Estimating the Resolution of Historic Film Images: Using the Resolving Power Equation (RPE) and Estimates of Lens Quality

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1 – Introduction

Determining the resolution of an image in a specific piece of modern film has become common when the film type and taking-lens are known; see Section 2 for RPE use. Doing the same for images made before 1940 is complicated by the lack of information on native film resoution and lens quality.

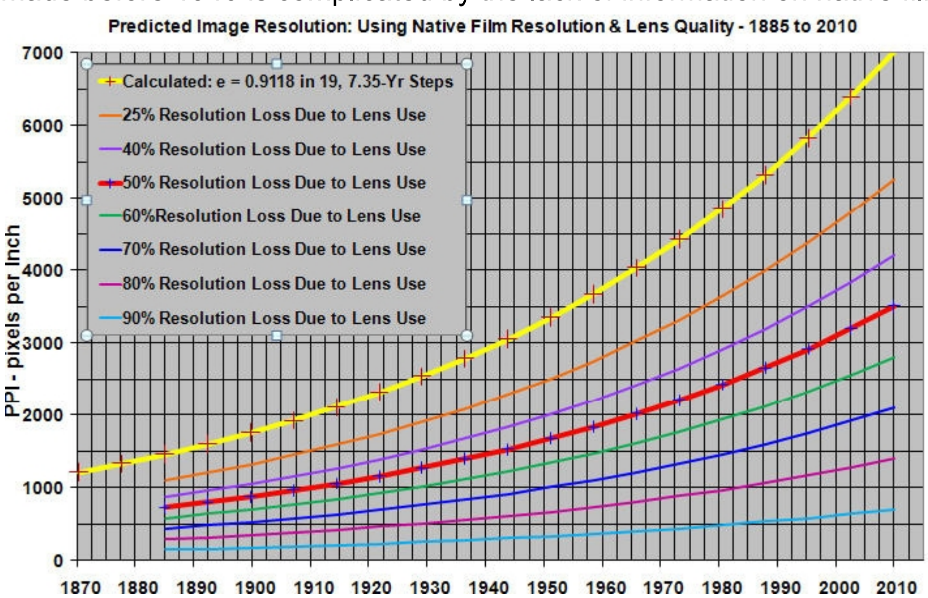

Figure 1: The set of curves predicts the image resolution of B&W film from 1889 to present. The yellow curve is the native resolution of film; half the data used to calculate image resolution using the RPE, see Section 2. Lens quality is the other component required by the RPE; see Sections 3 & 6 for details. The series of colored lines below the bold yellow line represent the actual image resolution, at various lens qualities. Note that using a lens with resolution equal to the film will fall along the **50% Resolution Loss Due to Lens Use** line in **red**. Kodak Plus-X (5080 ppi or 100 lp/mm native resolution) shot through a Canon SLR with a 50/1.4 prime lens (100 lp/mm) will have an image resolution of about 2500 ppi (49 lp/mm).

Detrmining lens quality in the absence of a photographer's notes, or direct knowledge of their equipment, is dificult, but not impossible; a set of 12 guidelines for estimating lens quality has been developed, see Table 6. The native resolution of film has been publically available from about 1935-40 in the form of high-contrast (1000:1) resolution-target data. Beginning about 1975 the more precise MTF data began to be published. Before about 1935-40 this data appears not to be availbale, therefore a method of predicting the native resolution of film prior to that date was developed using a version of "Moore's Law" technological innovation, see Section 5.

Before the middle of the twentieth century, 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 in their publications and film data sheets. Usually the company library no longer exists, an unfortunate victim downsizing or closure. A Kodak professional who used their technical services department, noted that the MTF measurements took a week (40 person-hours) to create, and even then, one week's test data often did not match the data from the following week. MTF data was difficult to come by even for the professionals; much of it was kept confidential.

The process of calculating the resolution of an image on-film involves using the system resolving power equation (RPE). The RPE requires two pieces of data:

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

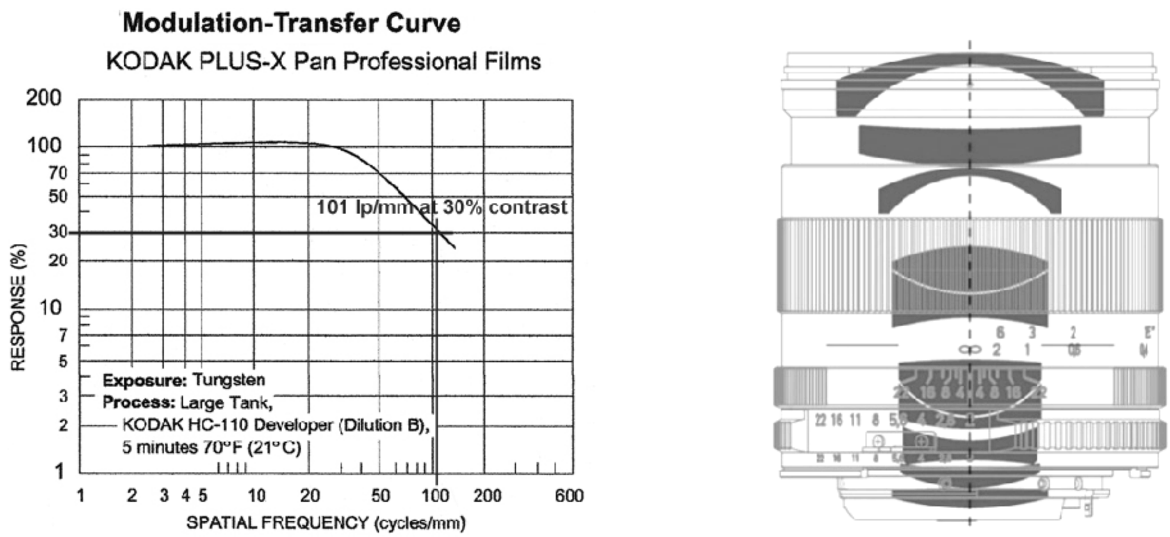

Figure 2a & 2b: The MTF curve (left) from the Kodak data sheet for Plus-X Pro Pan PXP and a cross-section of 35mm-format Zeiss lens (right) from their data sheet for the Zeiss Distagon f/2 28mm (28/2) prime manual focus lens.

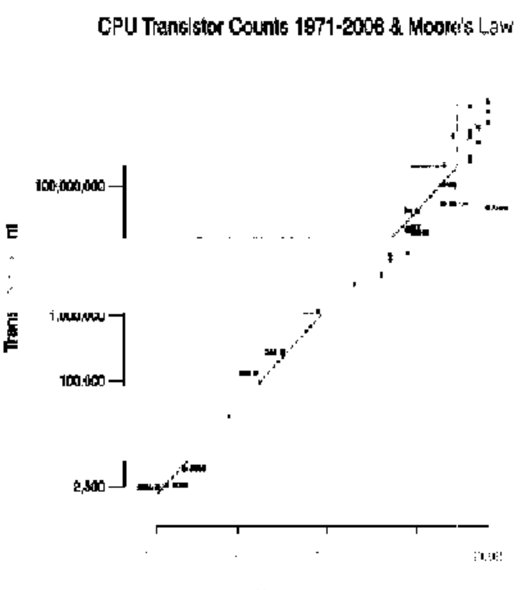

Figure 3: Plot of Moore's Law data, found on Wikipedia; see URL above.

In order to predict historic film resolution back to the beginning of film (1889) and slightly before (commercial silver-gelatin on glass plates began about 1875/78), published data was gathered and analyzed. The relevant data was entered into a database, from which Table 4 was created. Over the 65 years of published film resolution data, the resolution of film doubled 1.2 times, for a "resolution-doubling" cycle of 58-years.

