INSTRUCTIONS FOR MEASURING THE RESOLVING POWER OF CAMERA SYSTEMS AND COMPONENTS

Important Note: Please do not be intimidated by the length of this tutorial on measuring resolution. The basic idea is simple; just photograph the chart at the specified distance and examine the film.

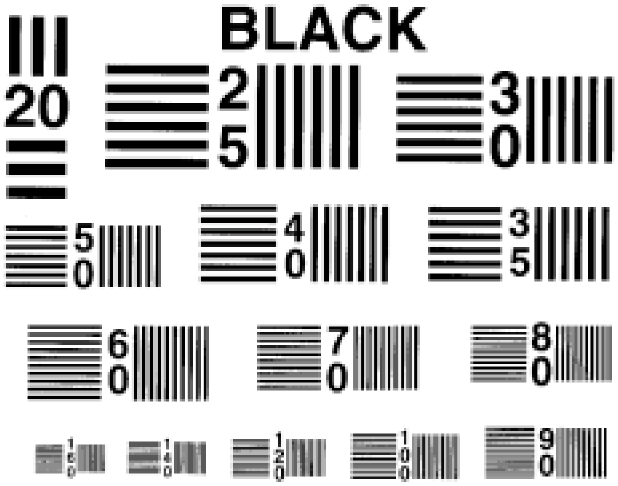
Summary

The chart should be rigidly mounted and photographed as directed. Examination of the film will reveal the resolving power (resolution) of the camera-film system. The chart is useful for comparing lenses and films, quantifying the loss of resolution from filters, finding the combination of factors that yield "tack sharp" photographs, checking lens alignment and accuracy of focus, and testing loss of resolution by digital manipulation.

Overview

This 24 by 36 inch chart is an invaluable tool for photographers. It provides (1) a convenient, accurate way of measuring the resolving power (resolution) of a camera system and its components; (2) a way to evaluate the effect on resolution of shutter technique, filters, tele-extenders, tripods, mirror lock-up, cable releases, other devices, and film processing; and (3) a means of testing the accuracy of focus of the camera and alignment and astigmatism of lenses. A photograph of the chart can also be used to test quantitatively the quality of scanners or service bureaus and to determine the effect of digital operations on resolution.

The chart is useful for comparing lenses and for finding f stops will be sharpest throughout the film plane. To measure resolution, the chart is photographed and its image on the developed film examined with a microscope or magnifier. The 84 resolution targets on the chart are strategically distributed and printed in black, red, green, and blue. Each target contains 14 pairs of grids spanning the range 20 to 160 line pairs per millimeter (l/mm) at the film plane when the camera is at the proper distance from the chart. An enlargement of one of the targets is shown below.



The resolution measured with a target is necessarily the resolution of the entire camera system. Degradation of resolution may be caused by imperfections in the camera, camera support, lens, film, lighting, exposure, focus, shutter technique, or processing, or by movement of the target. Although one use of this chart is to measure the resolution of the whole camera system, more often the purpose is to measure the resolution or reduction of resolution caused by a particular part of the system, usually a lens. To do that requires eliminating the influence of all other factors.

The resolving power of a lens system is an important measure of its quality. A lens that will resolve 20 l/mm will yield good 4x6 inch photographs. However, about 40 l/mm **as measured on the film** is about the minimum for a lens of professional quality. A resolution of 60 l/mm is very good, 80 is excellent, and 100 l/mm is exceptional. It is important to note that fine-scale resolution is but one measure of lens quality. Other desirable qualities are low distortion, low flare, high contrast, absence of color distortion, uniformity of light across the image, mechanical reliability, and quality of construction. ***High resolution, however, is a necessary attribute of a good lens and usually correlates well with overall lens quality.***

Accuracy of the Targets

The grid patterns were drawn on a computer, printed at 7.76 times target size, reduced for final printing, and then printed with a state-of-the-art commercial press on heavy paper designed to minimize bleeding. The targets were examined with a microscope equipped with an eyepiece line moved by a calibrated wheel. The center-to-center spacings of the lines are accurate to within about 1% for all the grids. The spaces between the lines are intended to be the same as the width of the lines, in accord with the NBS (now NIST, National Institute of Standards and Technology) standard for resolution targets. However, the finer grids push the limit of modern commercial printing capability; minute differences in fabrication and inking of the printing plates can cause the lines of one grid to be slightly thicker or thinner than those of another grid of the same size.

