Estimating the On-film Image Resolution of Historic Film: Using the Resolving Power Equation (RPE) and Estimates of Lens Quality to Predicted the Resolution of Historic Film Images Beginning in 1875 (thru the Present)

Version 8 - October 2009 - Tim Vitale © 2009 use with permission only

1 – Introduction

Estimating the probable resolution of an image on a specific piece of modern film has become common when the film type and taking lens are known. The process involves using the system resolving power equation (RPE) and technical data on lenses. The RPE requires two pieces of data:

- **native film resolution (at 30% residual contrast between line pairs)**
- **resolution of the lens used for exposure**

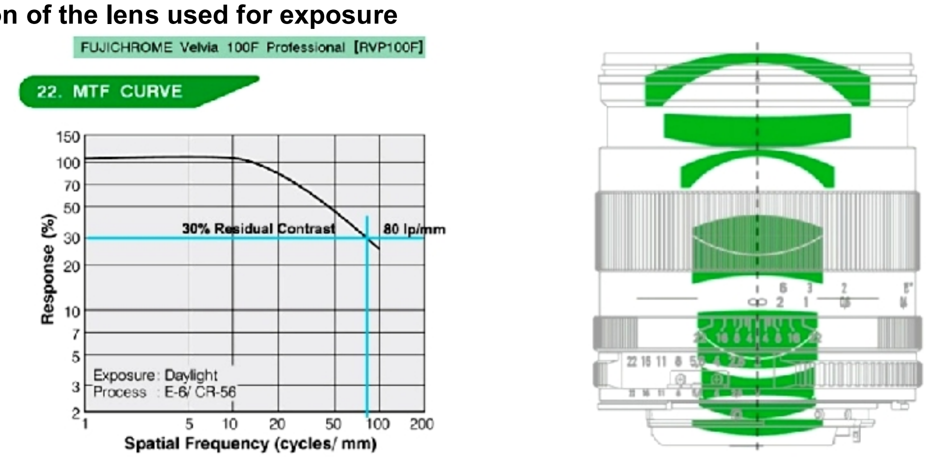


Figure 1a &1b: The (left) MTF curve from the Fuji Velvia 100 RVP data sheet and (right) a cross-section of 35mm-format Zeiss lens from their data sheet for the Zeiss Distagon f2 28mm prime manual focus lens.

However, predicting the on-film image resolution of historic film is more complicated because the native resolution of the film needs to be determined in the absence of actual film resolution data for historic film. Prior to about 1935/40 film resolution data was not distributed to the public, if it even existed. Queries made to the technical libraries at Kodak, Agfa and Ilford were not successful in uncovering data beyond that which is already published. Usually the company library no longer exists, a victim downsizing or closure. A Kodak professional who used the Kodak technical services department noted that the MTF measurements took a week (40 man-hours) to create, and even then, one week's test data often did not match next week's data. MTF data is difficult to come by, even for the professionals; much of it was kept confidential.

In order to predict historic film resolution back to the beginning of film (about 1889) and slightly before on glass plates (1875), the available historic data on film resolution was gathered and collected into a date table, see Table 4. Over the 65 years of published data, the resolution of film doubled 1.2 times.

In an attempt to generate resolution data for film made prior to 1940, mathematical regression technology was employed to predict historic film performance based on modern data; see Section 5 on pages 15-16. Using Moore's Law http://en.wikipedia.org/wiki/Moore's_law, an estimation of performance back to 1875 was made; see Figure 13 on page 16.

Using predictions of historic film resolution, technicians can make well-educated estimates of the on-film image resolution of historic film negatives. This information is invaluable when determining the digital capture resolution needed to migrate analog film into the digital domain. Remember to use the Nyquist Sampling Theorem when setting the digital sampling rate (pixels per inch).

Two methods of predicting on-film image resolution are provided, the more complex and more accurate **RPE method** and the simplified **Easy method**. On the bottom of the last page, using a 1906-film example, widely different results were produced by the complex RPE method and the simplified Easy method. The simplified method yields an on-film image resolution estimate of about 620 ppi, while the more precise method yields an estimate of 1130 ppi. The 82% difference is due to the precision of the technology and the ability to fine tune the film and lens resolution input (when the exact product in known) using the RPE method.

2 - System Resolving Power Equation (RPE)

There are many factors rolled onto the system resolving power equation. A "system" is the whole photographic unit, (a) camera [image plane alignment], (b) lens, (c) film/media and (d) processing. In to the basic RPE equation there is one term (1/r) is for the media and another (1/r) for the lens. Adding a print will add a third term for the enlarging lens and a fourth for the printing paper; see EQ1. Making a print lowers the system image resolution profoundly. EQ2 is used here exclusively.

EQ1: $1/R = 1/r_{[media]} + 1/r_{[camera\ lens]} + 1/r_{[enlarging\ lens]} + 1/r_{[printing\ paper]}$

The **FujiFilm** Resolving Power equation found in the *FujiFilm Data Guide* (p102, 1998) is EQ2:

EQ2: $1/R_{[system]} = 1/r_{[media]} + 1/r_{[lens]}$

Where: (1) R = overall resolving power, and (2) r = resolving power of each component

Kodak uses the following equation in its datasheets and handbooks. It is more complicated, but yields almost the same results. It is NOT used in this document.

EQ3: $1/R^2_{[system]} = 1/r^2_{[media]} + 1/r^2_{[lens]}$

Lens Issues Affecting Resolution

There are at least 8 different types of lens aberrations that are folded into the RPE lens term:

- **Chromatic aberration**
- **Spherical aberration**
- **Coma (uneven magnification)**
- **Astigmatism (non-flat focus)**
- **Flare (external light scattering)**
- **Dispersion (internal light scattering)**
- **Misaligned lens elements**
- **Dirt and haze on lens surface (light scatter)**

The center of the lens is generally the sharpest region. Resolution declines towards the edge of the image circle defined by the lens construction and iris diameter. Good modern lenses are not capable of more than 80-140 line-pairs per millimeter (lp/mm) at the center of the lens, and much less, towards the edges. Using wide apertures (large opening or small f-number) compromises image quality dramatically because the light must use more of the glass in the lens elements, see Figure 11 below. Large f-stops (f3.5 to f5.6) in large format (LF) lenses are only capable of 20-40-lp/mm at the edges where aberrations can be extreme.

Film Issues Affecting Resolution

The problems with exposing film well have been described in detail in many online resources.
Achieving crisp focus for all colors of light in a flat-field is the principal problem. However, keeping the

film flat and perpendicular to the lens axis in LF cameras is a significant problem. The issues forming an image on film include:

- **Goodness of focus**
- **Trueness of lens axis perpendicular (90°) to film axis**
- **Warp of the film in the film holder or film path**
- **Vibration in all phases of exposure**
- **Dirt and haze of CCD/CMOS Sensor**
- **Film developing variables (exhaustion, impure water or impure chemicals)**
- **Heat and humidity in storage of film before and after exposure and processing**
- **Time since exposure, and, possible x-rays exposure during airport screening**
- **Shutter Speed issues**

Shutter speed affects sharpness through vibration and silver particle size. Slow shutter speeds allow for hand-induced shake during exposure decreasing image sharpness. In SLRs the vibration caused by the mirror moving up and down during the exposure cycle has a large effect on short exposures, while, in long exposures it is only a portion of the exposure time. Fast shutter speeds (less light) require longer processing times which enlarges silver particle size and decreases resolution. A short exposure self-selects the more sensitive silver particle, which happens to be the larger silver particles.

Evaluating a System: Camera, Lens and Film

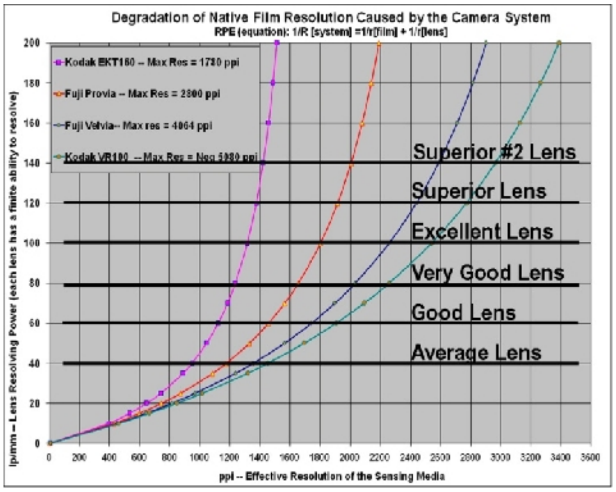
Using the photographic system Resolving Power Equation **EQ2,** the native resolution of films and lens quality below are calculated for you and reported in Table 2 on the following page.

Table 1: Selected Film and Lens Resolution Data

Film	Resolution	$1/r_{[film]}$	Film Resolution in ppi No Lens in Path at 30% Contrast
Kodak Ektachrome 160	35 lp/mm	0.0286	1778
Fuji Astia RAP	45 lp/mm	0.022	2286
Fuji Provia 100F RDP	55 lp/mm	0.0182	2794
Kodak Ektachrome 100GX	60 lp/mm	0.0167	3050
Kodak Tri-X 400 (2004)	65 lp/mm	0.0154	3302
Fuji Velvia RVP	80 lp/mm	0.0125	4064
Kodak Portra 160NC Color Neg	80 lp/mm	0.0125	4064
Kodak Plus-X 125 (2006)	80 lp/mm	0.0125	4064
Kodak VR100 Color Neg	100 lp/mm	0.0100	5080
Kodak Technical Pan (2004)	142 lp/mm	0.007	7214
Kodak Panatomic-X	170 lp/mm	0.0059	8636

Lens	Resolution	$1/r_{[lens]}$	Lens Cost, in relevant era Dollars
Old lens (1840-1930) & LF lens	20 lp/mm	0.05	$50-1500
Average Modern lens	40 lp/mm	0.025	$150-500
Good LF lens	60 lp/mm	0.0167	$300-800*
Very Good lens	80 lp/mm	0.0125	$1000-3000**
Excellent 35 mm format lens	100 lp/mm	0.01	$350-5000***§
Superior 35 mm lens	120 lp/mm	0.0083	$350-1000Δ
Exceptional lens	140 lp/mm	0.0071	$350-1000

* Many 35 mm, medium format and large format lenses at f/5.6; many first tier zoom lenses at optimal f-stop
** Schneider 150 APO Symmar f5.6 at f/8; good second-tier lenses
*** Many first tier prime lenses at optimal f-stop; Nikkor, Canon & Zeiss 50mm & 85mm lenses at f8



In cameras, resolution is degraded by the parameters described above in the lens and film issues sections. Loss of image quality can range from 23% to 90% of native resolution, as shown in Table 2. Rigid cameras such as 35-mm SLRs and rangefinders, and, medium format (MF) (2¼ x 2¼, or 6 x 6 cm and 2¼ x 2¾, or 6 x 7 cm) have fairly flat film planes and rigidly fixed lens-to-film axis. They will achieve generically better results than large format (LF) cameras which require the film and lens axis to be aligned for each series of exposures using a tool such as the Zig-Align. Figure 2 shows the effect of the various lens quality levels on four specific films with a range of native resolutions. The higher resolution films are affected more by lens quality. A more detailed version of Figure 2 is shown as Figure 7 on p 8.

Figure 2: Effect of lens quality on film resolution. Plot shows the effects of lens quality (y axis, vertical is lp/mm) on film resolution (x axis, horizontal ppi of film). Four common films (listed above) are exposed through the theoretical lenses listed above them using the Fuji RPE. The graphic shows that poor quality lenses have a huge effect on lowering resolution, while improving lens quality past about 100-lp/mm has less effect. However, lenses over about 80-90 lp/mm "quality" are very expensive; the return for dollar spent is not as great past "very good" lenses. The films are Kodak Ektachrome 160 (1780 ppi), Fuji Provia (2800 ppi), Fuji Velvia 100 (4064 ppi) and Kodak VR 100 (5080 ppi), right to left.