Gordon Moore co-founder of Intel postulated in 1965 that the number of transistors in a computing chip (CPU) would double every two years; this proved to be correct. Moore's Law http://en.wikipedia.org/wiki/Moore's_law was used to estimate the resolution performance of analog imaging media back to 1878; see Figures 16 (p 18) and Fig. 17 (p 24). Moore's Law is exponential, but linear on a semi-logarithmic scale.

Mathematical regression technology was employed to predict historic film performance based on modern data; see Section 5 on pages 15-16. Using these predictions, technicians can make well-educated estimates of the on-film image resolution of historic negatives. This information is invaluable when determining the digital capture resolution needed to migrate images from analog film into the digital domain. Remember to employ the Nyquist Sampling Theorem when setting the digital sampling rate (pixels per inch). Nyquest says to use at least twice the analog resolution when capturing in the digital domain; see Section 7 on p 22.

Two methods of predicting on-film image resolution are provided in Section 6 on page 17. The methods are (1) **RPE method** (more complex and accurate) and (2) the simplified **Easy method**. On the bottom of page 22, two widely different results were produced by the complex RPE method and the simplified Easy method, using a real world 1906 film example. The simplified method yields an on-film image resolution estimate of about 615 ppi, while the more precise method yields an estimate of 1154 ppi. The 88% 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) when using the RPE method.

2 - System Resolving Power Equation (RPE)

There are many factors rolled onto the system resolving power equation (RPE). A "system" is the complete photographic unit, (a) camera [lens axis to film plane alignment], (b) lens, (c) film/media and (d) processing. In to the basic RPE [EQ2] there is one term (1/r) is for the media and another (1/r) for the lens. Adding a print to the system [EQ1] will add a third term for the enlarging lens and a fourth for the printing paper. Making a print from a negative profoundly lowers the system resolution. 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 a wide lens aperture (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 13 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 almost-flat film planes and rigidly fixed lens-to-film axis. They will achieve generically better results than large format (LF) cameras that require the film and lens axis to be aligned for each series of exposures using a tool such as the Zig-Align. Figure 4 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, while low-resolution media suffer less by exposure through lower quality equipment. A more detailed version of Figure 4 is shown as Figure 7 on p 8.

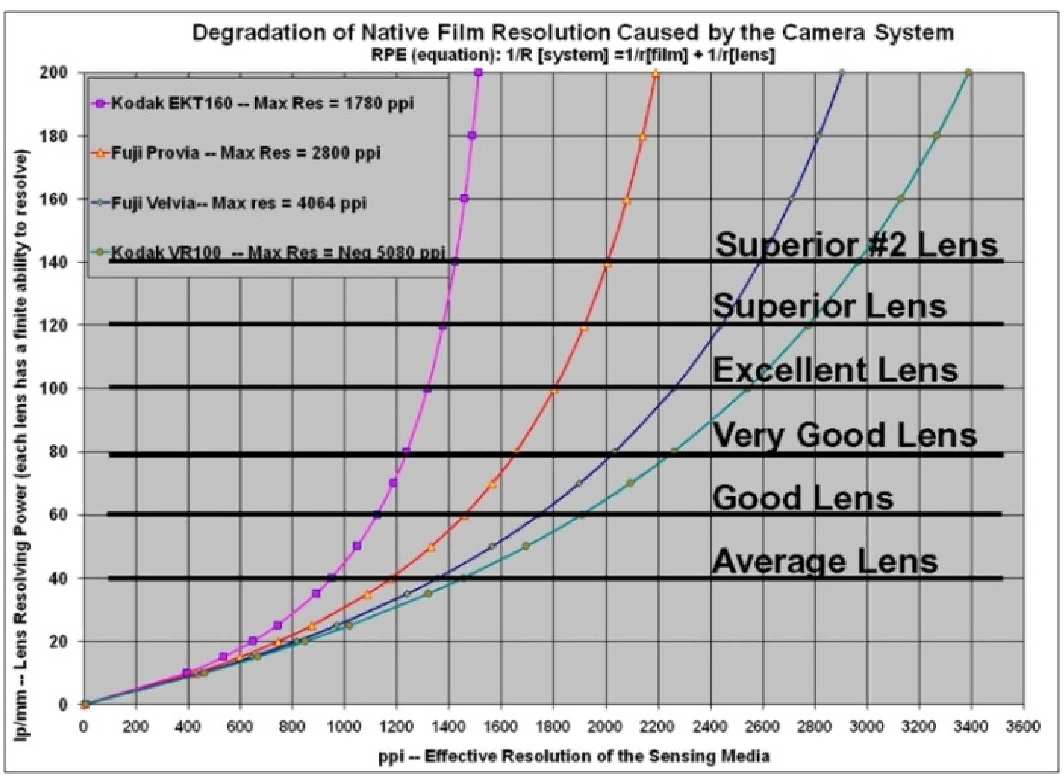

Figure 4: This plot shows the effects of lens quality (y-axis, vertical is lp/mm) on film resolution (x-axis, horizontal ppi of film). Four common films (listed above) are exposed through the theoretical lenses listed above them using the Fuji RPE. The graphic shows that poor quality lenses have a huge 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 (glass plates, 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 rare, exceptional lens, which 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, Nikon, Zeiss or Leica. The Canon EF 50/1.4 USM prime has a street price of $360-400. Standard lenses can be had for $100-125, but a modest $380 buys a lot of resolution. The history of lens design and technology is on pp 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.

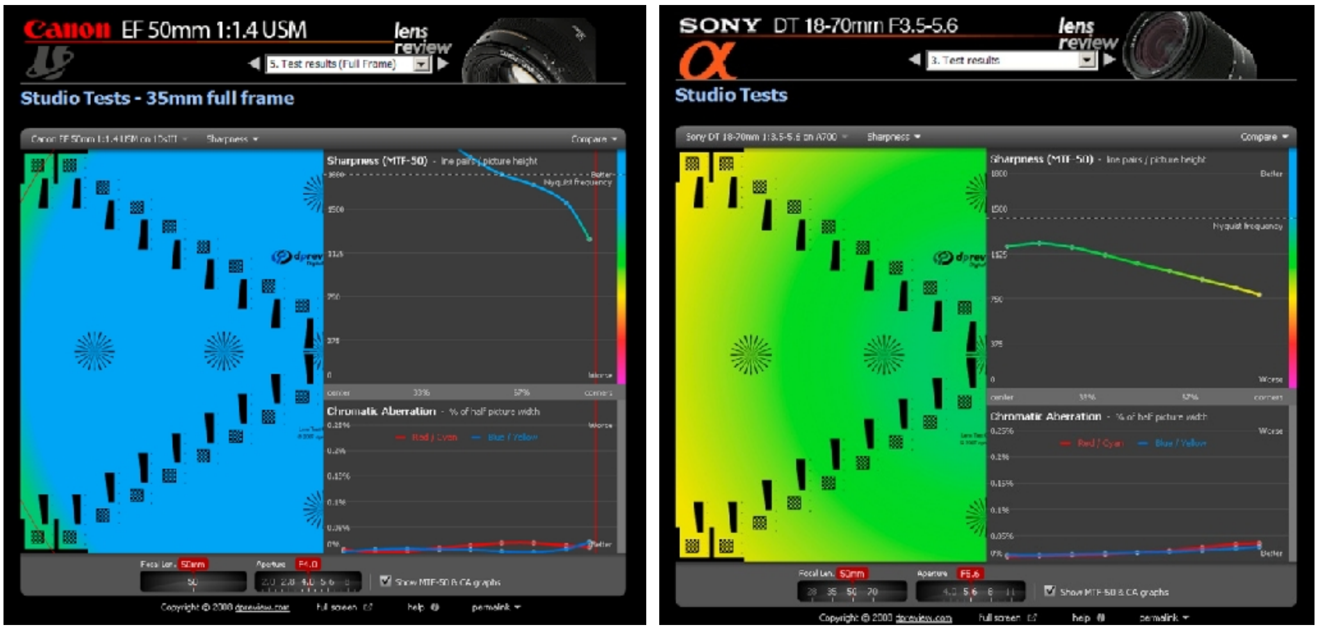

Figure 5a & 5b: Performance of Prime vs Zoom lens. Screen shot from <dpreview.com> website on the left evaluates a Canon 50/2 EF prime lens at f4 (sweet spot) revealing superior performance, on the right, <dpreview.com> evaluates a Sony Alpha (Minolta) 18-70mm/f3.5-5.6 DT zoom lenses, set at 50mm & f5.6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

On the digital camera review website http://www.dpreview.com, their lens evaluation tool has a wealth of information condensed into an interactive graphic; see Fig 5a & 5b 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 66-75% out from the center (0), at 15 (mm), on the horizontal axis of the MTF chart (in the Figure 6a & b 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 6b, its 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 6 (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.