A 5% increase in grid line width causes a 5% decrease in space width and hence a 10% difference between the two. Grids in which the bar and space widths differ by less than 10% should give good results in resolution tests. A table at the end of the instructions gives the finest grid, in each of the 84 targets, in which the bar and space widths differ by less than 10%. All coarser grids are more accurate. Note that 78 of the 84 grids are satisfactory at the 100 l/mm level. Only one group of four grids is of relatively low accuracy - the one at the middle of the right edge. These targets exceed the accuracy of all other printed charts that are available, some of which are grossly inaccurate for the high resolution grids.

Mounting and Placing the Chart

The chart should be mounted on a wall, plywood, or foam board (available from frame shops or art stores). Foam board is best but tends to warp, so the board should be glued to a rectangular frame on the back. A good frame can be made from wood 5/8 to 3/4 in. thick by about 1.5 in. wide.

The targets have been sized so that when the camera-chart distance is correct and a photograph taken, the spacing of the grid lines (in l/mm) on the developed film will be those given beside each grid on the targets. At this correct distance the width of the chart (36 inches) will (and must) measure 36 mm on the film. The proper camera-chart distance can be found in two ways. One way is simply to measure the distance. For any camera the correct distance can be calculated from the formula $D = 0.089f$ where D is the distance in feet from the chart to the film plane of the camera and f is the focal length in millimeters. The following table gives the correct distance for most lenses.

focal lgth mm	D ft	D in	focal lgth mm	D ft	D in	focal lgth mm	D ft	D in	focal lgth mm	D ft	D in	focal lgth mm	D ft	D in	focal lgth mm	D ft	D in
20	1	10	40	3	7	70	6	3	180	16	1	400	35	9	600	53	7
24	2	2	50	4	6	100	8	11	200	17	10	420	37	6	700	62	4
28	2	6	55	4	11	105	9	4	280	25	0	500	44	8	800	71	6
35	3	2	60	5	4	135	12	1	300	26	10	560	50	0	840	75	0

For a 35 mm camera, the proper camera-chart distance is best found by placing the chart so that its image exactly fills the frame of the negative (or slide), which measures 24 by 36 mm. However, in most 35 mm cameras the field of view seen in the viewfinder is but 85-95% of the area that appears on the film. (The viewfinders are designed that way because slide mounts typically mask 7-12% of the image area, and because commercially enlarged prints reduce the full area by about the same amount.) For these cameras the correct distance occurs when the two vertical red lines on the chart are at the edges of the viewfinder image. When this is done, there will be at most a 3% error (negligible) in the camera-chart distance for viewfinders that cover from 84 to 95% of the film image. For cameras in which the viewfinder and film images are about the same (Canon F1 and EOS and Nikon F2, F3, F4, F5) the proper camera-chart distance can be found by exactly filling the viewfinder with the image of the entire chart.

For medium or large format cameras at the correct distance the chart will not, of course, fill the frame, but the image of the chart on the film must still be 24x36 mm. To test these cameras off axis requires either that the chart be photographed at all desired positions in the frame or that the chart be cut up so that individual targets can be located as desired.

Important - In all cases, but especially when the target-camera distance is determined from the focal length (as it must be for all but 35 mm cameras), the image on the film should be measured to be sure that its size is correct, i.e., the width of the chart image should be 36 mm or the width between the red lines 34 mm. If it is not, a correction to the resolution numbers on the targets must be made. This is be done by multiplying the resolution numbers (l/mm) by 36 divided by the number of millimeters between the vertical edges of the image of the chart on the film. For example, if the chart measures 33 mm on the film, the grid numbers must be multiplied by 36/33 = 1.09. If the edges of the chart are not visible, measure between the vertical red lines on the chart image, in which case the correction is 34 divided by the number of millimeters between the red lines. (Note: multiplying the numbers by a correction factor will give numbers of misleading accuracy; they should be rounded to the nearest 5 of 10 l/mm. See the third paragraph in the subsection, About the Shape of the Grids, in the Appendix for further discussion of accuracy of resolution measurements,