Table 2: System Resolving Power Data Table

Kodak Ektachrome 160 has 1778 ppi (35-lp/mm) native resolution

EKT 160	0.0286	+ 0.05	= 0.0786	= 13 lp/mm	= 646 ppi	64% loss	thru 20 lp/mm lens
EKT 160	0.0286	+ 0.025	= 0.0536	= 19 lp/mm	= 948 ppi	47% loss	thru 40 lp/mm lens
EKT 160	0.0286	+ 0.0167	= 0.0453	= 22 lp/mm	= 1121 ppi	37% loss	thru 60 lp/mm lens
EKT 160	0.0286	+ 0.0125	= 0.041	= 24 lp/mm	= 1236 ppi	30% loss	thru 80 lp/mm lens
EKT 160	0.0286	+ 0.010	= 0.0386	= 26 lp/mm	= 1316 ppi	26% loss	thru 100 lp/mm lens
EKT 160	0.0286	+ 0.0083	= 0.0369	= 27 lp/mm	= 1377 ppi	23% loss	thru 120 lp/mm lens

Fuji Astia RAP has 2286 ppi (45 lp/mm)native resolution

Fuji RAP	0.022	+ 0.025	= 0.045	= 22 lp/mm	= 1121 ppi	51% loss	thru 40 lp/mm lens
Fuji RAP	0.022	+ 0.0167	= 0.0387	= 26 lp/mm	= 1316 ppi	42% loss	thru 60 lp/mm lens
Fuji RAP	0.022	+ 0.0125	= 0.0345	= 29 lp/mm	= 1473 ppi	36% loss	thru 80 lp/mm lens
Fuji RAP	0.022	+ 0.010	= 0.032	= 31 lp/mm	= 1575 ppi	31% loss	thru 100 lp/mm lens
Fuji RAP	0.022	+ 0.0083	= 0.0303	= 33 lp/mm	= 1575 ppi	27% loss	thru 120 lp/mm lens

Kodak Ektachrome 100GX has 3050 ppi (60 lp/mm) native resolution

EKT 100GX	0.0167	+ 0.025	= 0.0417	= 24 lp/mm	= 1220 ppi	60% loss	thru 40 lp/mm lens
EKT 100GX	0.0167	+ 0.0167	= 0.0334	= 30 lp/mm	= 1524 ppi	50% loss	thru 60 lp/mm lens
EKT 100GX	0.0167	+ 0.0125	= 0.0294	= 34 lp/mm	= 1727 ppi	43% loss	thru 80 lp/mm lens
EKT 100GX	0.0167	+ 0.010	= 0.0267	= 37 lp/mm	= 1880 ppi	38% loss	thru 100 lp/mm lens
EKT 100GX	0.0167	+ 0.0083	= 0.025	= 40 lp/mm	= 2032 ppi	33% loss	thru 120 lp/mm lens

Kodak Tri-X 400 (2004) has 3302 ppi (65 lp/mm) native resolution

Kodak Tri-X	0.0154	+ 0.05	= 0.0654	= 25 lp/mm	= 1257 ppi	58% loss	thru 40 lp/mm lens
Kodak Tri-X	0.0154	+ 0.0167	= 0.0321	= 31 lp/mm	= 1582 ppi	52% loss	thru 60 lp/mm lens
Kodak Tri-X	0.0154	+ 0.0125	= 0.0275	= 36 lp/mm	= 1847 ppi	44% loss	thru 80 lp/mm lens
Kodak Tri-X	0.0154	+ 0.010	= 0.0254	= 39 lp/mm	= 2000 ppi	39% loss	thru 100 lp/mm lens
Kodak Tri-X	0.0154	+ 0.0083	= 0.0237	= 42 lp/mm	= 2143 ppi	35% loss	thru 120 lp/mm lens
Kodak Tri-X	0.0154	+ 0.0071	= 0.0225	= 44 lp/mm	= 2258 ppi	32% loss	thru 140 lp/mm lens
Kodak Tri-X	0.0154	+ 0.005	= 0.0204	= 49 lp/mm	= 2490 ppi	25% loss	thru 200 lp/mm lens

Fuji Velvia RVP has 4064 (80 lp/mm) native resolution
Kodak Portra 160NC color negative film has 4064 ppi (80 lp/mm) native resolution
Kodak Plus-X 125 (2006) has 4064 ppi (80 lp/mm) native resolution

Kodak Plus-X	0.0125	+ 0.05	= 0.0625	= 16 lp/mm	= 813 ppi	75% loss	thru 20 lp/mm lens
Kodak Plus-X	0.0125	+ 0.025	= 0.0375	= 27 lp/mm	= 1355 ppi	66% loss	thru 40 lp/mm lens
Kodak Plus-X	0.0125	+ 0.0167	= 0.0292	= 34 lp/mm	= 1740 ppi	57% loss	thru 60 lp/mm lens
Kodak Plus-X	0.0125	+ 0.0125	= 0.025	= 40 lp/mm	= 2032 ppi	50% loss	thru 80 lp/mm lens
Kodak Plus-X	0.0125	+ 0.010	= 0.0225	= 44 lp/mm	= 2235 ppi	45% loss	thru 100 lp/mm lens
Kodak Plus-X	0.0125	+ 0.0083	= 0.0208	= 48 lp/mm	= 2442 ppi	40% loss	thru 120 lp/mm lens
Kodak Plus-X	0.0125	+ 0.0071	= 0.0196	= 51 lp/mm	= 2592 ppi	36% loss	thru 140 lp/mm lens
Kodak Plus-X	0.0125	+ 0.005	= 0.0175	= 57 lp/mm	= 2896 ppi	29% loss	thru 200 lp/mm lens

Kodak VR100 color negative film has 5080 (100 lp/mm) ppi native resolution

Kodak VR 100	0.010	+ 0.05	= 0.06	= 17 lp/mm	= 847 ppi	83% loss	thru 20 lp/mm lens
Kodak VR 100	0.010	+ 0.025	= 0.035	= 29 lp/mm	= 1473 ppi	75% loss	thru 40 lp/mm lens
Kodak VR 100	0.010	+ 0.0167	= 0.0267	= 37 lp/mm	= 1880 ppi	63% loss	thru 60 lp/mm lens
Kodak VR 100	0.010	+ 0.0125	= 0.0225	= 44 lp/mm	= 2235 ppi	56% loss	thru 80 lp/mm lens
Kodak VR 100	0.010	+ 0.010	= 0.020	= 50 lp/mm	= 2540 ppi	50% loss	thru 100 lp/mm lens
Kodak VR 100	0.010	+ 0.0083	= 0.0183	= 54 lp/mm	= 2776 ppi	45% loss	thru 120 lp/mm lens
Kodak VR 100	0.010	+ 0.0071	= 0.0171	= 54 lp/mm	= 2776 ppi	45% loss	thru 140 lp/mm lens
Kodak VR 100	0.010	+ 0.005	= 0.015	= 67 lp/mm	= 3387 ppi	33% loss	thru 200 lp/mm lens

Kodak Technical Pan (2004 & discontinued) has 7214 ppi (142 lp/mm) native resolution

Technical Pan	0.007	+ 0.05	= 0.057	= 18 lp/mm	= 891 ppi	88%loss	thru 20 lp/mm lens
Technical Pan	0.007	+ 0.025	= 0.032	= 31 lp/mm	= 1587 ppi	78%loss	thru 40 lp/mm lens
Technical Pan	0.007	+ 0.0167	= 0.0237	= 42 lp/mm	= 2143 ppi	70% loss	thru 60 lp/mm lens
Technical Pan	0.007	+ 0.0125	= 0.0195	= 51 lp/mm	= 2605 ppi	64% loss	thru 80 lp/mm lens
Technical Pan	0.007	+ 0.010	= 0.017	= 58 lp/mm	= 2988 ppi	59% loss	thru 100 lp/mm lens
Technical Pan	0.007	+ 0.0083	= 0.0153	= 65 lp/mm	= 3320 ppi	54% loss	thru 120 lp/mm lens
Technical Pan	0.007	+ 0.0071	= 0.0141	= 71 lp/mm	= 3602 ppi	50% loss	thru 140 lp/mm lens
Technical Pan	0.007	+ 0.005	= 0.012	= 83 lp/mm	= 4216 ppi	42% loss	thru 200 lp/mm lens
Technical Pan	0.007	+ 0.00167	= 0.00867	= 115 lp/mm	= 5859 ppi	19% loss	thru 600 lp/mm lens

Kodak Panatomic-X (1976, probably high) has 8636 ppi (170 lp/mm) native resolution

Panatomic-X	0.0059	+ 0.05	= 0.0618	= 16 lp/mm	= 822 ppi	90% loss	thru 20 lp/mm lens
Panatomic-X	0.0059	+ 0.025	= 0.0321	= 32 lp/mm	= 1628 ppi	81% loss	thru 40 lp/mm lens
Panatomic-X	0.0059	+ 0.0167	= 0.0238	= 42 lp/mm	= 2134 ppi	75% loss	thru 60 lp/mm lens
Panatomic-X	0.0059	+ 0.0125	= 0.0184	= 54 lp/mm	= 2755 ppi	68% loss	thru 80 lp/mm lens
Panatomic-X	0.0059	+ 0.010	= 0.0159	= 63 lp/mm	= 3195 ppi	63% loss	thru 100 lp/mm lens
Panatomic-X	0.0059	+ 0.0083	= 0.0142	= 70 lp/mm	= 3577 ppi	59% loss	thru 120 lp/mm lens
Panatomic-X	0.0059	+ 0.0071	= 0.013	= 77 lp/mm	= 3908 ppi	55% loss	thru 140 lp/mm lens
Panatomic-X	0.0059	+ 0.005	= 0.0109	= 92 lp/mm	= 4661 ppi	46% loss	thru 200 lp/mm lens
Panatomic-X	0.0059	+ 0.00167	= 0.00867	= 115 lp/mm	= 5860 ppi	32% loss	thru 600 lp/mm lens

Table 2: shows the incremental effects of (a) lens issues and (b) film issues on the final resolution of a system (camera) using the FujiFilm Resolving Power Equation. Modern films (Table 1) are processed through EQ2 using lenses of increasing quality ranging from (1) 20-lp/mm, (2) 40-lp/mm to (3) 60-lp/mm, (4) 80-lp/mm, (5) 100-lp/mm, (6) 120-lp/mm, (7) 140-lp/mm, (8) 200-lp/mm and sometimes the (9) mythical 600- lp/mm lens. The best 35-mm format lenses will have a resolution of 80-120 lp/mm; in most cases the quality will no better than 80-lp/mm and will likely be only 40-60 lp/mm.

3 - Lens Limits the Resolution of all Imaging Systems (film, digital or the future)

In the universe of photographic lenses, most lenses have less resolution that the media they are used to expose. This is understandable because good film is inexpensive, while high quality lenses are expensive. The lens used to expose photographic media (film, CCD, CMOS, etc.) has equal mathematical value to the media itself when determining the final resolution of the image according to the Resolving Power Equation (RPE). It is only the exceptional lens that meets or exceeds the native resolution of the film.

In 35-mm format photography, the best lenses are the standard focal length prime lenses (35mm, 50mm and 85mm) made by first-tier lens makers such as Canon, Nikkor/Nikon, Zeiss or Leica. The Canon EF 50/1.4 USM prime has a street price of $320. Standard lenses can be had for $100, but a modest $320 buys a lot of resolution. The history of lens design and technology is on pages 16-18.

The equivalent large format (LF) lens would be the 150mm or 180mm apochromatic (APO) made by either Schneider or Rodenstock (about $800-1500). Much of the price difference between the standard small format lens (50mm) and the standard large format lens (150mm) is due to the small number made and the size of the glass; see Figures 1b vs Figure 11. LF lenses can equal the resolution of the film when their optimal f-stop (2-3 stops below wide-open) is used; usually f/8 or f/11.

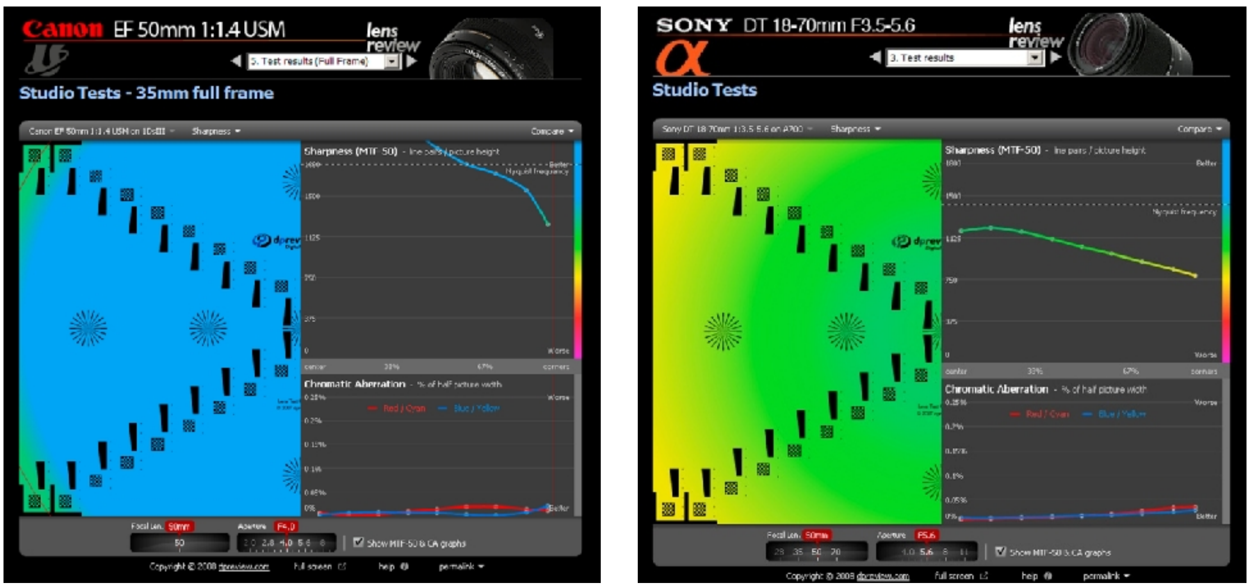


Figure 3a & 3b: Performance of Prime vs Zoom lens. Screen shot from <dpreview.com> website on the left evaluates a Canon 50/2 EF prime lens at f4 (sweet spot) revealing superior performance, on the right, <dpreview.com> evaluates a Sony Alpha (Minolta) 18-70mm/f3.5-5.6 DT zoom lenses, set at 50mm & f5.6 (sweet spot), revealing only average performance.