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 a minimum of 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 is a critical tool for evaluating lenses; it is well explained at http://www.photozone.de/3Technology/mtf.htm and http://www.normankoren.com/Tutorials/MTF.html. There is a wealth of resolution information on the web, Google: MTF lens.

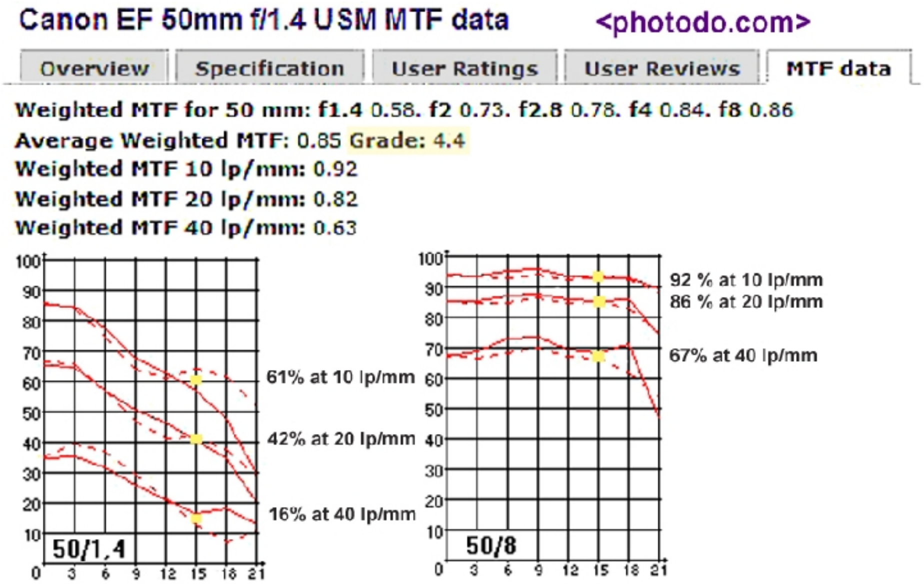

Figure 6a: Shows MTF data for the Canon EF USM 50/1.2 prime lens. The figure was constructed from the <photodo.com> website, showing their (older) MTF data. . The y-axis of the MTF plots shows residual contrast between line pairs, while the horizontal axis shows distance (in mm) from the center of the lens' front element. Note that wide-open performance plot (left, of the pair) is much worse than stopped down to f8 (right, of the pair). While the performance at f/8 for both Canon lenses is virtually the same, the wide-open performance is far superior for the Canon 85/1.2.

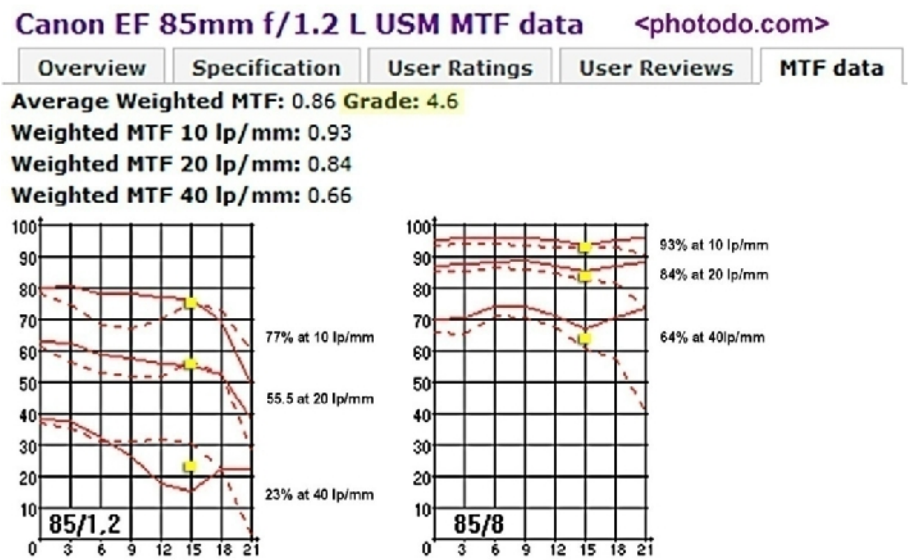

Figure 6b: Shows MFT data from the <photodo.com> website from the Canon 85/1.2 prime lens. It was given a very high grade of 4.6; only one lens is given a higher rating of 4.8, the Canon EF 200f/1.8 USM. The 85/1.2 lens performs better than the fabled Canon 50/1.4. The y-axis of the MTF plots shows residual contrast between line pairs, while the horizontal axis shows distance (in mm) from the center of the lens' front element. Note that wide-open performance plot (left, of the pair) is much worse than stopped down to f8 (right, of the pair. The wide-open performance is superior to the 50/1.4.

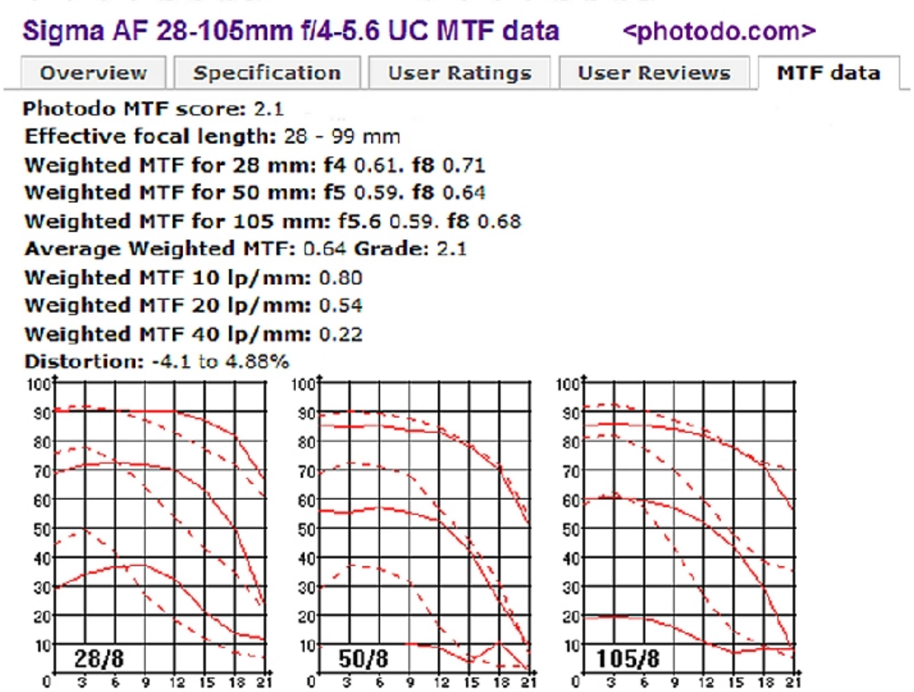

Figure 6c: Shows MFT data from the <photodo.com> website for the Sigma AF 28-105 zoom lens. Note that the data shown is for f/8; at larger f-stops, the performance is far worse. The lens is only rated at 2.1. This is not the lowest score possible (0.9) but quite low. The point being made by the inclusion of this lens in this series of lenses with superior performance is to (a) show a second-tier lens, (b) a zoom lens and (c) the normal drop-off of resolution towards the edge of the lens.