The resolution of some lenses is a function of the subject distance. Most lenses are not designed to give the highest resolution when the subject is close to the lens. In particular, the resolution of wide angle lenses at the proper chart distance may differ from the resolution at larger distances. Therefore, for lenses with focal lengths in the range 20-50 mm, it is sometimes useful to double the camera-chart distance described in the previous paragraphs. In this case, the resolution numbers shown on the targets must also be doubled. With a 35 mm camera this doubling should be done by placing one corner of the chart at the center of the viewfinder and the opposite corner at one corner of the viewfinder, i.e., the chart should occupy 1/4 of the image on the developed film. For viewfinders that cover 84-95% of the image on the film, the corner of the viewfinder should hit a point near a corner that is 2 inches from each edge of the chart. An alternative procedure, especially useful for short lenses, is to photograph larger targets, and a set of five such targets, together with separate instructions, is supplied with the chart.

On the other hand, the camera-chart distance may become awkwardly large for lenses in the 500-1200 mm range. In that case, it is possible to photograph the chart at, say, one-half of the specified distance. In this case the numbers on the chart must be halved, and the finest grid on the film then becomes 80 l/mm. (Telephoto lenses rarely match this resolution.)

Alignment of the Chart

When the chart is centered in the viewfinder, the plane of the chart must be aligned at right angles to the line from the chart center to the lens. There are at least three ways to do this. (1) A carpenter's square can be held against the chart and made to aim at the camera. (2) When the chart fills the viewfinder, the alignment is correct when the chart image is symmetrical. This method is ineffective with lenses of long focal lengths. (3) The best method is to glue a small mirror (about 3x4 in.) on the chart just under the center grids. When the image of the camera can be seen in the mirror through the viewfinder, the alignment is correct. With long lenses it may be difficult to locate and see the camera in mirror. The solution is to position the camera approximately and then walk to the chart and wave a white hankerchief near your face so that its image can be seen, and then walk backward toward the camera while keeping the hankerchief in view. Readjust the chart and camera until the camera can be seen in the mirror through the viewfinder. (Suitable mirrors can be purchased for about $2. They are often imbedded in a plastic holder, which must be removed.)

Lighting

The contrast of the target seen by the camera is a strong function of the lighting, and high chart contrast is important for the reasons discussed in the next section. To achieve maximum contrast, glare must be avoided, so lighting should be from the sides or above. The background behind the photographer should be dark so that no bright light is reflected directly from the chart toward the camera. A lens hood should be used.

Film

When testing the resolution of a lens, it is essential to use a film that has high resolution since both the film and the lens contribute to the degrading of an image. Good lenses resolve more than 200 l/mm at some f stops (See Appendix.), and for those lenses a good film to use is Kodak Technical Pan, a black-and-white film of very high resolution when properly exposed and developed. T-Max 100 is also an suitable film to use. A convenient alternative is a fine-grain color film. Good choices are Royal Gold 25, Ektachrome 100S or 100SW or 100VS, Elite 100 II, Sensia 100, Provia 100, and Velvia.

The resolving power of a film depends strongly on exposure, development, and target contrast. The resolving powers of films are usually reported by the manufacturer at contrast ratios (reflectivity of white area to reflectivity of black area) of 1000 and 1.6. A contrast ratio of 1000 can only be achieved by a transmission target - one in which light is passed through the target to the film. (The black area can cut off nearly all the light, thus giving a very high ratio.) For a reflectance target, such as the chart, the maximum contrast is much lower primarily because black ink typically reflects 2-10% of the incident light. The contrast ratio of the black grids on the chart was measured under typical lighting conditions (cloudy bright sky, target on a high wall, dark trees behind photographer) and was found to be about 30. The contrast ratio of the colored grids is about 5-10. Since these numbers are between 1000 and 1.6, the maximum resolution of a photograph of the chart will fall between the two manufacturer's figures.

The following table gives the manufacturer's figures for the maximum film resolution in l/mm at two contrast ratios for several films.

Film	R_{max} at Ratio 1000	R_{max} at Ratio 1.6	Estimated at Ratio 30
Kodak Tech Pan	320	100	130
Royal Gold 25	200	80	110
T-Max 100	200	63	90
Agfapan	200	-	
Velvia	160	80	110
Provia 100	140	60	100
Kodachrome 25	100	63	
Kodachrome 64	100	50	
Ektachrome E-100	-	-	100

The resolutions in the column at Ratio 1000 cannot be approached by photographing a chart with a conventional camera. The manufacturer's resolution figures are obtained with transmission targets, a system of highly corrected apochromatic lenses, and optimal exposure and development.