On the camera equipment review website http://www.dpreview.com, their lens evaluation tool has a wealth of information condensed into an interactive graphic; see Fig 3a & 3b above. The only downside is that there are still only a limited number of lenses reviewed (about 36 as of 9/09). The more traditional lens evaluation website, http://www.photodo.com, has the standard MTF data for a huge selection of lenses. Unfortunately, most of that data is now 5-15 years old, thus, do not reflect the majority of lenses being sold today. However, the information helps to evaluate historic photographic equipment. The “modern” lenses that <photodo.com> shows rely on “user” evaluations which often track reality, but are in not measurement-based, they are subjective evaluations by users. Thus, only the data on the older lenses will fulfill the needs of the RPE equation.

Much of the lens MTF data used in this work was harvested from the http://www.photodo.com/products.html. When evaluated a lens using the MTF data, a point 66-70% out from the center (0), at 15 (mm), on the horizontal axis of the MTF chart (in the Figure 4 http://www.photodo.com/product_50_p4.html) is used. Using MTF data from the center of most lenses would show inflated overall performance. In the lens shown below in Figure 4, however, it very high quality shows little difference between center (0) and edge (21). In the plots, the solid line is for on-axis performance and the dashed line is the perpendicular (or tangential) axis; the two data points are averaged in this work. Note the yellow boxes in Figure 4 (at “15”) show where the percent contrast values were pulled using the MTF plots for the Canon 85mm f/1.2 EF USM lens. This is one of the best performing lenses available; graded as 4.6, using MTF data.

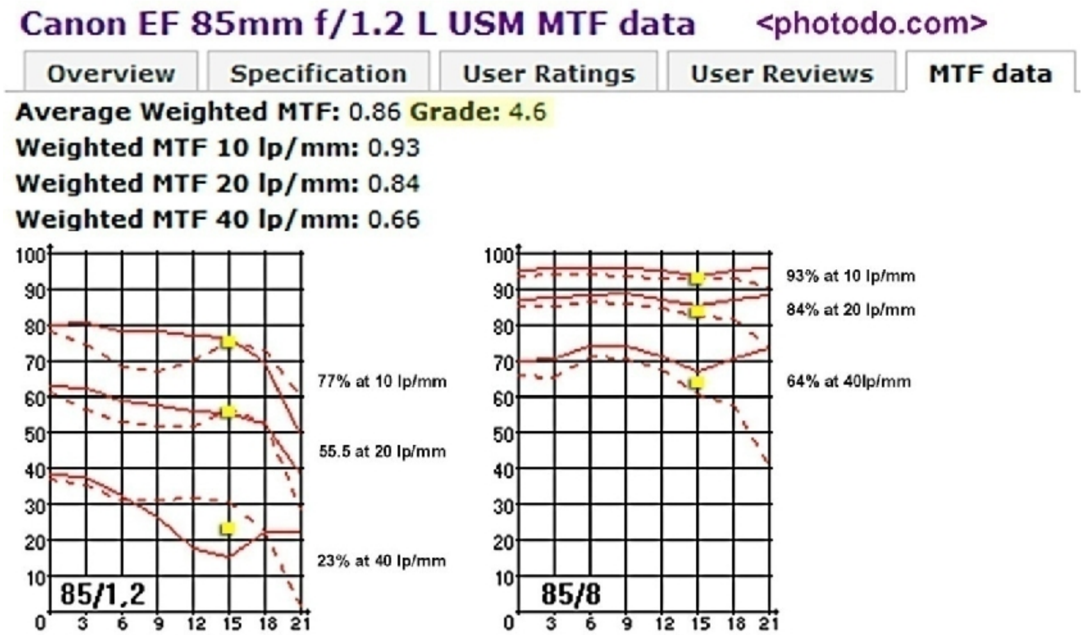


Figure 4: Photodo MTF data for the Canon EF 85 mm f/1.2 prime lens. The Data taken from the <photodo.com> website shows their MTF plots for the Canon EF autofocus USM 85/1.2 lens; it was given a grade of 4.6 (quite high). This lens performs better than the fabled Canon 50/1.4 (manual focus), which is given the grade of 4.4. The y-axis shows residual contrast between line pairs, while the horizontal shows mm-distance from the center of the lens' front element. Note that wide open the performance is much worse than stopped down to f8.

Spend a few minutes with the <Photodo.com> website checking lens performance. It can be seen that prime lenses have the best generic performance, while zoom lenses have 15-50% less resolution because of their complexity and the numerous compromises made to achieve a fast performance over the range of the zoom. Most zoom lenses being sold in DSLR kits perform at about 60-75% of their prime equivalents. MTF (modulation transfer function) is a critical tool for evaluating lenses; it's well explained at http://www.photozone.de/3Technology/mtf.htm & http://www.normankoren.com/Tutorials/MTF.html. There is a wealth of resolution information on the web, Google: MTF lens.

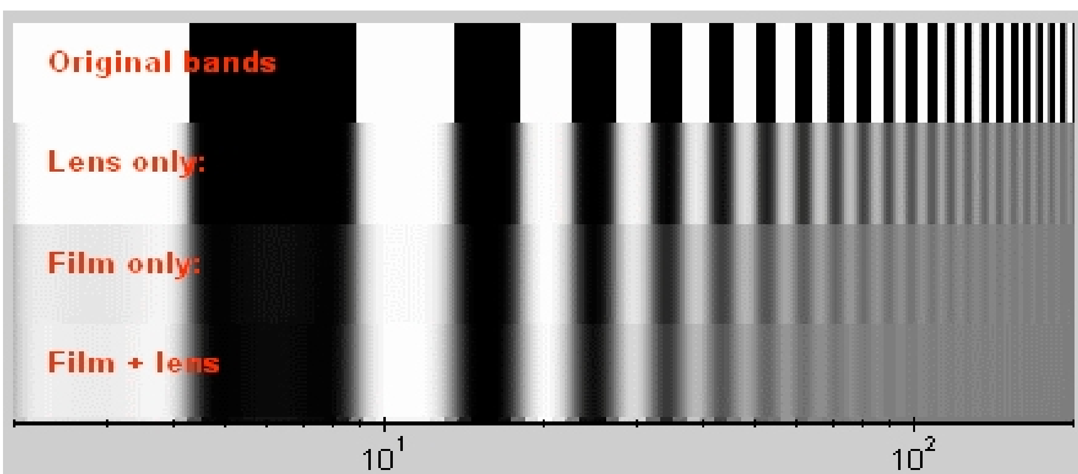


Figure 5: Contrast between black & white line-pairs, decreased by film, lens and both. Norman Koren shows how contrast between black and white line-pairs is decreased by a lens, film and then both -- the system (in the camera).

In the image above (Fig 5) taken from the Norman Koren website, the effects of imposing media and lens on the contrast of black and white line pairs is shown. Note that in the lower right corner all detail is lost, contrast is at 0% different. At about the "10^2"on the x-axis the contrast difference is about 30%, the point where most workers evaluating MTF performance define the limit of performance. Many workers with higher standards, such as Koren, use 50% residual contrast; this lowers the native resolution of the media and the lens.

Another method of evaluating lenses is to use USAF resolution targets. The method is simple and affordable, but of less value when evaluating overall lens performance. The method is useful for ranking individual lenses within a group of lenses. Chris Perez and Kerry Thalmann use the method to evaluate many 1980s & 1990's lenses at http://www.hevanet.com/cperez/testing.html.

Some workers have assumed than large format lens are inferior in quality to small and medium format lenses because their overall performance is lower. LF lenses, however, must use much more glass to cover the larger image circle needed for the larger film sizes (4 x 5 to 8 x 10). The image circle of a 35-mm format lens is about 39-45 mm, while a normal lens (150mm) on a 4 x 5 view camera has an image area of 145-165 mm. The difference in image circle area ($A = \pi \cdot r^2$) between a 50mm lens and a 150mm lens is almost 13-times -- 1500mm^2 vs 20000 mm^2.

The best LF lenses will have resolution capabilities that range from 40-lp/mm to 80-lp/mm with the average about 50-60 lp/mm. Only the rare LF lens will reach 80-lp/mm; none will reach beyond 100-lp/mm. View cameras also have the very real problems of achieving uniform focus from center-to-edge and aligning the lens-axis accurately perpendicular to the image (film) plane. The best LF lenses will have no more than 100-lp/mm in the center, with about 25-50% fall-off at the edges of the lens image circle; the best average performance is often quoted at 80-lp/mm.

No film can actually reach its native resolution when exposed through a lens, even if the film was exposed through the fabled "spy lens" reported to be capable of 500-600 lp/mm. The top of Figure 6 shows depicts a lens rated at 1000 lp/mm; note that not even a lens of impossible specification could preserve the native resolution of the films. Kodak VR100 only reached 90% of native resolution (5080 ppi). The lowest resolution film, Kodak EKT 160 (1780 ppi) performed best, because lower resolution films are harmed the least by lens performance.

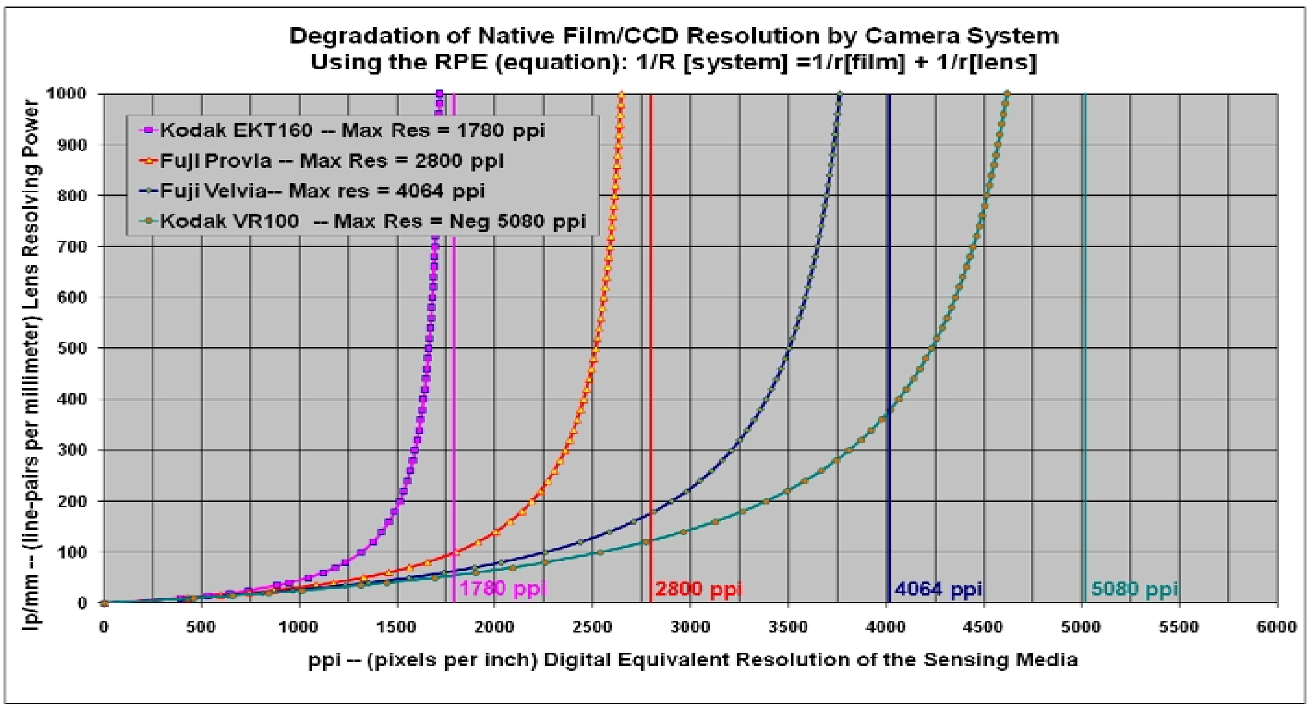


Figure 6: Media (Film/CCD) resolution degraded by the lens (1000-lp/mm full scale). Plot shows how film/CCD resolution is degraded by the lens used. Even a theoretical lens, with 1000 lp/mm resolution (top of plot), can never deliver all the native resolution capabilities of the film/CCD. Note that the bold vertical colored lines represent the native resolution of the media, while the curved line with the same solid color depicts system resolution [1/R] or on-film image resolution. Also note corresponding numeric native resolution values to the right of the colored vertical lines.

Modern Lens (1950-2010)

Lenses reached a penultimate state just before WWII, and topped out in the 1970s. Computer-aided-design continues to help improve zoom lens designs which are inherently less sharp than prime lenses. Most prime lens designs were developed over 80-110 years ago by the great German manufactures. See pages 16-18 for more historic details on lenses. Modern lenses (post-1950) possess small incremental improvements such as (i) multiple vacuum deposited coatings; (ii) non-yellowing element-to-element cement, (iii) exotic lens element shapes and (iv) exotic glass formulations to (a) reduce flare, (b) limit inter-element light scattering while (c) increasing sharpness and contrast out to the edge of a flat field. In general, the street value of a lens is a rough indicator of its quality. The cost of specific lenses within a group, such as the 35mm, 50mm or 85mm primes, or the ubiquitous 18/35mm to 70/85mm zoom, are examples. The best small format prime lenses perform at 100-120-lp/mm; see Figures 8, 9 & 12. Most experienced photographers assume a 50% loss of media resolution (film, CD or CMOS) when using the best lenses (80-100-lp/mm).