Figure 7a, taken from the Norman Koren website, shows the effects of imposing media, lens and then both on the contrast of black-and-white line-pairs. 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.

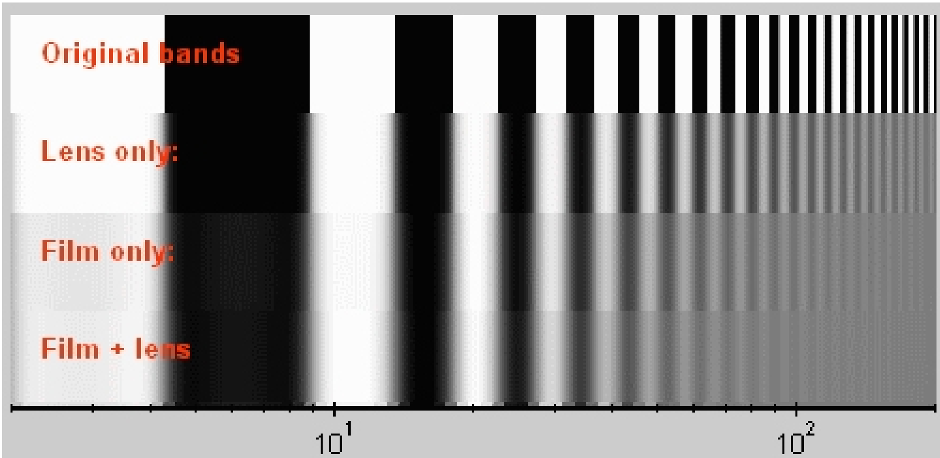

Figure 7a & 7b: Fig 7a shows Norman Koren graphic on the change contrast between black and white line-pairs decreased by the lens, film and then both (the system - in the camera). Fig 7b shows a glass USAF 1951 resolution target used for evaluating the native film resolution.

Another method of evaluating lenses is to use USAF resolution targets, see Figure 7b. 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 use much more glass to cover the 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 circle of 145-165 mm. The difference in image circle area ($A = \pi \cdot r^2$) is between 1,500 mm^2 and 20,000 mm^2.

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 8 depicts a lens rated at 1000 lp/mm (impossible to achieve). Kodak VR100 (100-lp/mm or 5080 ppi) only reached 90% of its native resolution (4600 ppi). Kodak EKT 160 (35-lp/mm or 1780 ppi) performed best, because lower resolution films are least harmed by poor lens performance.

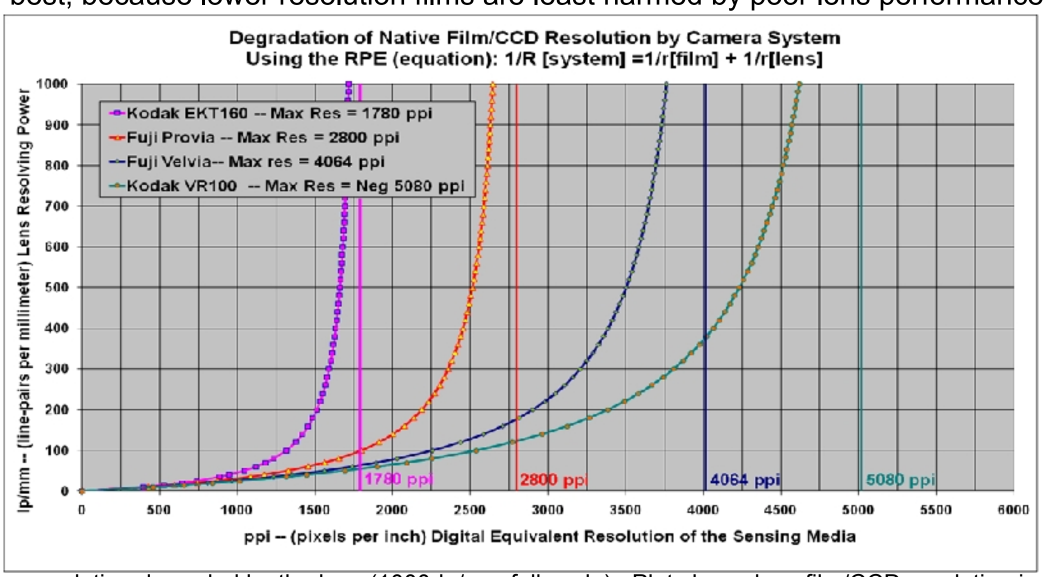

Figure 8: Film resolution degraded by the lens (1000-lp/mm full scale). Plot shows how film/CCD resolution is degraded by the lens used. Even a theoretical lens, with 1000 lp/mm resolution (top of plot), can never deliver all the native resolution capabilities of the film/CCD. Note that the bold vertical 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 is 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).

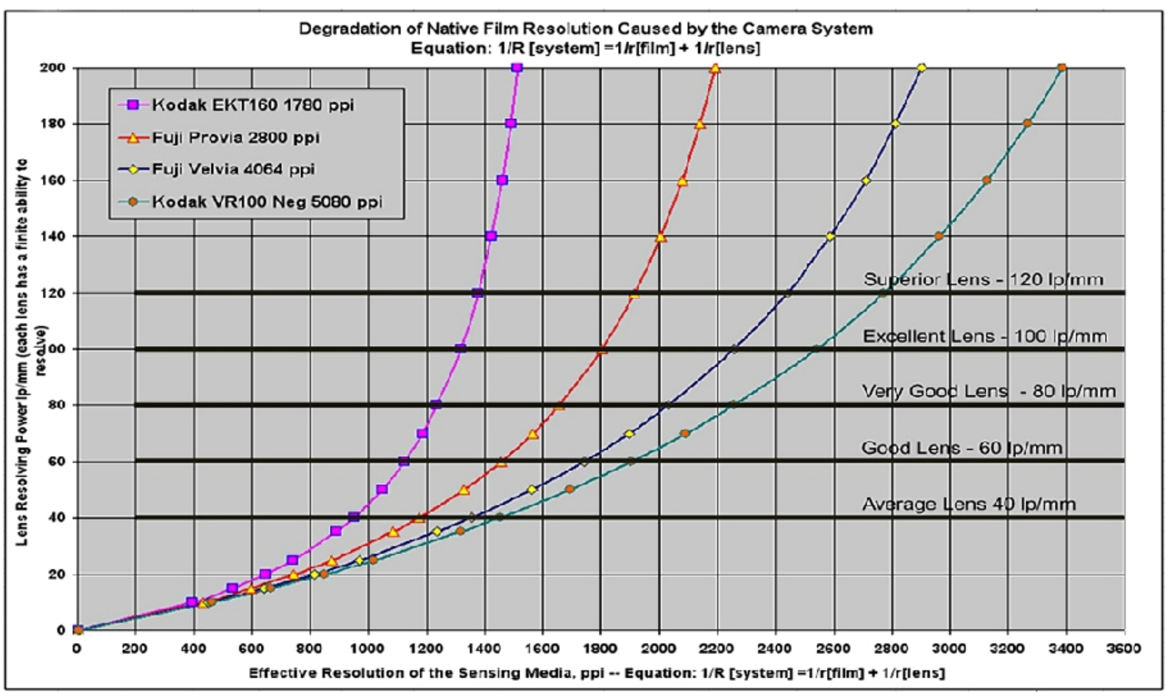

Figure 9: Media (Film or CCD) resolution degraded by the lens. Effects of lens quality on films with increasing native resolution (highest on right: teal colored line). The data points in the plot are the System Resolution calculations for the combination of film and lens; see Table 2 (p 5) for numbers. 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.