Exposure and Development

With color film the highest resolution is usually obtained when the chart is metered through the camera and then over-exposed by about 1/2 stop. To determine optimum exposure for your system, you may wish to bracket your first test. With Technical Pan here are two procedures that yield excellent and nearly identical results: (1) set the ISO to 60, use center-weighted or matrix metering on the chart, and develop in Kodak HC110 dilution D for 8 minutes or (2) set the ISO to 100 and develop in 1:25 Rodinal for 6 minutes. **For comparisons of lenses and other variables, however, it is vital that all exposures and development be the same.**

Precautions to Avoid Loss of Resolution

Obviously, the chart should be accurately focused. For that purpose half of a "Seimens star," a good focusing aid, is provided near the center of the chart, though the individual targets can also be used. Unless you are confident of the camera's focus accuracy, you should consider a test in which you bracket the focus. In fact, a major source of poor resolution is not having the image plane within the emulsion. There are three causes of this: inaccurate focusing by the photographer, imperfect flatness of the film against the film plate, and imperfect agreement between the location of the focused image on the focusing screen and the image at the emulsion (i.e., damage, faulty design, or poor manufacturing tolerances in the camera body or focusing screen).

Neither the camera nor chart should be moved in the slightest by wind or vibration from any source. The lines on the 100 l/mm grids on the chart are only 0.005 inch apart, so a movement of that magnitude would blur those grids completely and would, of course, degrade all other grids as well. Correspondingly, the lines of the images of the 100 l/mm grids **in the camera** are only 0.0002 inch apart. Thus the camera must be rock solid. It should be rigidly mounted on a sturdy tripod, and a cable release, electronic release, or self timer should be used to trip the shutter unless a high shutter speed can be achieved. With lenses longer than about 300 mm the mirror should be locked up, if possible, when the shutter speed is less than 1/125 sec. It is helpful to brace the camera with a second tripod for lenses of 500 mm or longer. In addition, some photographers place a shot-filled bag or other weight on the camera.

One way to reduce loss of resolution by camera or target movement is to use a flash. The flash should be at an angle of about 60 degrees to the chart and at least 8 ft. from its center. (At 45 degrees and 6 ft. the light at the edge of the chart nearest to the flash will be one stop brighter than at the far edge.) A flash on either side of the target provides better illumination. A tripod should be used since the duration of a typical flash may be as long as 1/300 second. A way to eliminate camera motion due to the shutter and mirror movement is to place the camera and chart in a room that can be completely darkened and set the f stop to the desired value. Then turn off the lights, open the shutter, turn on the lights for a pre-determined time, and close the shutter in the dark.

Finally, it is useful to put on the chart a Post-it note on which you write the lens and f stop of each photograph.

Interpreting the Results

After photographs of the chart have been made, the target images can be examined in several ways: (1) with a microscope or powerful loupe, (2) by projecting the image with a good enlarging lens and examining the image with a focusing magnifier (The images from most 35 mm projectors do not have sufficient resolution.), or (3) by using a loupe or magnifying glass to examine an enlarged print made with a high-quality enlarging lens.