Historic Lenses (1915-50)

Older B&W films (1930s & 40s) were capable of 40-60-lp/mm native resolution (2100-3100 ppi). A lens of equivalent quality, 40-60-lp/mm, will limited the resolution on-film to between 1000-1500 ppi in the center (50% loss due to lens) with an additional 15% loss at the edge. Lens quality was generally stable from 1915 to 1935, but had major advances around WWII, from about 1935 to 1950; see page 17. After looking at many glass plates shot on anthropological expeditions from the era, the actual on-film image resolution for negatives would probably range from 750 ppi to 1250 ppi (15- to 25-lp/mm).

Early Lens (1835-1910)

Before photography lenses were used in devices such as telescopes, microscopes and the Camera Obscura. In fact, lens use is traced back to 5000 years ago where polished clear minerals were used as crude magnifiers. The Chevalier Achromatic lens, a 2-element flat-field design was developed in 1835. It's still used today in many point-and-shoot cameras, but in the coated plastic lens variant. By 1841 Petzval designed the 4-element Achromatic portrait lens (two glass formulations to shape light path, making it Achromatic) which became a photographic standard for decades. It was in common use through 1900 and still used through the middle of the 20th century in cine and projection application; the resolution in the era is thought to be 20-30 lp/mm. More information on the history of lens technology can be found on pages 16-18.

Using an Average Lens (40-lp/mm)

The average lens resolves approximately 40-line-pairs per millimeter (lp/mm). Assuming Fuji Velvia RVP (80-lp/mm or 4064 ppi digital equivalent) is exposed through an average lens, the final system resolution will be about 27-lp/mm; a loss of 66% of the native resolution (1355 ppi digital equivalent).

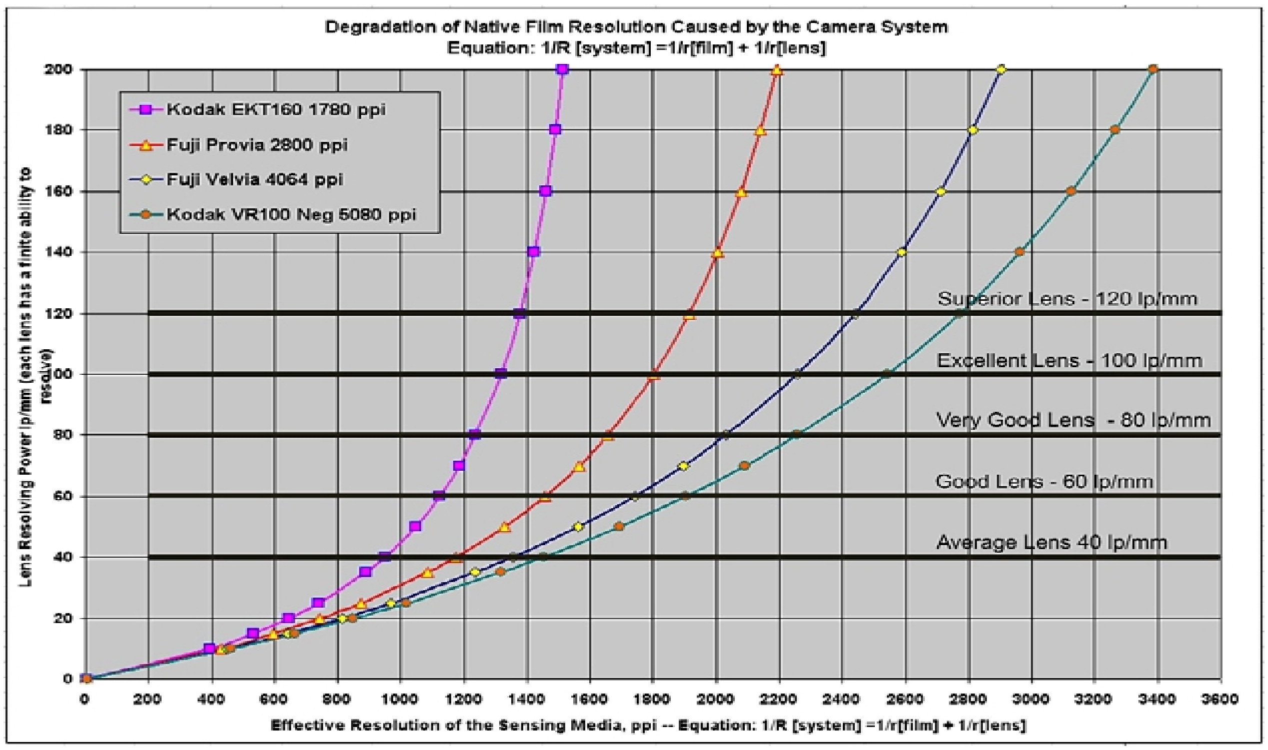


Figure 7: Media (Film or CCD) resolution degraded by the lens. Effects of lens quality on films with increasing native resolution (highest on right: teal colored line). The data points in the plot are the System Resolution calculations for the combination of film and lens; see Table 2 (p 5) for numbers. Kodak Ektachrome 160 (far left line) has a native resolution of 1780 ppi; using an average lens yields a 948 ppi image; using a good lens yields a 1121 ppi image; using a very good lens yields a 1226 ppi; using an excellent lens yields a 1316 ppi image; using a superior lens yields a 1377 ppi image.

Using an Excellent Lens (100-lp/mm)

Using an excellent lens with Fiji RVP Velvia color transparency film (80-lp/mm or 4064 ppi digital equivalent) would produce a system resolution to 2235 ppi (44 lp/mm), about half the native resolution of the film. This is about twice the performance when compared to using an average quality lens.

Using a "superior" lens (140-lp/mm) will produce an on-film image resolution of 2592 ppi, only a 14% performance improvement over the excellent lens. An excellent lens can be purchased for $250-450.

After studying the MTF data on <Photodo.com>, the only superior lenses are Leica primes that run 3-5 times as much as Canon and Nikon primes.

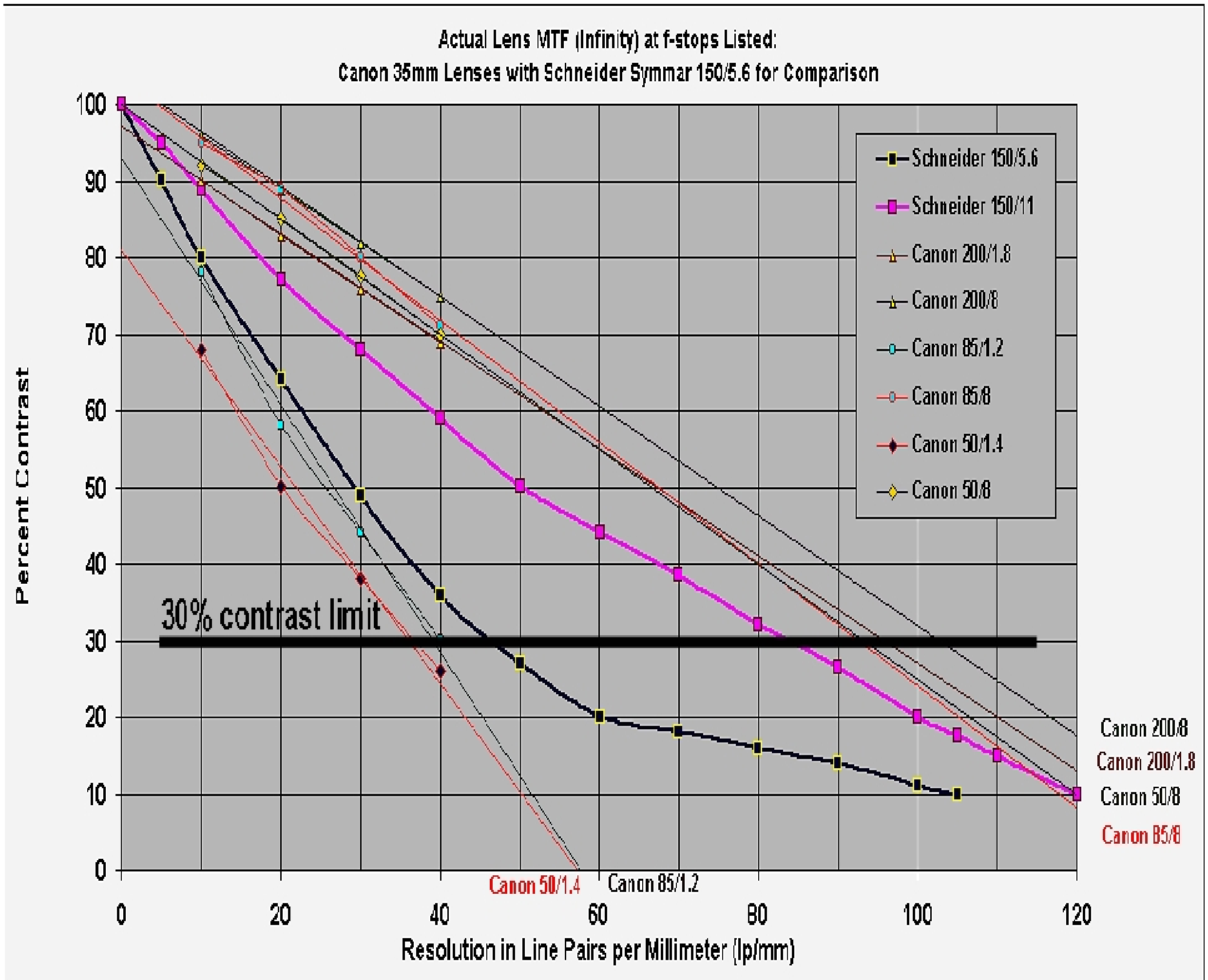


Figure 8: Lens MTF plots: Canon 35-mm format lenses; affects of lens quality on native film resolution. Canon prime lenses (not the smaller "digital format" lenses) have an image circle of about 1.5" compared to a Schneider Symmar APO 150 mm f5.6, large format lens have a 6.5" image circle. The performance in the center of the image circle is superior to the edges. The overall performance of large format lenses is often lower because their size.

Canon Lenses: Some of the best performing Canon lenses have been listed in the plot above, such as the (a) EF 50mm f/1.4 USM, (b) EF 85mm f/1.2 USM and (c) EF 200mm f/1.8 USM. They are projected to have a resolution of 90-110 lp/mm at their optimal f-stop (f/8) based on MTF data (at 30% contrast limit) from http://www.photodo.com/nav/prodindex.html.

The data reported by Lars Kjellberg <photodo.com> used one of the pre-2000 standard high-end lens evaluation protocols that measured MTF out to 40-lp/mm, but not higher. Figure 4 shows MTF performance is reported from the center of the lens to the edge of the lens glass; evaluating MTF performance at three resolutions (a) 10-lp/mm, (b) 20-lp/mm and (c) 40-lp/mm. Three MTF points were harvested (yellow squares in Fig.4) from the MTF data plots. A line is drawn through the three points and extended past 30% contrast. The plots from the three Canon prime lenses above cross the **30% contrast limit** line between 90- and 110-lp/mm, showing excellent lens performance.

In reality, the crossing points at 30% contrast are most likely somewhat to the right (even better performance), as shown by the shape of black (f/5.6 wide open) and purple (f/11, ideal f-stop) plot lines, made with multiple-point curves for the Schneider APO 150/5.6 lens. It is rare to find MTF lens data plotted to an low extinction point (10% contrast), thus the curves were included in the graphs to show the probable shape of MTF curves for the Canon lenses, shown as straight lines in Figures 8. It's possible that the Canon primes deliver as much as 120-130-lp/mm when used at their optimal f-stop.