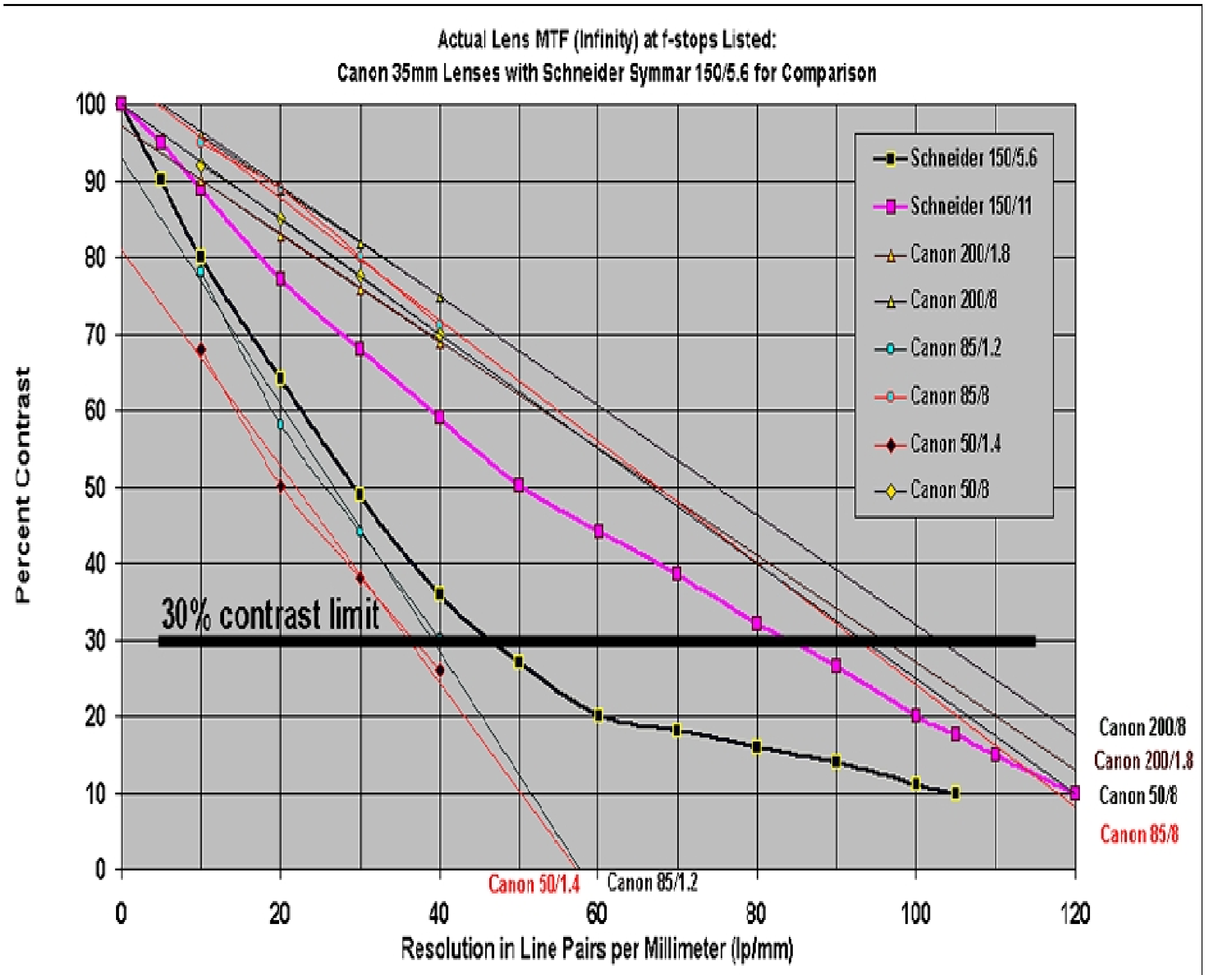

Figure 10: Lens MTF plots: Canon 35-mm format lenses; affects of lens quality on native film resolution. Canon prime lenses (not the smaller "digital format" lenses) have an image circle of about 1.5" compared to a Schneider Symmar APO 150 mm f5.6, large format lens have a 6.5" image circle. The performance 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 no higher. Figures 6a & b 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.6a & b) 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 9 &

10. It's possible that the Canon prime lenses deliver as much as 120-130-lp/mm when used at their optimal f-stop.

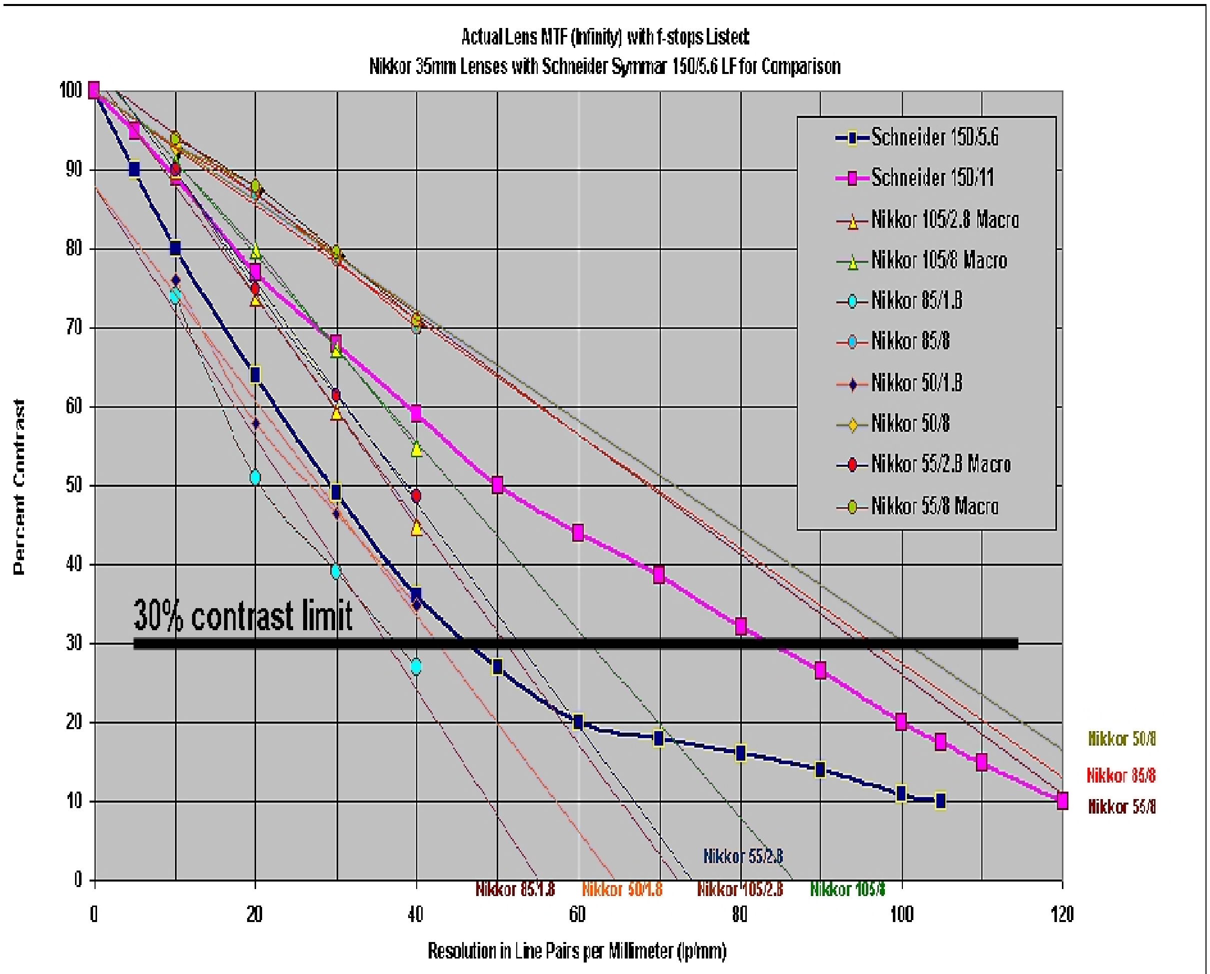

Figure 11: Lens MTF plots: Nikon 35-mm format lenses. Nikkor 35-mm format lenses (not the smaller digital format lenses) which have an image circle of about 1.5" compared to the Schneider Symmar APO 150 mm, f5.6, large format lens have 5-6" image circle. The performance in the center of the image circle 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 90-110-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: prime lenses, such as 35mm, 50mm and 85mm, from first-tier manufactures such as Canon, Nikon, Zeiss or Leica generally have similar behavior, as can be seen in Figures 10, 11 & 14. This is not true of second-tier manufacturers (aftermarket lens) such as Cosina, Sigma, Tamron, Tokina, etc. Browse the <photodo.com> website for MTF lens data (far right column on the list page) 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 to 3.5), while first-tier lenses are generally the only ones rated 3.6 to 4.8. Some first-tier lenses will be rated below 3.6, but they will usually wide-angle, medium telephoto 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).