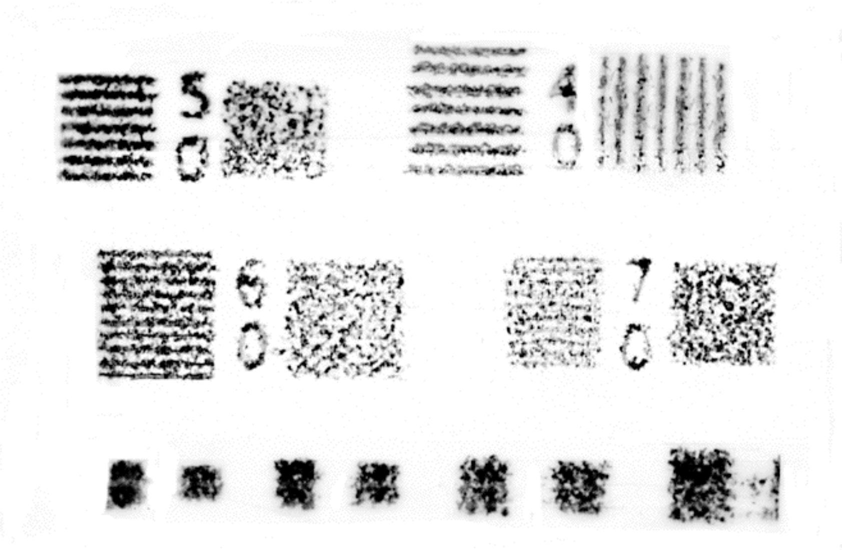
The unaided human eye can typically see at most 6 l/mm. Thus with a good 8-power loupe one should be able to see 48 l/mm. In practice, this is a stretch but you can probably see the difference between a poor lens (20 l/mm) and a fairly good one (40 l/mm). To examine grids in the 50-100 l/mm range, however, it is necessary to use a microscope of at least 50 power. The 50-power pocket microscope from Edmund Scientific Co., Stock No. V36-118 is suitable for grids up to about 50 l/mm, The company's address is 101 E. Gloucester Pike, Barrington, NJ 08007-1380. The order phone is 800-728-6999. To observe higher resolution, a microscope of higher quality is necessary, or one must resort to one of the other techniques.

To determine if your microscope or technique is capable of resolving 100 l/mm, a slide has been enclosed that has at least one grid pair that shows 100 l/mm - the black grid near the chart center.

One examines the images to locate the finest grid whose lines are distinct enough to be seen clearly and counted. The next finest grid will appear to be uniform in color density or will show only a modulation, i.e., a wave-like vestige of a grid, which is not considered resolved. **One should start with coarse grids and work up to the finer ones.** Each grid should "racked through" the focal plane several times to be sure that accurate focus has been achieved. Then the **first** grid that is not resolved means that the resolution limit has been passed. It sometimes (rarely) happens that a finer grid, beyond the first one not resolved, will appear to be resolved. This phenomenon, called "spurious resolution," can occur when the image is imperfectly focused, is caused by the nature of the defocusing process (technically called *convolution*), and must be disregarded.

When the resolution is higher than about 80 l/mm, it is best to view the emulsion side of the film because viewing the grid through the base may cause a slight loss of resolution. Often one grid of a pair will be resolved while the other will not, which is caused either by movement of the camera in the direction of one of the grids or by astigmatism of the lens. Occasionally there will be borderline cases; a grid that one observer says is resolved might be called a mere modulation by someone else. In such cases the quality of the microscope may make a difference. What is most important for comparisons is consistency on the part of any one observer.

Following is an instructive reproduction of a photograph of a target taken through a microscope. Note that this camera lens has considerable astigmatism. The vertical lines are resolved at 40 l/mm but not at 50, while the horizontal lines are resolved at 60 l/mm. There is wave-like vestige of the horizontal grid at 70 l/mm, so horizontal resolution could be regarded as about 65 l/mm.



The black-and-white targets give a good single measure of lens resolution and will suffice for most purposes. They do not give a complete test of resolution, however, because most lenses do not focus all colors onto the same plane nor do they resolve all colors equally well. The resolution found with colored grids is less than that found with black-and-white grids, largely because of lower contrast. It should be noted that since black and white films are sensitive to color, they can be used for evaluating the colored targets. Therefore, the color of each target has been printed on the target.

The resolution found with the chart, R, is the resolution of the film-camera system, not the resolution of the lens. However, for comparison of lenses, for studying the effect of variables on system resolution, and for investigating focus accuracy, a measurement of R is sufficient provided the film resolution is high enough. For these purposes, comparisons of images should, of course, be made only among images made with the same film, exposure, and development.

Below is a table that gives the highest resolution, approximately, that can be obtained with Technical Pan and selected color films (Kodachrome 25, Royal Gold 25, Ektachrome 100S or SW, or VS, Elite 100 II, Sensia, Provia 100, and Velvia.), a "perfect" (diffraction-limited) lens and all conditions optimal. The numbers are rounded to the nearest 5 or 10 l/mm since higher accuracy is not justified. You can judge your lens and technique by reference to these figures. See further details in the Appendix. Bear in mind that the observer's judgment of "resolved" affects the results.

