm as an example. For that case, the position of the ground glass for the post at 20 feet from the lens is 217.49 mm behind the lens, while the position of the ground glass for the tree located 50 feet from the lens is 212.93 mm behind the lens. So, if we focus on one and then the other, we will find that the ground glass will move a distance of 4.56 mm. If we refer to figure 2, we can see that the optimal f-stop for optimal focus for this case is about f/42. So, at f/42, the circle of confusion on the negative would be about 0.075. We determine this by going to figure 1 and locate a point on the plot that is close to the 5 mm line and along a vertical line above f/42. We can then decide if this is good enough for our purposes. Note that were we to use a 120 mm lens instead, then the two positions of the ground glass would be 121.19 mm and 120.95, a difference of 0.24 mm. This tiny shift tells us (by reference to figure 2) that we could use a very large aperture (like f/11, presuming there are no aberration effects), and have a very small circle of confusion. This is one reason why people use wide angle lenses.

Of course, there is no free lunch. So, in the example above, the 120 mm focal length lens provided a much smaller shift in the position of the ground glass than did the 210 mm lens. But, the negative that we would make with that lens compared to that made with the 210 for the same camera position would have a much wider field of view. If we wanted to restrict the final print to the same field of view as that provided full frame with the 210 mm lens, we would have to use only part of the negative made with the 120 mm lens and consequently have to do a bigger enlargement to get the same final image. So, in a sense, what you gain directly with the 120 mm lens in this case, you loose later when you make the print, unless the wider field of view is what you really want.

Much of what is represented here in the table and the discussion can be readily seen in the field with a little patience and a good loupe or a good very strong pair of reading glasses (to substitute for the loupe and give you a more global view of your ground glass). But, in general, this is all rather useful information, even if all it does is confirm what you already know.