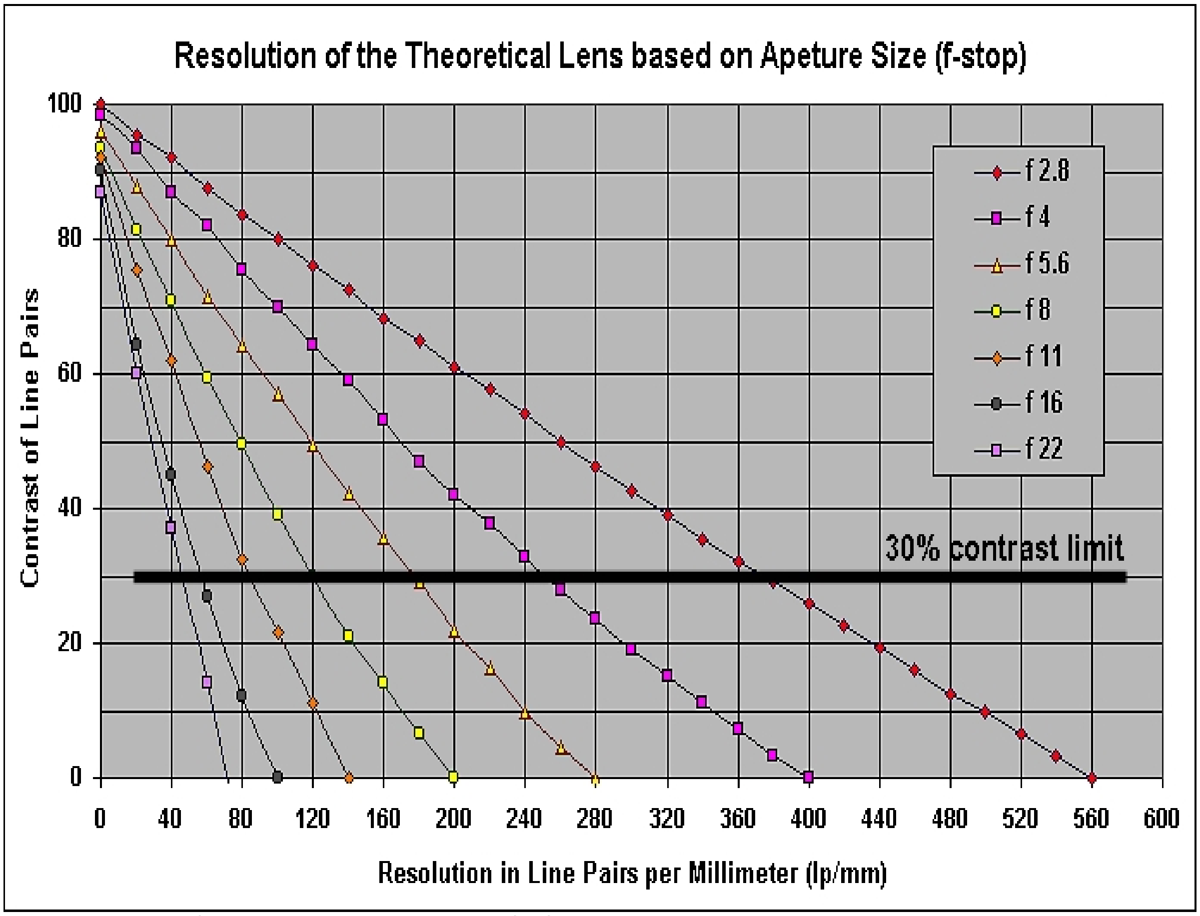

Figure 12: Behavior of a theoretical lens at specific f-stops.

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.

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.

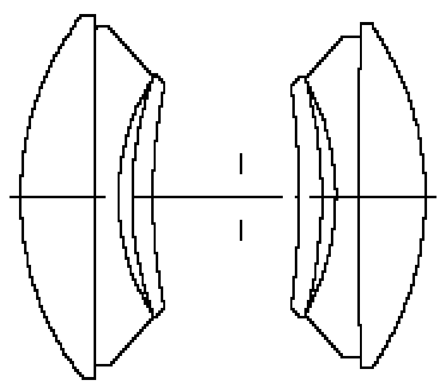

Figure 13: Cross-section of Schneider APO Symmar 150/5.6 film lens; designed before the flat field digital era.

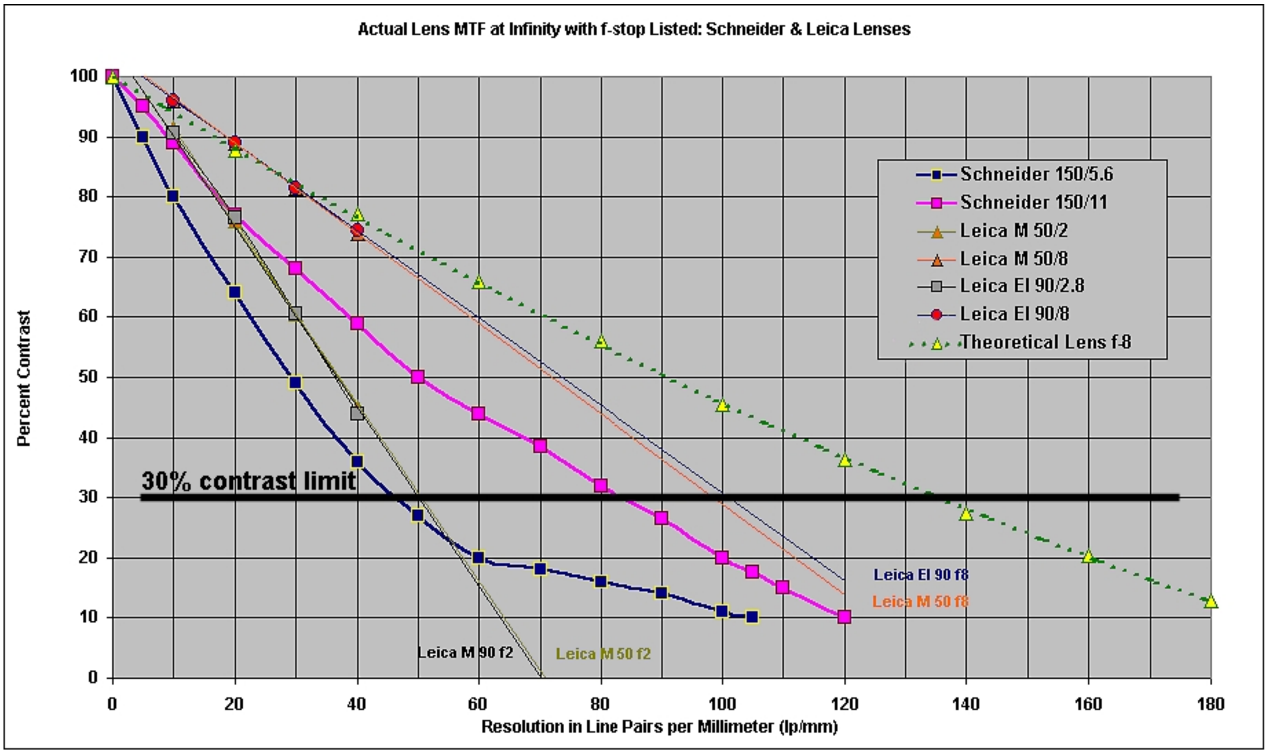

Figure 14: Comparison large format and small format (35-mm) lenses; shows a comparison of high quality large format (LF) and high quality small format (35-mm) lenses at the ideal f-stop (f 8 & f11) and wide open (f 2-2.8) with a theoretical lens at f-8.