Highest Resolution Possible, l/mm, Approximate

f stop	Diffraction Limit	Tech Pan	Color Film
2	800	75	70
2.8	600	85	80
4	400	100	90
5.6	300	120	100
8	200	120	100
11	150	100	95
16	100	80	80
22	75	70	70
32	50	50	50

The "diffraction limit" is an upper limit on resolution set by the laws of optics. It is given by about 1500/(f stop) to 1800/(f stop). and depends in part on how resolution is judged.

Note: The resolution of a lens itself can be found by examining what is called an "aerial image" of the chart. This can be done by modifying a high-quality microscope. The microscope stage is removed, and the microscope is rotated so that its axis is horizontal. The lens is then mounted to the microscope on this axis, and the image of the chart that is formed by the lens is examined with the microscope.

We have constructed such a device and used it with a variety of lenses. The results are astonishing. While some lenses could resolve no more than 20 l/mm at the edges, many tested at more than 200 l/mm throughout, and one lens (a Nikon 50 mm f1.8) resolved 640 l/mm at its center at f1.8 and 560 at f2.8, which required placing the chart at four times the full-frame distance and using a microscope magnification of 400. None of these lenses gave resolution on film of more than 110 l/mm even with Kodak Technical Pan. A possible explanation is given in the Appendix.

Clearly, **for good lenses**, resolution at large aperture is degraded more by the film than by the lens whereas at small aperture there is more degradation by the lens. As detailed in the Appendix, however, both film and lens contribute to loss of resolution of the image on the film. In other words, the loss of resolution on the film is the result of adding the dispersion caused the lens to the dispersion caused by the film.

APPENDIX

Estimation of Lens Resolution From Film Resolution and the Chart Measurement

An equation recommended by Kodak and by John Williams in his book *Image Clarity* that relates the resolution of the image on a film, R, to the lens resolution, R_L, and the film resolution, R_F, is

$$\frac{1}{R^2} = \frac{1}{R_L^2} + \frac{1}{R_F^2} \qquad (1)$$

This equation should be regarded as strictly empirical. Moreover, it assumes no loss of resolution caused by filters, camera vibration, target movement, imperfect development, imperfect focusing, or other factors. Here $1/R_L$ and $1/R_F$ can be thought of as dispersion, so Eq.(1) shows how the dispersions of the lens and film add to give the dispersion on the developed film.

Another empirical equation sometimes used to relate R, R_L, and R_F is

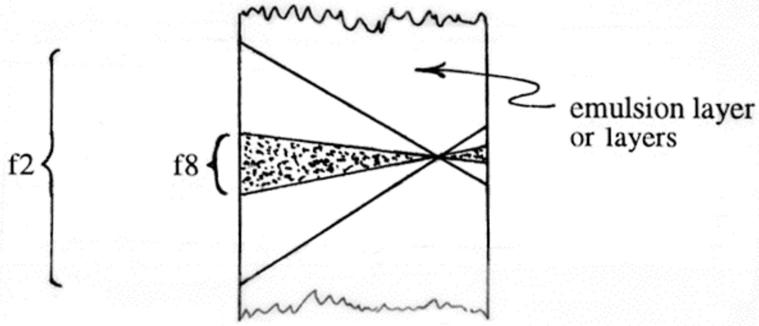
$$1/R = 1/R_L + 1/R_F \qquad (1a)$$

Which equation is best is uncertain, though Eq. (1) has a firmer theoretical basis. Perhaps the best fit to data would be an equation with an exponent on R, R_L, and R_F between 1 and 2.

Lens resolution is limited by the design of the lens and the diffraction limit. A few lenses are so well designed that R_L is essentially diffraction limited. Note that for fine lenses, those near the diffraction limit, R_L **decreases** continuously as aperture decreases. (See table on page 6.)

A problem with these equations is what to use for R_F. The resolution figures given by the manufacturers cannot be used because (1) they were not measured at the contrast ratio of the chart (about 30 for the black and white grids), (2) they were measured with laboratory equipment under conditions that cannot be met with a conventional camera, and most importantly (3) R_F, when used in this equation, is not a constant, as implied by the manufacturer's numbers but, like R_L, is a function of the aperture.