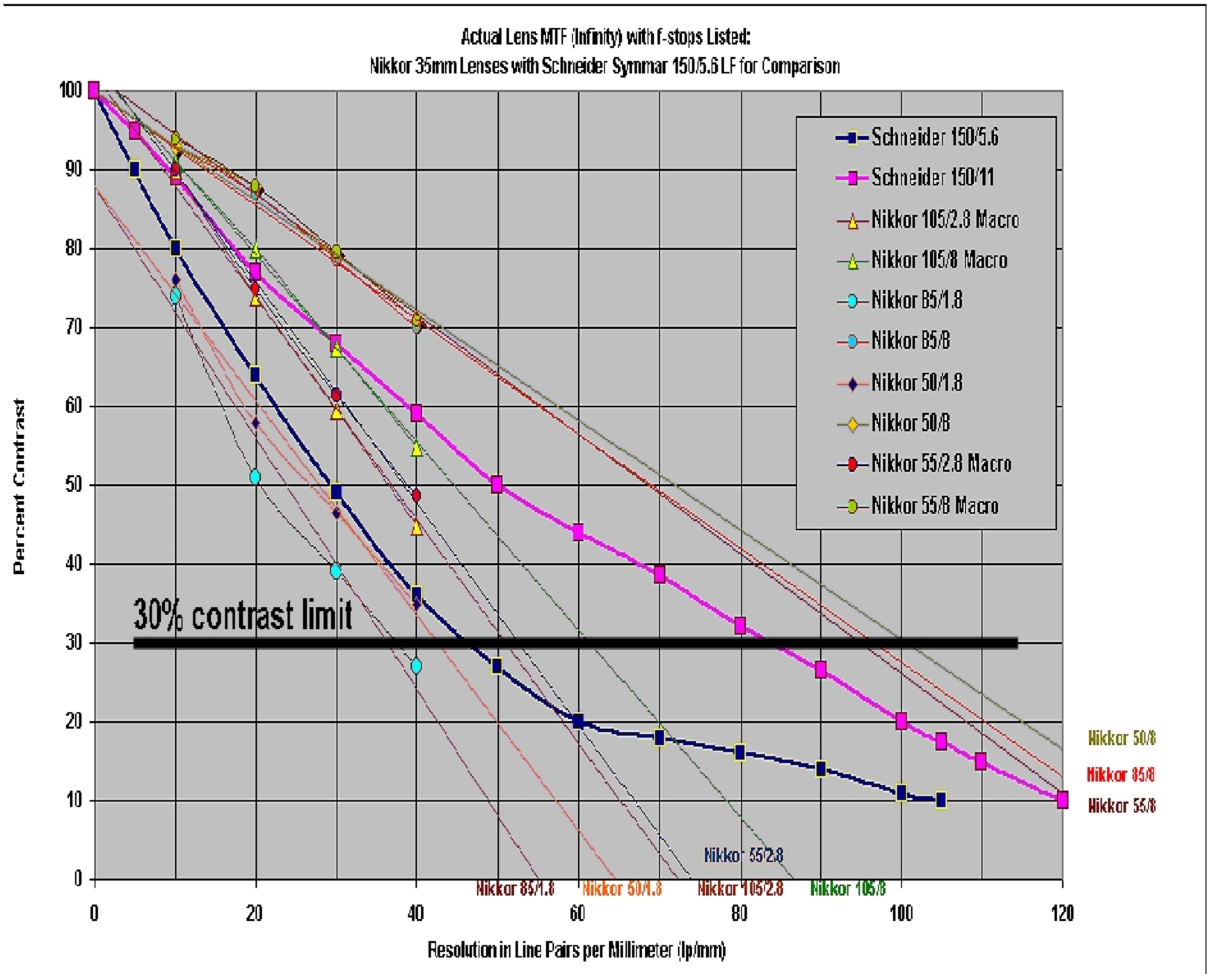


Figure 9: Lens MTF plots: Nikon 35-mm format lenses. Nikkor 35-mm format lenses (not the smaller digital format lenses) which have an image circle of about 1.5” compared to the Schneider Symmar APO 150 mm, f5.6, large format lens have 5-6” image circle. The performance in the center of the image circle is superior to the edges. The overall performance of large format lenses is often lower because the glass elements used are larger.

Nikon Lenses: note that in the Nikkor/Nikon lens MTF plot above the (a) AF 50mm f/1.8, (b) MF 55 mm f/2.8 and (b) AF 85mm f/1.8 lenses show excellent behavior at f/8. As with the Canon lenses, their resolution range is 90- to 110-lp/mm, this is referred to as excellent quality in this essay. Nikkor zoom lenses have a reputation for good performance, unfortunately this isn’t the case except for a very few listed at <photodo.com>. Their performance is not rated above 3.9; prime lenses have performance rated up to 4.6. Note that the crossing points at 30% contrast are most likely somewhat to the right base on the Schneider lens performance data included. It’s possible that the Nikon primes deliver as much as 120-130-lp/mm when used at their optimal f-stop.

Rating lens quality: first-tier prime lenses, such as 35mm, 50mm and 85mm, from major manufactures such as Canon, Nikkor, Zeiss or Leica generally have similar behavior, as can be seen in Figures 8, 9 & 12. This is not true of second-tier manufacturers (aftermarket lens) such as Cosina, Sigma, Tamron, Tokina, etc. Browse the <photodo.com> MTF lens data (far right column) using the “Nikon AF” or “Canon EF” mount, which will include lenses from all manufacturers. The second-tier lenses are all in the lower rated range (0.9 3.5), while first-tier lenses are generally the only ones rated 3.6 to 4.6. Some first-tier lenses will be rated below 3.6, but they will usually wide-angle or zoom lenses.

Theoretical Lens Resolution

In the plot below, the resolution performance a “theoretical lens” is based on the limitations produced by the diffusion of light around the iris aperture. The smaller the aperture (f/16 and f/22) the greater the proportion of light diffused from the edge of the iris, thus, the smaller the lens aperture the lower the resolution. Unfortunately, the small apertures (f/16, f/22 and f/32) are considered best by most large format photographers, because depth-of-field is greater when the aperture is smaller.

In real lenses the performance of the glass lens elements is always better in the center of the lens element then at the edges. Therefore, reducing the f-stop limits the area of glass elements being used, thereby effectively increasing lens performance.

The trade-off between light scattering from the iris edges and reducing the amount of glass being used to focus the light appears to be optimal at 2-3 stops above the maximum opening (smallest f-number, largest opening). For large format lenses this is often f/8 to f/11, while for 35-mm format lenses range is from f/2.8 to f/5.6 (if the lens is a 50/1.4).

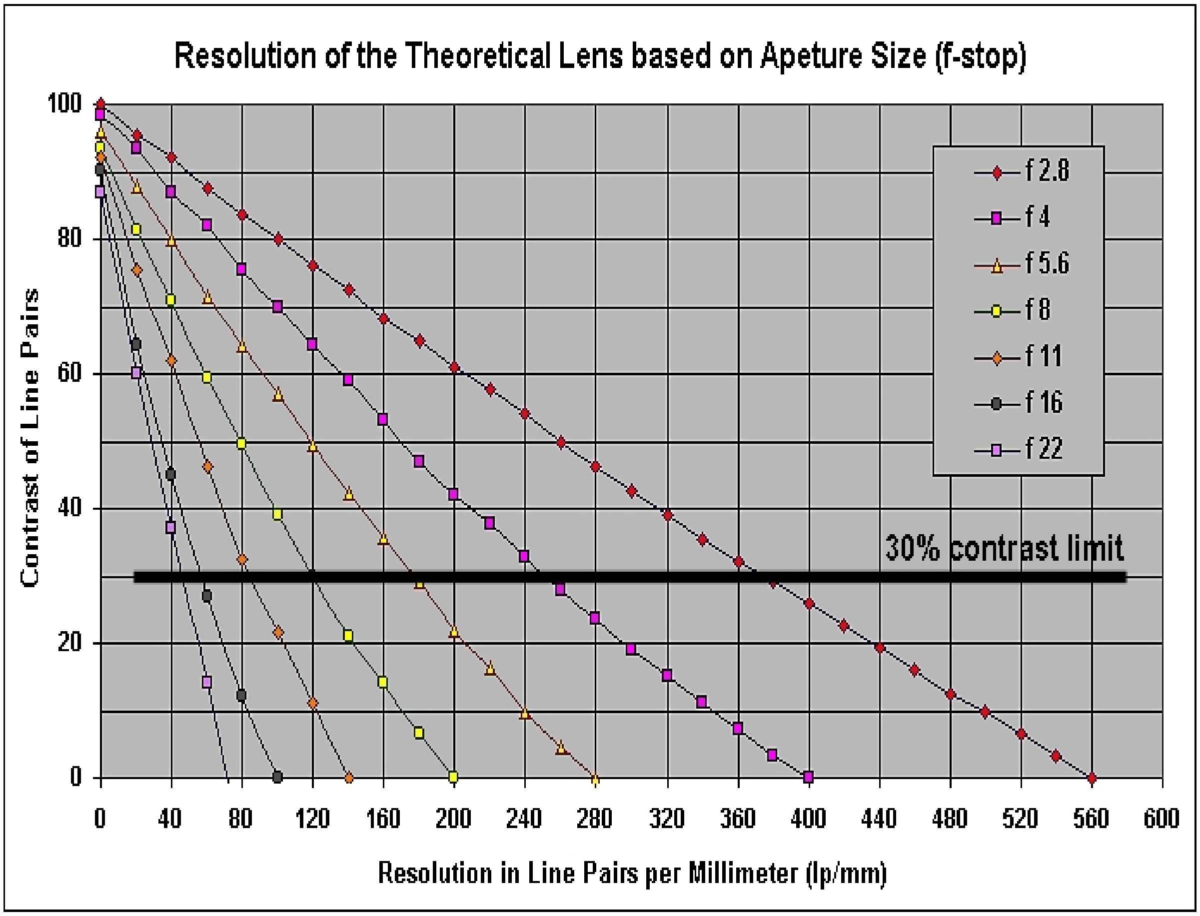


Figure 10: Behavior of a theoretical lens at specific f-stops.

Few lenses can perform in a theoretical manner. However, note that the Schneider Apo Symmar 150/5.6 lens has close to theoretical behavior at f/11; compare the third curve from the left in Figure 10 to the bold purple line in Figure 12 (next page), both cross the 30% contrast line at 85-lp/mm.

Because large format lenses use huge hunks of glass they perform poorly wide-open (maximum area of the glass). In Figure 12, the dark blue plot shows the performance of the Schneider 150/5.6 wide open (at f/5.6). The "theoretical" behavior of f/5.6 aperture is the third from the right in Fig 10; about 175-lp/mm at 30% contrast; the actual lens has a quarter of that performance. Note that the plot of the f/5.6 aperture for the Schneider 150/5.6 is similar to the f/22 plot (furthest left) for the theoretical lens shown in Figure 10. The f/11 aperture is commonly considered the best aperture for large format lenses, this is true for this lens; see the purple line in Figs 8, 9 & 12.

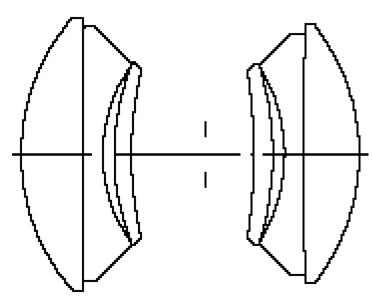


Figure 11: Cross-section of Schneider APO Symmar 150/5.6 film lens; designed before the flat-field digital era.

Astigmatism, spherical and chromatic aberrations, coma and non-flat field of focus along with the flare from the eight air-glass interfaces, coatings and glass types have been balanced very well, producing very good image quality for the excellent quality Schneider APO Symmar 150/5.6. The equivalent Rodenstock brand APO and Digital (flat field, CCD is flat) will have similar or better optical behavior.

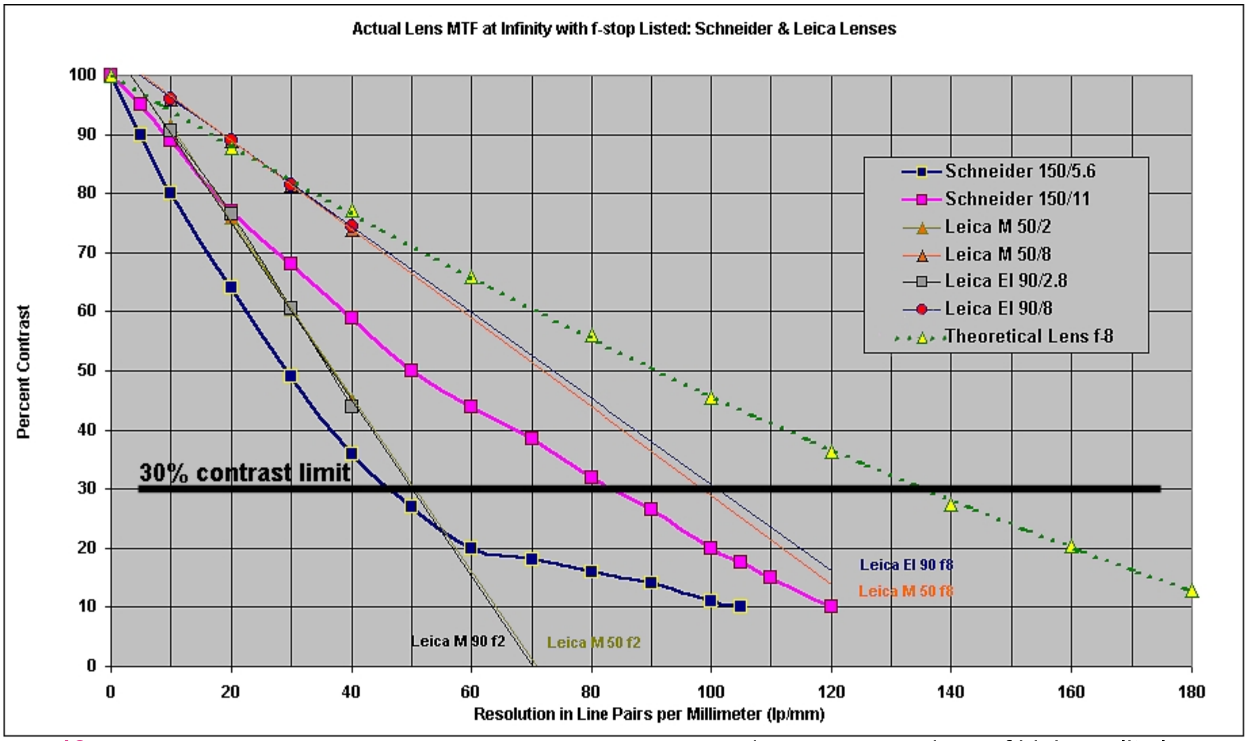


Figure 12: Comparison large format and small format (35-mm) lenses; shows a comparison of high quality large format (LF) and high quality small format (35-mm) lenses at the ideal f-stop (f 8 & f11) and wide open (f 2-2.8) with a theoretical lens at f-8.

The relative performance of large and small format lenses can be seen in Figure 12. Because the glass in large format lenses is so much larger their relative performance is lower, about 80-lp/mm, while the very best of the small format lenses perform at 100-lp/mm, and possibly, at 120-140-lp/mm.