The relative performance of large and small format lenses can be seen in Figure 13. Because the glass in large format lenses is so much bigger, 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 (four 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 Images

The author has been collecting data on film for a few decades. There is no technical data on film resolution before about 1935-38. The need to understand the performance of early film comes from the capture of analog images digitally. Using published technical data (1935-2005), a method of predicting past (1870-1935) technological performance was developed using Moore's Law.

Discussion

A table of film data was compiled; see Table 4 on page 14-15. The films were sorted and then averaged into historic-era groups based on the date-of-manufacture information:

(1) **1940-period** (1935-45) 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 1935 to 1969 period has film resolution data, but it is reported based on resolution targets, an antiquated system that is not preferred today. The early resolution data has great value to this study, so it was adopted without modification.

If one looks back to the 1946 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.

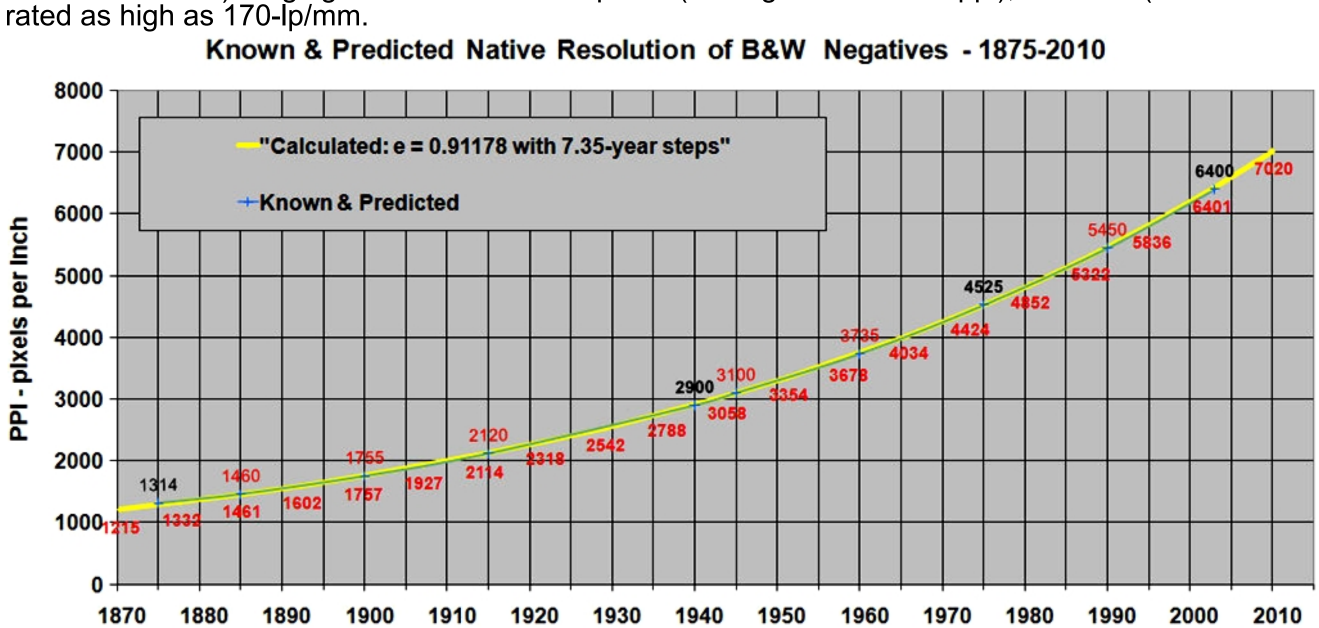

Figure 15: Predicting Resolution of Historic Film, based on the Rate of Technological Change defined by Moore's Law using **known average values** from 1940 (2900 ppi), 1975 (4525 ppi) and 2005 (6400 ppi). Over the 65-year period, the native resolution of the film doubled every 58 years, or 1.2 times from 1940 to 2005. Note that the blue curve (Known & Predicted values) perfectly bisects the yellow curve (calculated). The 3 known film resolution points are in **bold typeface**, while the values predicted using curve fitting are in red above the curve. The calculated values are in red below the line.

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

(1) 55-lp/mm* (2794 ppi) in 1939 *Kodak Film: Data Book on Negative Materials* (15¢)
(2) 100-lp/mm* (5080 ppi) in the 1947 version of the same data book (35¢)
(3) 95-115lp/mm* (4750-5842 ppi) in 1956 *Kodak Data Book on Films* listed as "high" resolving power
(4) 136-225-lp/mm* (6908-11430 ppi) 1965 *Kodak Advanced Data Book* (50¢) listed as "very high"
(5) 170-lp/mm (MTF data) (8636 ppi) in 1976 Kodak book on *B&W Professional Films* (F-5, $5.95)
(6) NA, not listed in the 1984 version of Kodak 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.]

It is clear that one film does not track on the curve in Figure 15, and that some of the published data was either wrong or optimistic. Thus, averaging groups of data was the better methodology choice.

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 adopted as 58 years, and broken down into 8 steps of 7.35 years, and applied through the full range of 135 years (1875 to 2010) in 19 increments. The curve in Figure 15 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 notes or proprietary publications that were never revealed to the public allowing for greater precision in the estimates of early film resolution.

The smoothness of the plot on the right side of the curve (late tranche), with its seamless projection into the past (left side) suggests that this exercise has value. Note that the middle value of 2900 fits very neatly on the (x^e = 0.9118 in 7.35 steps) curve.

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 3. 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 that is best-determined using direct measurement by the manufacturer (MTF). Image resolution 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 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.