A possible explanation for why R_F is function of aperture is that when film is exposed through a lens, the light rays impinging on the emulsion from a point object are not parallel. Consider the following sketch. It shows two beams of light from a distant point source coming through a lens and focusing at a point near the rear plane of the emulsion layer. One beam is from a lens set at f2 and the other at f8. Clearly, the one at f2 exposes a larger volume in the film emulsion than does the one at f8. Thus there is more dispersion at f2 than at f8, i.e., this effect causes R_F to **increase** as aperture decreases.



Another factor that contributes to loss of resolution is halation, which is image dispersion caused by reflection of light from the back of the film base and through the emulsion again. The path taken by the reflected light depends on the angle of incidence; the larger the angle from the normal, the more the reflected path differs from the entry path and the greater the dispersion. Thus the larger the aperture the greater the dispersion. In reality the dispersion mechanism is much more complex than these simple ideas suggest, i.e., this explanation for why R_F is function of aperture is not the whole story, nor perhaps even the major part of it.

With the foregoing information can be empirically modify Eq.(1) to the following

$$\frac{1}{R^2} = \frac{1}{R_L^2} + \frac{1}{R_{F1}^2} + \frac{1}{\phi(f)} \tag{2}$$

where R_{F1} is a constant for a given film and $\phi(f)$ is a function of the f stop, f , as well as the film. (We have tried to fit data with several other empirical formulae, but the best fit was obtained with Eq. (2).) With a lens whose ultimate resolution is effectively diffraction-limited for $f > 2.8$, we used the chart to determine R_{F1} and $\phi(f)$ empirically for several films. Results that fit the data fairly well are obtained when $R_{F1} = 180$ and $\phi(f) = 3100f$ for Technical Pan and $R_{F1} = 160$ and $\phi(f) = 3000f$ for Ektachrome 100S, Royal Gold 25, Kodachrome 25, Sensia 100, and Velvia. Little difference in sharpness was found among these six color films. All were nearly as sharp as Technical Pan. These results show that for fine lenses, the maximum resolution on film is typically between f5.6 and f8 and that 11 is nearly as sharp. Bear in mind, however, that each lens has its own sharpest aperture as well as sharpest focal distance. Moreover, the resolution at edges and corners is usually lower than at the center and often increases in the range f5.6-16 as the lens is stopped down.

Two Details

If you do your own black and white developing, it is important that the developer, stop bath, fixer, and all rinses be within about 2 degrees F of each other because a sudden change of temperature of the film may cause the gelatin to wrinkle slightly, with consequent loss of resolution.

Ideally, when measuring the resolution of a lens as a function of aperture, all other variables should remain fixed. Unfortunately, shutter speed is one of those variables, and for a given illumination, it must be changed when the aperture is changed. Resolution may vary with shutter speed primarily because the vibration of the camera caused by mirror slap degrades resolution more at some shutter speeds than others. This source of degradation is particularly important for lenses of focal length of 300 mm or longer with shutter speeds in the range 1/2 to 1/60 sec. There are two ways around this problem. One is to mount the camera so rigidly that camera shake can be ignored. The problem with this method, of course, is that one can never be certain that camera vibration was, in fact, made negligible. The second method is to keep the shutter speed constant and vary the illumination as the aperture is changed. One way to do this is choose a shutter speed and then illuminate the chart with one or more lights for the correct time at f 2.8 (or whatever the lowest f stop you wish to use). Then keep the shutter speed constant, decrease the aperture, and maintain exposure by leaving the lights on for longer times as the aperture is decreased.

Finest Accurate Grids.

See section Accuracy of the Targets, which explains why some grids are more accurate than others. Below are shown the finest grids at each location for which the bar width and bar space differ by no more than 10%. These grids and all coarser grids should yield accurate results. Bear in mind that less accurate grids will give slightly conservative results.