Leica lenses: shown in the plot above, the two Leica lenses at f/8 come close to theoretical lens f/8 behavior (dotted green line). Note that the 10-40 lp/mm data points (4 red dots, upper left) almost match the f/8 theoretical lens performance. The "straight line" estimation of their performance, which goes through the 4 data points, shows 100-lp/mm at the 30% contrast limit. When using the shape of the f/8 theoretical lens plot, the actual performance may be as high as 130-140-lp/mm. This is probably also true for the excellent Canon and Nikkor lenses shown in their respective plots.

Table 3: Relative Resolution of Film and Digital Imaging Media, with Typical Lens Resolution Data

Film Type* -- Averages	Native Film Resolution, ppi MTF @ 30	Native Film Res in lp/mm MTF @ 30%	thru 80-lp/mm lens in ppi MTF @ 30%	thru 80lp/mm lens in ppi from USAF 1951 Chart
Color Negative Film	3240	64*	2170 (43%)ß	
Color Transparency Film	2684	53*	1620 (40%)ß	
B&W (all eras)	4282	84*	2080 (49%)ß	
B&W 1940 data only	2900	57*	1700 (41%)ß	
B&W 1970 data only	4525	89*	2144 (53%)ß	
B&W Modern only	6400	126*	2485 (61%)ß	
Specific Modern Films				
Ektachrome 100	2285	45**	1465 (36%)ß	
Kodachrome 25	2700	53**	1620 (40%)ß	
Ektachrome 100GX	3050	60**	1740 (42%)ß	
Fuji Velvia 50	3454	68**	1870 (46%)ß	
Fuji Velvia 100F RVP	4064	80**	2032 (50%)ß	
Kodak VR 100 (color neg)	5080	100**	2260 (56%)ß	
Kodak T-Max 100	7112	140**	2585 (64%)ß	
Fuji Neopan 100***	8130	160***	2710 (67%)ß	
Kodak Technical Pan	8636	170**	2605 (65%)ß	
DSLR (digital single lens reflex 35 mm)				
Canon EOS 1Ds MkII	3328	66+		
Canon EOS 1Ds	2704	53+	2032§	2800Φ
Canon EOS 1D Mk II	2336	46+	2540§	2800Φ
Nikon D2x	2848	56+		
Kodak DCS	3205	63+		
Canon EOS 20D	2344	46+	2185§Ψ	3150ΦΨ
Nikon D70	2000	39+		

Scanning Backs (used in 4x5 view camera body)		
BetterLight 4000E-HS (3750x5000)	1323	26
BetterLight 6000E-HS (6000x8000)	2120	42
BetterLight 8K-HS (12000x16000)	2822	56
BetterLight 10K-HS (15000x20000)	3598	71
Flatbed Scanners		
Epson 10000XL, tabloid	2400	47
Aztek Plateau, tabloid	4000	79
Creo iQsmart2, tabloid	4300	87
Epson 4990, 8x10	4800	94
Creo iQsmart3, tabloid	5500	108
FlexTight 646, sheet film	6300	124
FlexTight 949, sheet film	8000	157
Drum Scanners		
Howtek 4500	4500	89
Fuji Celsis 6250	8000	157
Aztek Premier	8000	157
ICG 380	12000	236
Resolution Limitations imposed by Lens -- 30% contrast of black and white line pairs		
Old Large Format Lens	1016	20
Average Large Format (LF) Lens	2032	40
Good LF or Average SLR Lens	3036	60
Excellent LF or Very Good SLR	4048	80
Excellent SLR Lens	5060	100
Superior SLR Lens	6096	120
Theoretically Perfect Lens at f-16	3300	65Ω
Theoretically Perfect Lens at f-11	4318	85Θ
Theoretically Perfect Lens at f-8	6096	120ω
Theoretically Perfect Lens at f-5.6	9144	180Σ
Theoretically Perfect Lens at f-4.0	17800	350Π

* Pulled from data table on pp 16-17.
** Pulled from film manufactures data sheet found on the web or in official publications.
*** Resolution is based on the vastly inferior “1000:1” resolution target; it is probably inflated by 25-40%, over 30% MTF.
ß Resolution figure is based on the System Resolving Power EQ2; percent loss in parentheses.
+ No contrast information on digital pixels, such as the “30% of full scale” for film, pulled from MTF curves.
§ Actual resolution http://www.wlcastleman.com/equip/reviews/film_ccd/index.htm using Koren process at 50% Contrast.
Φ Measured using the 1951 USAF Resolution Test Pattern (Edmund Scientific) on the <wlcastleman> website above
Ψ The 1000 ppi difference is actual data pulled from the <wlcastleman> website.

4 - Resolution of Modern Film: Film Data (1938/40-2005)

The native resolution data in Table 4 provides information on the published resolution of specific films from three manufacturers, and then averages the groups based on type

- **B&W**
- **Color transparency**
- **Color negative**

and historic eras

- **1940 (historic)**
- **1940-1970 (old)**
- **1970-2004 (modern)**

The resolution data is based on direct contact printing of the film resolution target onto the film. Exposing film through a lens will decrease a film’s resolution from 25% up to 90%; see Sections 2 & 5. The nomenclature use is native resolution vs on-film image resolution for the latter.

Unfortunately there is little MTF data for film earlier than about 1970s. Therefore resolution data for film between 1970-75 and 1940 is projected from either 1000:1 high-contrast or 30:1 low contrast resolution targets. Prior to 1950, and sometimes through the 1960s, it was common for only words to be used to describe film resolution, making evaluation difficult. In addition, film grain was often confused with film resolution in the 1920s-1970s popular photographic literature (this error is even seen in the 1990s popular photographic literature). A comment on film resolving power in the 1946 Morgan & Lester *Photo-Lab-Index* might be “excellent fine-grained” film.

Table 4: Published Native Resolution Data for Still Film (averaged by type and historic era)

	Native Film Resolution lp/mm, MTF@ 30%	Digital Equivalent ppi	40% loss from system thru lens	60% loss from system thru lens
Color Negative Film (modern)				
Kodak Vericolor 5072 (neg-pos)	60	3050		
Kodak VR 1000 (neg film)	45	2290		
Kodak VR 400 (neg film)	50	2540		
Kodak VR 100 (neg film)	100	5080		
Average	**64**	**3240**	**1944**	**1300**

Color Transparency Film	lp/mm, MTF 30%	ppi		
Kodachrome 25 (discontinued 2003)	53	2692		
Kodachrome 64	50	2540		
Kodachrome 200	50	2540		
Ektachrome EDUPE	60	3050		
Ektachrome 5071 (dup)	50	2540		
Ektachrome 50	40	2030		
Ektachrome 64	40	2030		
Ektachrome 100	45	2290		
Ektachrome 100GX	60	3050		
Ektachrome 100plus EPP	45	2290		
Ektachrome 160	35	1780		
Fuji Velvia 50 RVP (2002)	68	3454		
Fuji Velvia 100 RVP100F (2004)	80	4064		
Fuji Provia 100F RPD	55	2800		
Fuji Astra 100 RAP	45	2290		
Fuji Astra 100F RAP100F	65	3300		
Fujichrome EI 100	45	2290		
Average (excluding Velvia 100F)	**48**	**2440**	**1464**	**975**
Average	**53**	**2692**	**2013**	**1610**

B&W Film	lp/mm, MTF 30%	ppi		
Kodak T-Max 100 (2005)	140	7112		
Kodak T-Max 100 (1987)	110	5600		
Kodak T-Max 400 (2005)	138	7010		
Kodak T-Max 400 (1987)	60	3048		
Kodak T-Max 3200 (2005)	134	6807		
Kodak Technical Pan Technidol (2004)	200	10160		
Kodak Technical Pan (2004)	170	8636		
Kodak Technical Pan HC100 (Dis'04)	135	6860		
Kodak Technical Pan (1984)	85	4320		
Kodak technical Pan (1976)	170	8636		
Kodak BW400CN, RGB dye B&W (2006)	80	4064		
Kodak Pro Copy Film SO-015 (1975)	80	4064		
Kodak Plus-X 125 (1970)	100	5080		
Kodak Plus-X Pan Pro 4147 (1976)	100	5080		
Kodak Plus-X 125, 2147/4147 (2004)	80	4064		
Kodak Plus-X 125 5062 (2004)	110	5600		
Kodak Ektapan 4162 (1970)	70	3556		
Kodak Panatomic-X (1976)	140	7112		
Kodak Royal-X (1970)	65	3150		
Kodak Royal 4141 (1976)	75	3810		
Kodak Recording Film 2475 (1976)	63	3200		
Kodak Tri-X 400 (1976)	50	2540		
Kodak Tri-X 320 (Ortho) (1975)	55	2794		
Kodak Tri-X 400 (2005)	65	3300		
Agfa Pan 25 (old ≈ 1935-45)	80	4064		
Agfa APX 25 (old ≈ 1935-45)	160	8128		
Kodak Verichrome Pan (1976)	110	5588		
Kodak Verichrome (1940)*	40‡	2030		
Kodak Panatomic-X (1940)*	55‡	2795		
Kodak Super-XX (1940) *	45‡	2286		
Eastman Panatomic-X (1940)**	55‡	2795		
Eastman Super-XX (1940)**	45‡	2285		
Eastman Portrait Pan (1940)**	40‡	2030		
Eastman Tri-X (1940)**	40‡	2030		
Kodak Plus-X Pan (1940)*	50‡	2540		
Kodak Micro-Fine (1940 microfilm)*	135‡	6860	4116	2744
Kodak Safety Positive (1940)**	50‡	2540		
Kodak High Contrast Positive (1940)**	70‡	3555	2134	1422
B&W Average 1940, excl Micro-Fine	**49**	**2590**	**1555**	**1035**
B&W Average all 1940	**57**	**2900**	**1740**	**1160**
B&W Average all "old"	**70**	**3530**	**2120**	**1412**
B&W Average all 1970s film	**89**	**4525**	**2715**	**1810**
B&W Average (all)	**85**	**4435**	**2580**	**1775**
B&W Average modern (only)	**126**	**6400**	**3840**	**2460**

* Nitrate base film

** Safety Film, acetate base film;

‡ Film resolution protocol based on Kodak's 1940-56 resolution procedure: "30:1 contrast" target, between the black and white line pairs; printed as l/mm, but is actually lp/mm.

ß Based on Kodak's "1000:1 contrast" resolution target; the measurement is inferior to MTF data by about 25%.

Table 4: shows a comparison between Native Film Resolution (no lens in path), taken from manufacture data sheets reported in both lp/mm (for analog systems) and ppi (for digital systems), and (in blue) the film after being exposed through a lens that has been modified by the RPE. The data was pulled from (1) "Kodak Films," Eastman Kodak 1939; (2) "Kodak Films" Kodak Data Books, Eastman Kodak 4th ed., 1947; (3 & 4) "Kodak Films & Papers for Professionals" (1978) & (1986); (5) Kodak Film Color and B&W (1975); (6) Kodak Professional Products website (film data is being removed) at URL: http://www.kodak.com/global/en/professional/products/colorReversalIndex.jhtml?id=0.3.10.8&lc=en and the (7) Fuji Professional Products website, film data sheets http://home.fujifilm.com/products/datasheet/.

5 - Predicting the Native Resolution of Historic Film

The author has been collecting data on film for a few decades. Generally, there is no technical data on film before about 1935-38. However, we need to understand the performance of early film when it comes time to capture the images digitally. Using published historic (1940-1975) and modern technical data (1984-2005), a method of predicting past technological performance (1889-1940) was developed. A modification of Moore's Law was applied to the 130-year range of film data.

Discussion

A table of film data was compiled; see Table 4 on page 13. The films were sorted and then averaged into historic-era groups based on the date-of-manufacture information:

(1) **1940-period** (1938-45) with 12 examples
(2) **1970-period** (1970-76) with 11 examples
(3) **2005-period** (1984-2005) with 13 examples

There is little precise data on the resolution of film before about 1970-76 because manufactures were not reporting modulation transform function (MTF) data. The 1938 to 1969 period has film resolution data, but it is reported based on high and low resolution targets, an antiquated system that is no longer used. The information has great value to this study, so it was adopted without modification.

If one looks back to the 1940s Morgan & Lester handbooks on photography, the resolution of individual films was of little concern; of most interest was evaluating the influence of the various developers and development times. It's almost as if film was seen as generic, all types behaving the same. Kodak published softbound books on films back to 1935 (earliest found thus far), which sometimes included data on film resolving power, however, no method was specified for determining resolving power prior to the 1970s-era publications.

In 1940-era Kodak data books, the resolving power values listed were modest, ranging from 45- to 70-lp/mm (average about 3100 ppi). By the mid-1950s Kodak Film data books advertized that their films had resolving power jumped to 70- to 100- lp/mm. By 1965, the film resolution ratings had increased dramatically suggesting that some films had resolving power as high as 225 lp/mm, although no film was directly associated with that rating. In 1976, for the first time MTF curves were published, many of the same films found in the earlier publications were included. They had native resolutions (at 30% residual contrast) ranging from of 65- to 110-lp/mm (average about 4500 ppi), with one (Panatomic-X) rated as high as 170-lp/mm.

Panatomic-X was often rated with the highest resolving power in the Kodak data books referred to above. The data on this film was followed through the Kodak books noted above:

(1) 55-lp/mm* in 1939 *Kodak Film: Data Book on Negative Materials* (15¢, 55 pp)
(2) 100-lp/mm* in the 1947 version of the data book (4th ed., 72pp, 35¢)
(3) 95-115-lp/mm* in 1956 *Kodak Data Book on Films* it was listed as having "high" resolving power
(4) 136-225-lp/mm* in 1965 *Kodak Advanced Data Book* (7th ed., 68 pp, 50¢) listed as "very high" RS
(5) 170-lp/mm (MTF data) in 1976 Kodak book on *B&W Professional Films* (pub. F-5, 60 pp, $5.95)
(6) NA, not listed in the 1984 version of Pub. F-5

[* - Value was reported in the data book within the films data section with an lp/mm value but no method was given.]

Based on about a dozen film examples from two manufacturers the average 1940's B&W film has a resolution of 2900 ppi. The average of 12 film examples, taken from three Kodak data book (1970, 1975 & 1976), showed a 89-lp/mm (4524 ppi digital equivalent) resolution for the 1970-period films. The average B&W film from the 2005-period was found to have a resolution of 126-lp/mm (6400 ppi digital equivalent) using about a dozen examples. It is interesting to note that Fuji does not publish MTF curves in its B&W film data sheets. Data summary:

- **1940-period has an average resolution of 57-lp/mm or 2900 ppi digital equivalent**
- **1970-period has an average resolution of 89-lp/mm or 4525 ppi digital equivalent**
- **2005-period has an average resolution of 126-lp/mm or 6400 ppi digital equivalent**

Between 1940 and 2005 (65 years) the resolution of B&W film increased 1.2 times. The rate for doubling the resolution of B&W film is 58 years. Moore's Law of digital technology innovation was adapted to the problem. The rate of "resolution doubling" was set at 58 years, through a range of 130 years (1875 to 2005). The top line (yellow) of Figure 13 is the result.

Fortunately, the late 65-year tranche (1940-2005) of the 130-year range is well characterized. This has resulted in the early 65-year tranche (1875-1940) being characterized even though no known film resolution information exists. Researchers may someday find a worker's research notes or proprietary publications that were never revealed to the public allowing for greater precision in the estimates.

The smoothness of the plot on the right side of the curve (late tranche), with its seamless projection into the past, suggests this exercise has value. Note that the middle value of 2900 fits very neatly on the (x = 0.916) curve. Since this is the only "late tranche" data we have, it is a close as we can get to predicting past performance in the early tranche.

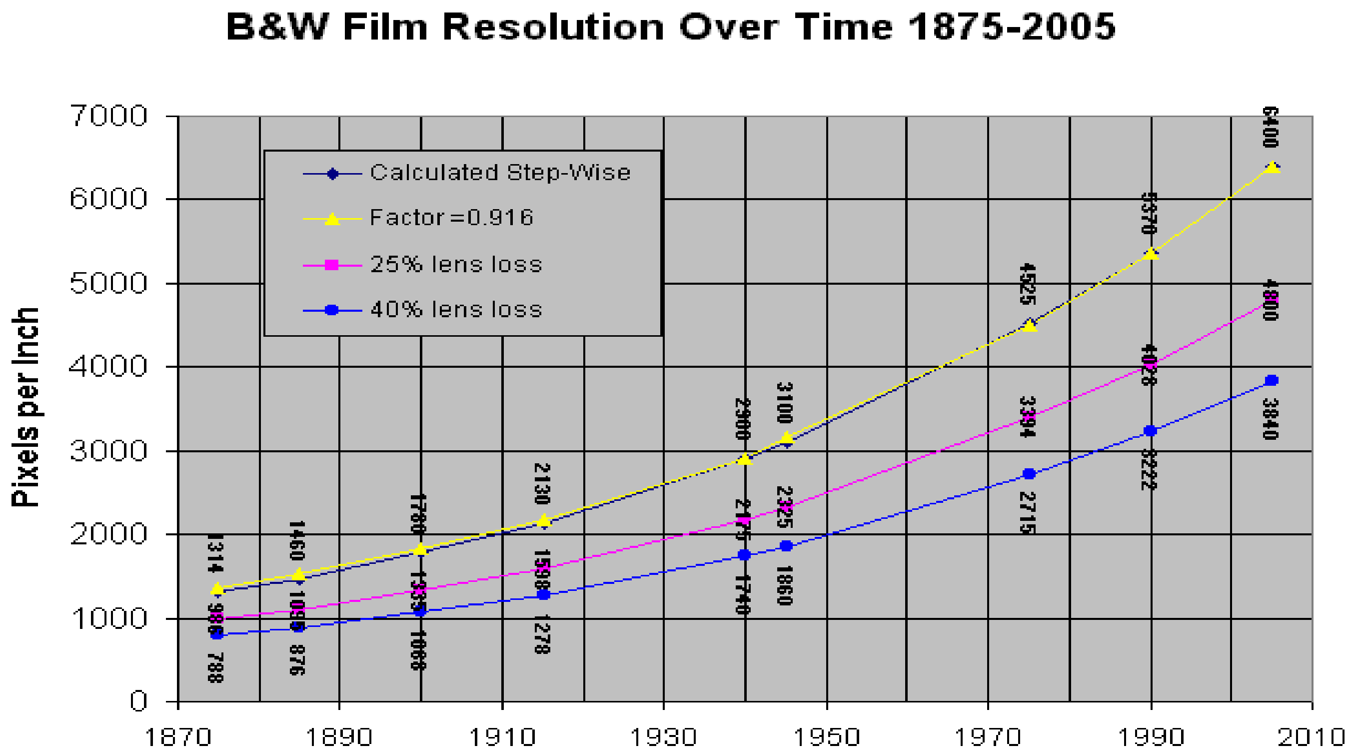


Figure 13: Predicting Resolution of Historic Film, based on Rate of Technological Change defined by "Moore Law" using known average values from 1940, 1970 and 2005, which show that resolution doubled every 58 years.

6 - Two Methods for Predicting On-film Image Resolution: (1) RPE method & (2) Easy method

The process of predicting on-film image resolution can be complex because it utilizes the RPE; however, a simplified method has been provided using look-up tables: Tables 6 & 7. Both methods are detailed below.

The more precise **RPE method** calculates the exact image resolution using the Resolving Power Equation (RPE) explained in Section 2 on page 2. The simpler and less time consuming, **Easy method** uses Table 6 (Twelve Guidelines) to estimate the effect of the taking lens on the average film of a specific date. Using that date, the on-film image resolution value is read from Table 7 (Film Resolution Estimator) based on the "% loss due to lens" just determined in Table 6. The Easy method has more error in the resulting value, because the number involves making estimates of historic information that was never measured and thus never known.

Discussion: Film and Lenses

Both film and lens resolution information is used to predict on-film image resolution. Determining historic film resolution has been detailed in Section 5, above. The technical and historical information needed to evaluate and determine estimates of lens resolution through time are covered below.

Film has a native resolution which is best determined using direct measurement by the manufacturer; it can also be estimated using regression math to a time when manufactures did not make such measurements. Native resolution data can be obtained using:

(1) MTF values pulled from a manufacturers' film data sheet or film data guide booklets or
(2a) using the yellow line in Figure 13 (based on the date of manufacture) or
(2b) from Table 6 look-up table (but a 10-20% error is built-in due to the 15 years steps).

The precision of the native resolution value does not need to be exact, the second whole digit is sufficient. In reality, even the 10-20% error introduced when using Table 6 will not prove harmful to the final application of the results. In addition, Figure 13 is based on averages calculated from the data list in Table 4 (Resolution of Modern & Historic Films); the averages have a 30-50% error which is endemic to the mathematical-averaging process.

Lenses have a resolution that is based on technical evaluation. Such information is reported at <photodo.com> and other websites listed on page 5. Lens resolution data needed for both the methods can found using:

(1) published information available from photodo,com, dpreview.com or other resources or
(2) estimates of lens quality in Table 5 (Lens Resolution Estimator) or
(3) estimates of the effects lenses on film resolution found, in Table 7 (Twelve Guidelines).

Determining lens quality without exact information is problematic, but reasonable estimates can be made using a collection of pertinent information on camera formats (lens size) and lens history. Since historic cameras and lenses are seldom evaluated using MTF technology, most of the information is based on 50 years of photographic experience and research.

Small format (35-mm) photography will tend to have better lens quality (60-100-lp/mm) due to the fact that many SLRs were sold and used with their high resolution standard 50mm lens (standard for 35-mm SLR about 100-lp/mm), or, with 85mm and 200mm telephoto lenses also capable of 80-100-lp/mm when made by first-tier manufacturers. Wide-angle lenses such as the 24/2.8 and 28/2.8 are only capable of about 60-lp/mm even when made by first-tier manufacturers. Professional photographers will tend to use better quality lenses (60-100-lp/mm) while non-professionals often used second-tier lenses that are less expensive and thus have lower resolution (30-60-lp/mm).

Medium format (MF) photographers tend to use high quality first-tier lenses such as Zeiss, but the glass elements are about 2-3 times larger than 35-mm lenses. The Rolleiflex (new in 1929) had a very good taking lens (80-lp/mm with small area) while the knockoffs (Yashica and Seagull) had questionable (20-40-lp/mm?) quality. The Hasselblad 1600 (new in 1948) was a MF SLR with a focal plane shutter (FPS) which used the Kodak Ektar 80/2.8 lens (1949-53); this was its weak point. While good, using coatings and rare-glass formulations for flare and color correction, only one or two of the Ektar's (50/1.9 was best and the other 50/3.3) could even come close to Zeiss engineering. By 1953-57 the Hasselblad 1000F used the Zeiss Distagon 60/5.6 or the Tessar 80/2.8. In 1957 the flagship 500C, with modified leaf shutter, became very popular with professional photographers. In general, the relatively larger glass used in MF lenses means that they can't compete in resolution with the small format lenses (35-mm), yielding about 60-100-lp/mm performance. This is borne out by an average of one-point lower performance in the <photodo.com> MTF-based ratings (3.7/3.9 vs 4.6). Amateurs working in medium format systems during the 1950-1970's era, often used the inexpensive Rolleiflex-knockoffs only capable of 20-40-lp/mm.

Large format (LF) photographers (4x5 and 8x10) tend to use good quality lenses because they are semi-professionals or professionals. However, the size of the lens elements used in large format systems lowers the overall performance of the lens. The resolution of the center of a large format image will tend to be good to excellent (60- to 100-lp/mm), while the resolution falls off markedly towards the edge (20-60-lp/mm), which is an inch or more from the center of the lens. An overall rating of lens resolution for LF photography is about 40-80-lp/mm.

Amateur camera photographers often used Kodak (or equivalent) box or folding cameras from about 1885 to the 1950s (capable of only 10-30-lp/mm). Amateurs also used the Yashica and Seagull DLRs (MF, above). However, most used the Kodak brand point-n-shoot cameras (PnS) such as the Brownie, Hawkeye, Bantam or Kodak Disk Camera. Those consumer products generally used very simple lenses such as the Chevalier Achromat capable of about 20-lp/mm. About the turn-of-the-century advanced amateurs began using folding cameras with the superior Goerz Dagor lens; it was capable of up to 40-lp/mm. Beginning sometime in the 1950-60 era PnS products may have used lens coatings limiting flare and internal light scattering, pushing lens resolution as high as 40-lp/mm, but not much more. Some consumer PnS cameras use optical plastic lenses. In all cases, image quality of amateur systems was hampered by hand-holding and inexperienced users.

Lens use history; photography begins about 1826. Even today, lenses are the limiting factor in image quality. The history of their use is a significant factor which must be laid over their performance based on size, which is defined by camera formats outlined above. For lens design details see <http://en.wikipedia.org/wiki/List_of_lens_designs> and *A History of the Photographic Lens* by Rudolf Kingslake (1989) pp345. Both the factors of (i) lens size and (ii) lens development thru photographic history are combined in Table 5 (Lens Resolution Estimator) at the end of this section.

Very early lenses tend to have one or two elements limiting the ability to focus all colors of light in the same flat-field, softening the resolution of the lens significantly and focusing in a curved plane. An example is Hall's 1750s Achromat curved-field doublet which uses two glass types (crown and flint) to focus red and blue light in the same place, but because green light focus point was shifted the resolution was soft. The 1812 Wollaston Landscape lens (curved-field) was the first properly designed lens, but it suffered from chromatic aberrations (focusing different colors in different planes); it's still used in use in low cost applications. The noted Chevalier Achromatic lens (1835) also used two different cemented glass elements, but the innovation was to focus in a flat-field. Daguerre officially adopted the lens in 1839 and it still gets heavy due to compactness and simplicity. In the era, it probably delivered about 15-20-lp/mm. Kingslake (noted lens historian) said: "…it is hard to understand why the development of a good camera lens was such a slow process …between 1840 and 1890." Early opticians were using lens elements as building blocks, seeking a happy accident. On the other hand, Petzval designed lenses on paper using optical formulae and then built them.