LOCATION	BLACK	RED	GREEN	BLUE
Top left corner	160	120	120	120
Top left diagonal	140	100	100	100
Top middle edge	160	140	140	120
Top middle interior	160	140	120	100
Top right corner	160	120	120	120
Top right diagonal	160	100	120	90
Left middle edge	140	140	120	140
Left middle interior	140	120	120	140
Center, upper left diagonal	90	160	140	160
Center, lower left diagonal	120	120	120	120
Center	120	140	140	160
Center, upper right diagonal	140	120	120	120
Center, lower right diagonal	160	160	140	160
Right middle interior	120	160	120	120
Right middle edge	80	80	80	90
Bottom left corner	120	100	120	120
Bottom left diagonal	160	140	120	120
Bottom middle interior	160	160	140	140
Bottom middle edge	160	120	140	160
Bottom right diagonal	160	140	120	120
Bottom right corner	160	160	160	160

About the Shape of the Grids - Comparison to the Air Force Targets

The grids on the chart resemble those of the old NBS grids in that they have up to ten lines per grid. The alternative Air Force grids, which have (unfortunately?) largely replaced the NBS grids as a de facto standard, have just three lines per grid. There are two reasons for three lines instead of more. One is so that more grids may be placed in the same space. Another is to diminish the possibility of spurious resolution discussed on page 5. When spurious resolution through defocusing occurs, the three grid lines are seen as four, which is easier to detect than ten lines seen as eleven. However, spurious resolution is easily eliminated by taking the care described on page 5.

There are two important reason for preferring more than three lines per grid. First, inspection of ten lines is easier and less ambiguous. The second relates to the film. No film is perfect. Every film has a spectrum of slight non-uniformities that may span the length scale from a whole roll of film to the size of a silver halide grain. Non-uniformities can include emulsion thickness, substrate thickness, chemical concentration, grain size and shape, and grain orientation. Any of these, as well as imperfect film flatness, can affect resolution. A grid must be large enough to cover these irregularities, and a 10-line square grid covers 14 times the area of a 3-line square grid. (The grid width is (N - 0.5)/(l/mm), so a three-line 70 l/mm square grid is only 0.042 mm or 0.0016 inch wide whereas a ten-line grid is 0.158 mm or 0.0062 inch wide.) On occasion I have seen ten-line 60-100 l/mm grids that were well resolved over 1/2 or 3/4 of the grid while the remainder was a gray blur because of a small film defect. If a three-line grid had been in the gray area, it would have given a spuriously low estimate of the lens resolution.

Another difference between the Air Force targets and the chart targets is that the difference in l/mm from one grid to the next in the Air Force targets is given by the sixth root of two or 1.122. This close and uniform spacing is good but suffers the disadvantage of yielding numbers whose three or four figures give a misleading representation of accuracy unless the user recognizes the limited accuracy and rounds off accordingly, which most photographers are not trained to do. The reproducibility and accuracy of resolution measurements is rarely better than 5%. It is for that reason that the grids on the chart are designed to give the particular l/mm values of 20, 25, 30, 35, 40, 50, 60, 70, 80, 90, 100, 120, 140, and 160. These values are sufficiently close for practical purposes. Indeed, first-time users are often surprised at how difficult it is to achieve reproducible results from one image to the next.

Getting High Resolution in the Field With Long Lenses

It is difficult to get high resolution with long lenses because focusing is difficult and because any camera vibration is magnified. When autofocus is used, or when there is time to focus manually with accuracy, camera movement is without doubt the most important single cause of image softness. Here is some of my personal experience. First, image stabilization technology can be a godsend. I have an extremely sharp image taken with a 500 mm Canon, image stabilized lens f4 with a 2x extender, wide open (f8) at about 1/30 of a second in fading light with the camera/lens resting on a bean bag. That would have been impossibility without image stabilization. Second, a sturdy tripod is essential for most photography in which high resolution is desired. Mirror vibration, even with a sturdy tripod, is a significant problem for lenses of 300 mm and longer. For 300 mm lenses, a shutter speed of 1/60 sec. may lead to slight loss of resolution, and I often lock the mirror up at that speed. For speeds of 1/30 sec and slower, locking the mirror up will usually yield much better resolution.

The Kirk brace that extends from a tripod leg to the camera is beautifully designed and made and is easy to use. It does help some but not nearly as much as a cheap, second tripod elevated under the camera.

With telephoto lenses I often push film one or two stops. Contrast increases a little, but resolution *of the film* is little if any affected, and the increased shutter speed often yields higher resolution. With a high-quality digital camera ISO settings of 800 or even 1600 can be used without problems – especially if a good noise reduction program is used. Noiseware by Imagenomic is one of the best.

I generally use a cable release for shutter speeds less than about 1/20 sec. For greater speeds a smooth, gentle pushing of the release button with the camera held firmly seems to work well for me. The chart, of course, is a good way to test what works best for you.

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