By 1841 Petzval designed the 4-element achromatic portrait lens which became a photographic standard used through middle of the 20th century; it's thought to be capable of 20-30 lp/mm. It had a long shape due to a large air gap, and couldn't be used in amateur cameras, which favored the compact Chevalier and Dagor designs. The Petzval lens pushed the use of different glass formulations to further improve light handling, but still only in two colors. Otto Schott joined Ernst Abbe and Carl Zeiss (in Zeiss workshop founded 1846) <http://www.smecc.org/ziess.htm> to produce glass capable of implementing the workshops Apochromatic lens flat field designs that corrected both spherical (3 colors) and chromatic aberrations (2 colors) in 1886; resolutions of 40-50-lp/mm are thought possible. By 1896, the Zeiss workshop develops the Protar and Planar lens designs, which were significant developments, but only came into wide use after lens coating was developed 40 years later. The compact, one-group, 3-element, Dagor Anastigmatic flat-field lens was produced by Goerz (Berlin) in 1904 and it is still being used today The design was a significant advance, correcting spherical aberration, coma and astigmatism, it's thought to be capable of 40-60-lp/mm.

Also at the turn-of-the-century, the next significant advancement in lens development was the 4-element 3-groupTessar design by Zeiss; it created higher contrast and thus greater resolution beginning in 1902; 40-60-lp/mm is thought possible. The German designers continued to refine lens glass formulations and introduced coatings through WWII, raising lens quality to a very high level, although the Allies did not share in the developments. Single lens coatings were introduced in 1935, but did not reach the Allies until later. The Swedish, Hasselblad HK7 (1941) reconnaissance camera, used by the Allies <http://www.hasselblad.com/about-hasselblad/history/a-man-with-small-hands.aspx>, was fabled to be better than the captured German equivalent. Film and lenses were strategic war materials facilitating reconnaissance and espionage; advancements didn't reach consumers until after the war.

Advanced lens coatings (multi-layer, such as alternating silica and magnesium fluoride) were the final "major" lens development, beginning about 1960-5 <http://en.wikipedia.org/wiki/Anti-reflective_coating>. Small format lens makers were the early adopters, while it took through the 1980s for the large format lens makers to fully implement multiple lens coatings. For more details on the significant lens and camera dates used in Table 5 see the "List of Imaging Events" at <http://videopreservation.conservation-us.org/library/brief_history_of_imaging_technology_v16.pdf> and <http://en.wikipedia.org/wiki/Lens_(optics)>.

Table 5: Lens Resolution Estimator

Date	Cause of Improvement	Professional Large Format in lp/mm	Amateur - Box Folding & PnS in lp/mm	Professional Medium Format in lp/mm	Pro & Amateur Small Format in lp/mm
1826	base line	**<20**	NA	NA	NA
1835	Chevalier Achromat	**20ish**	NA	NA	NA
1841	Petzval Achromat	**20-30**	NA	NA	NA
1873	Abbe Optics	**20-40**	NA	NA	NA
1886	Zeiss Apochromatic	**30-40**	<20	NA	NA
1893	Goerz Dagor Achromat	**40-60**	**20-40**	NA	NA
1902	Tessar hi-contrast	**40-60**	20-40	NA	NA
1925	Leica RF/FPS Elmar	40-60	20-40	NA	**50-70**
1929	Rolleiflex MF Zeiss	40-60	20-40	**40-60**	50-70
1935-40	optical coating	**40-70**	20-40	**50-70**	**50-80**
1948	Hasselblad MF Ektar	40-70	20-40	**50-80**	**50-60**
1949-59	first SLRs - C, N & Z	40-70	20-40	60-100	**40-80**
1960-70	adv lens coatings	**40-80**	20-40	**70-100**	**40-100**
1970	cheaper optics	**40-80**	**20-40**	**70-100**	**40-100**
1975-88	LF lens coating	**40-90**	20-40	**70-100**	**40-100**
1987	point-n-shoot	40-90	20-40	70-100	**40-100**

Bold Text indicates format affected by "Cause of Improvement" in second column.
Professional moniker assumes best possible lens; **Amateur** assumes an average quality lens.

KEY: LF = Large Format 4x5, etc.**; MF =** Medium Format 2¼x2¼, etc.**; PnS =** Point-n-Shoot compact cameras**; Small Format =** 35mm rangefinder (1925) and SLR (1950); **RF** = rangefinder 35mm format**; FPS** = focal plane shutter**; Elmar** = Leitz version of Zeiss Tessar high contrast lens; **Ektar** = Kodak's post WWII coated lens noted for color and contrast; **Lens Coating -** started on small format lenses (1935) in Germany & Sweden, by Allies after WWII and began for LF lenses in 1975-88**; C, N & Z** = Canon, Nikon and Zeiss-E/W (east and west); look in Wikipedia for excellent histories and data on equipment manufacturers listed above.

Simplification of Lens Technology - Guidelines for Modifying the Native Resolution of Film

Guidelines for predicting loss of native film resolution are based on the (1) magnitude of the films native resolution and the (2) quality of the lens. The guidelines are extracted from Table 5 (Lens Resolution Estimator) on p 18 and Table 2 (System Resolving Power Data Table) on p 4, which shows the effects of using the RPE on films of various resolution and lenses of increasing quality.

There are a few basic factors that direct the guidelines. First and foremost is that if the film and lens have equal resolution, there is a minimum of 50% loss in the native resolution. The higher the initial native resolution of the film the more it will be effected by the quality of the lens. Lower resolution films will be harmed less by lens quality. Older films will be harmed less by low lens quality. Very old films shot through low quality lenses will only be harmed about 65-70% by the lens. Amateurs tend to use lower quality lenses than professionals. Smaller format lenses often have higher resolution than medium and large format lenses. Modern film shot using early large format cameras lenses will fare the worst, with 60-90% loss of native resolution. The basic guidelines for modifying the native resolution of film are as follows.

Table 6: Twelve Guidelines for predicting percent film resolution loss due to lens era and film format

No.	**% loss**	**Description of Historic Era, Film Format and Lens Quality**
1	25	modern medium resolution film in 35-mm & 2¼x2¼", thru an excellent lens (100 lp/mm)
2	40	modern small format film thru an average good lens (80 lp/mm) with good processing
3	40	average small-format 1940-70 film exposed through excellent lenses
4	40-60	large format film (1890-1970) thru average quality (40-lp/mm) lens with fair processing
5	50-60	modern large format film exposed through a good quality (60-lp/mm) large format lens
6	50-70	very high resolution film thru an excellent lens (100 lp/mm)
7	55-70	modern high resolution (5000-7000 ppi) film exposed through a good lens (80 lp/mm)
8	60-70	all common modern film through an average (40 lp/mm) quality lens
9	60	large format film (including early roll film) from 1890-1930 through average quality lens
10	60-70	very early film (1890-1930) thru all possible lenses, assuming good alignment and focus
11	60-80	large format film and glass plates 1875-1900 through average LF lenses (10-20 lp/mm)
12	60-90	modern large format film exposed through older lenses or average large format lenses

Computation of On-film Image Resolution for both Methods

RPE method

First determine the native resolution of the film

(1) use film date in Figure 13 (B&W Resolution Over Time) or Table 6 (Film Resolution Estimator)
(2) use actual MTF data from a film data sheet supplied by the manufacturer (usually 1970 or later)

Second determine the quality of the lens

(1) from direct knowledge of the equipment used by photographer or
(2) based on either Table 5 (Lens Resolution Estimator) or
(3) use Table 7 (12 Guidelines for Selecting Percent Loss) [back-out lens resolution from percent loss]

Finally, use the Resolving Power Equation EQ2 (RPE) to calculate System Resolution [1/R]

(1) calculate the lp/mm value for the native resolution of the film (ppi number ÷ 50.8 = lp/mm)
(2) calculate the reciprocal (1/r) of the films' native resolution (1 ÷ lp/mm value)
(3) calculate the reciprocal (1/r) of the lens resolution (1 ÷ lp/mm value)
(4) run the RPE (EQ2: $1/R_{[system]} = 1/r_{[media]} + 1/r_{[lens]}$) to yield the System Resolution [1/R]

Example (1970-film): using a B&W film from 1970, which would have an average native resolution of 4300 ppi using Figure 13, and an SLR with a Nikkor 50/1.4 prime lens (100-lp/mm):

(1) 4300 ppi is 85 lp/mm (4300 ÷ 50.8 = 84.64), where [ppi value ÷ 50.8 = lp/mm]
(2) the reciprocal ($1/r_{film}$) of 85 is 0.012 (1 ÷ 85 = 0.118)
(3) the reciprocal ($1/r_{lens}$) of 100 lp/mm is 0.010 (1 ÷ 100 = 0.010)
(4) add the two terms, to give the R value (0.0118 + 0.010 = 0.0218)
(5) calculate the reciprocal (1/R) of R, which equals 46 lp/mm (1 ÷ 0.021 = 45.87)
(6) calculate ppi value for the 1/R value, where [lp/mm x 50.8 = ppi value]
(7) the on-film image resolution is: 2340 ppi (46 x 50.8 = 2337) [46% decrease in native resolution]

Note that in the preceding example the lens has somewhat better resolution than the film, so the loss of resolution is below slightly below 50%, which is the default prediction when film and lens have roughly the same resolution.

Easy method

The simple method is to use Table 6 to get a rough estimate of effects of lens quality and Table 7 to determine on-film image resolution. Note that the answer in the example below is 16% higher than when using the RPE method; the relatively quick and painless Easy method has a larger error due to series of simplifications made of the many unknown variables common to historic materials. Experimentation has shown that the error is larger for answers in the low range, and, lower for those in higher range of on-film resolution. For an extreme example see the 1906-film at the bottom of p 20.

Example (1970-film): select the closest date (1975) in column 1 of Table 7; the native resolution of the unexposed film would be 4525 ppi (digital equivalent). Next, select the percent loss of native resolution caused by lens, using columns 3 thru 8 of Table 7. In this case, column 4 is the probable choice based on the Guideline 3 in Table 6 (Twelve Guidelines). The answer is 2715 ppi.

Table 7: On-film Image Resolution Estimator

1	2	3	4	5	6	7	8
Date	**Native Resolution**	**25% loss due to lens**	**40% loss due to lens**	**50% loss due to lens**	**60% loss due to lens**	**70% loss due to lens**	**80% loss due to lens**
1885	1460	1095	876	730	**584**	**483**	292
1900	1780	1335	1070	890	**712**	**534**	450
1915	2130	1600	1280	**1070**	**850**	**639**	530
1940	2900	2175	**1740**	**1450**	**1160**	**870**	**725**
1945	3100	2325	**1860**	**1550**	**1240**	**930**	775
1960	3831	**2873**	**2299**	**1916**	**1532**	**1149**	767
1975	4525	3400	**2715**	**2260**	**1810**	**1358**	1130
1990	5400	4050	3222	**2700**	**2160**	**1620**	1350
2005	6400	4800	3840	**3200**	**2560**	**1920**	1600

Additional Examples using the "Easy method"

1915 Film – The average film from 1915 has a resolution of 2130 ppi (42-lp/mm) as show in Table 7. Because the film was probably used with a lens of average capabilities (40-lp/mm) the resolution of the image on the film is pulled from column 6 or 7, based on Guideline 10 in Table 6. The on-film image resolution would probably be around 745 ppi, if one averages the data in both columns.

1889 Film - The native resolution of film from 1885 would be about 1460 ppi (28-lp/mm). This is a low resolution film exposed through an average lens of the era, about 20-30-lp/mm. Using Guideline 10 in Table 6, the film would produce images with resolution in the range of 483 ppi, as shown in column 7, in Table 7. However, if the image was made with a hand-held camera such as a Kodak #3 Folding camera or the Kodak #2 Box camera, it could be even as low as 292 ppi, following Guideline 11, as shown in column 8 in Table 7.

[Note: Prior to 1889 Kodak cameras (back to 1885) were supplied with roll paper negatives that the consumer shot and then sent the whole camera back to Kodak for processing and printing. Prints made from paper negative would have much less resolution than film.]

7 – Using Digital to Capture Analog film

The Nyquist sampling theorem says that a digital system needs a minimum of twice the bandwidth of the analog system to capture it correctly. However, experience has shown that three to four times the analog resolution is a superior sampling rate. See *Film Grain, Resolution and Fundamental Film Particles* (v23, 2009), p23 for details. <http://videopreservation.conservation-us.org/library/film_grain_resolution_and_perception_v24.pdf>.

Example: a 1906 film using both methods

Easy method: Table 6 shows an historic film from 1900 has a predicted native resolution of 1780 ppi (digital equivalent). The average folding camera from that era would have a lens capable of 10-20-lp/mm. Thus, the native resolution would be decreased by about 65%, using Guideline 11 in Table 6, which would be a value halfway between columns 6 and 7 in Table 7. The on-film image resolution would be about 620 ppi (digital equivalent). Using a 4-times digital sampling rate (Nyquist), a scanner set at 2400 ppi would yield excellent digital capture results.

RPE method: Figure 13 (yellow line) predicts that an average 1906 film would have a digital equivalent native resolution of 1875 ppi (37-lp/mm). If the folding camera was an advanced amateur model, such as the Kodak #4 Folding with a Goerz Dagor lens, it could be capable of 55-lp/mm [according one published report for a 180/6.3 Dagor made around 1923]. The calculations [$1/r_{[film]}$ **(0.027)** + $1/r_{[lens]}$ **(0.018)** = $1/R_{[system]}$ **(0.045)**] would produce the result of 22-lp/mm or 1129 ppi (digital equivalent). Using a 4-times digital sampling rate (Nyquist), a scanner set at 4800 ppi resolution would yield excellent digital capture results.

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