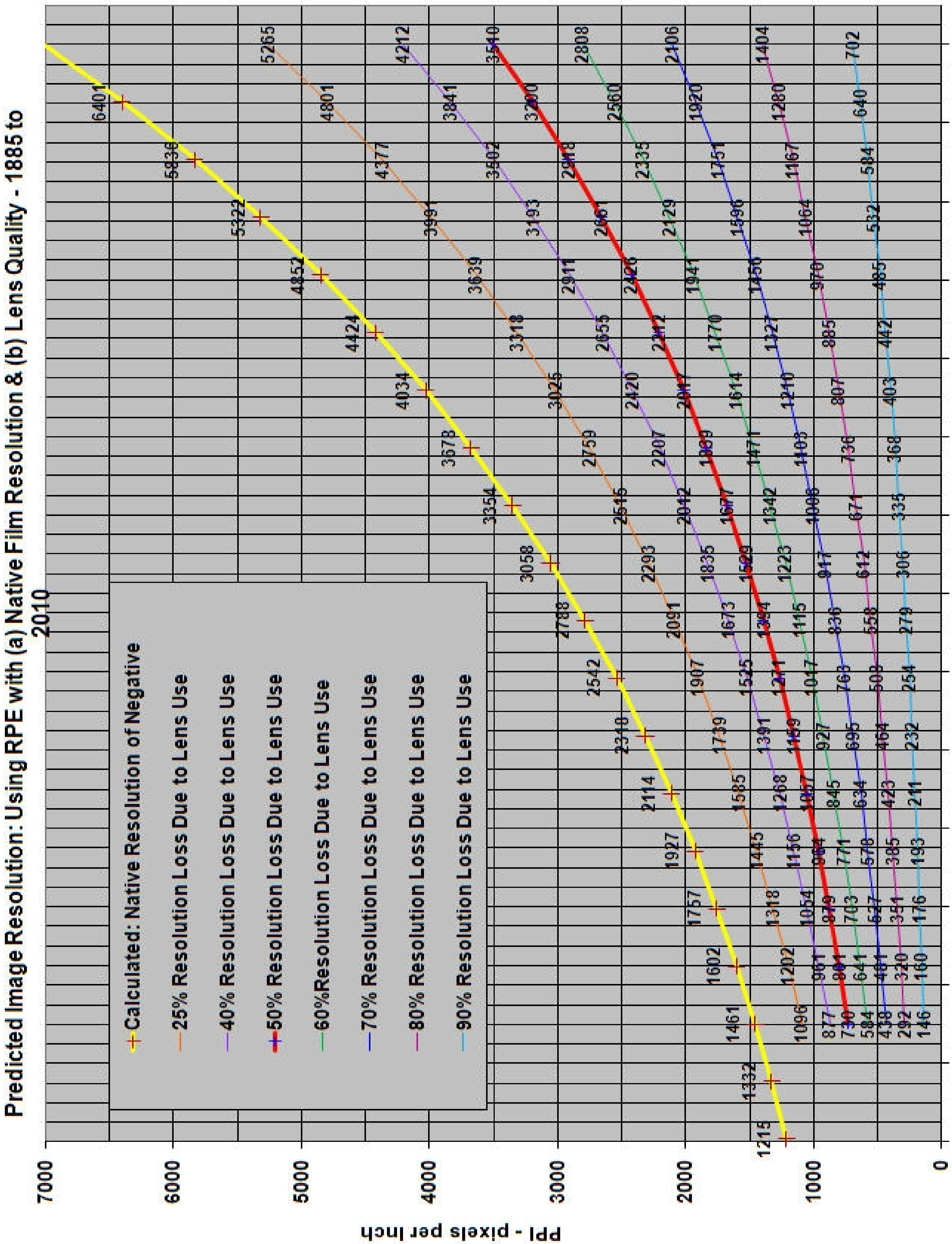

Figure 16: The set of curves predicts image resolution of B&W negatives from 1885 to present (film was introduced by Kodak in 1889). The yellow curve is the native resolution of the negative; component used for calculating Image Resolution using the RPE. Lens quality is the other component used in the RPE. The series of colored lines below the bold yellow line represent the actual "on-film" image resolution at various lens qualities. Note that a lens with resolution equal to film will fall along the 50% Resolution Loss Due to Lens Use line (red with blue crosses). The data is reported in PPI (pixels per inch), which is used to facilitate digital scanning; PPI is converted to lp/mm by diving with 50.8 [PPI/50.8 = lp/mm].

Small format (35-mm) photography will tend to have better lens quality (60-100-lp/mm). Generally, this is because many SLRs were sold with their high resolution standard 50mm lens (standard for 35-mm SLR about 100-lp/mm), or, were used 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 format lenses, lowering overall resolution by 15-30%. Numerous MF systems are built around Mamiya lenses; in general, they are comparable to lenses used with Hasselblad systems, but users report higher satisfaction with Mamiya. 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 good one is 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 body, 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 35-mml format lenses, yielding about 60-100-lp/mm performance. This is borne out by an average of one-full-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 1966-1970's era often used inexpensive Rolleiflex-knockoffs (Yashica or Seagull) that were 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- 100-lp/mm), while the resolution falls off markedly towards the edge (20-60-lp/mm) that is an inch, or more, from the center of the lens. An overall rating for lens resolution in 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 MF camera. However, most used the Kodak brand point-n-shoot (PnS) cameras 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 only about 20-lp/mm. At the turn-of-the-century, advanced amateurs began using folding cameras with the superior Goerz Dagor lens, which was capable of up to 40-55-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. Many consumer PnS cameras use optical plastic lenses. In all cases, image quality of amateur systems was hampered by handholding 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 that 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 is still used in use in low cost applications. The noted Chevalier Achromatic lens (1835) also used two cemented glass elements made with different glass formulations; the innovation was to focus in a flat field. Daguerre officially adopted the lens in 1839 and it still gets heavy use 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." An explanation offered was, 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 from the glass up.

By 1841, Petzval designed the 4-element achromatic portrait lens, which became a photographic standard used through middle of the 20th century; thought to be capable of 20-30 lp/mm. It had a long shape due to a large air gap, and thus couldn't be used in amateur cameras that 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 the technology didn't reach the Allies until after the war. 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 penultimate lens-development cycle, beginning about 1960-65 http://en.wikipedia.org/wiki/Anti-reflective_coating. Small format lens makers were the early adopters of multi-coatings, while it took through the 1980s for the large format lens makers to implement multiple 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). The current lens development cycle is reemphasizing glass composition, last seen during the turn of the twentieth-century, this time exotic lens element shapes are being made using molding and hybrid processes, rather than the more expensive grinding process, allowing computer aided designs not thought commercially viable, possible.

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 and Table 2 (System Resolving Power Data Table) on p 5, 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 up to 90% loss of native resolution for very old equipment. 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 & 2¼”x2¼”, 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) in Figure 15, use the date to pick-off the film’s native resolution
(2) in Table 7, (On-film Resolution Estimator) use closest date to determine native film resolution
(3) 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
(2) based on either Table 5 (Lens Resolution Estimator) base on date and film format

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 = reciprocal)
(3) calculate the reciprocal (1/r) of the lens resolution (1 ÷ lp/mm value = reciprocal)
(4) run the RPE (EQ2: $1/R_{[system]} = 1/r_{[media]} + 1/r_{[lens]}$) to yield the System Resolution [1/R]
(5) divide R value into 1 [1 ÷ R] to yield the resolution of the system, or on-film image resolution

Example (1970-film): using a B&W film from 1970, this 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) 4104 ppi is 81 lp/mm (410400 ÷ 50.8 = 80.8), where [ppi value ÷ 50.8 = lp/mm]
(2) the reciprocal ($1/r_{film}$) of 81 is 0.012 (1 ÷ 85 = 0.123)
(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 (0.0123 + 0.010 = 0.0218)
(5) calculate the reciprocal (1/R) of R, which equals 46 lp/mm (1 ÷ 0.0223 = 44.8)
(6) calculate ppi value for the 1/R value, where [lp/mm x 50.8 = ppi value]
(7) the on-film image resolution is: 2286 ppi (45 x 50.8 = 2286) [44% 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 22.

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 Resolution Estimator (see also Table 9 in the Appendix)

1 Date	2 Native Resolution	3 25% loss due to lens	4 40% loss due to lens	5 50% loss due to lens	6 60% loss due to lens	7 70% loss due to lens	8 80% loss due to lens
1885	1460	1095	876	730	**584**	**483**	292
1900	1755	1316	1053	878	**702**	**527**	351
1915	2120	1590	1272	**1060**	**848**	**636**	424
1940	2900	2175	**1740**	**1450**	**1160**	**870**	**620**
1945	3100	2325	**1860**	**1550**	**1240**	**930**	775
1960	3735	**2801**	**2241**	**1868**	**1494**	**1121**	747
1975	4525	3400	**2715**	**2260**	**1810**	**1358**	1130
1990	5450	4088	3270	**2725**	**2180**	**1635**	1090
2003/5	6400	4800	3840	**3200**	**2560**	**1920**	1280

Additional Examples using the "Easy method"

1915 Film – The average film from 1915 has a resolution of 2120 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 742 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 1755 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 615 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 1926 ppi (38-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 [**$1/r_{[film]}$ (0.026) + $1/r_{[lens]}$ (0.018) = $1/R_{[system]}$ (0.044)**] would produce the result of 23-lp/mm or 1154 ppi (digital equivalent). Using a 4-times digital sampling rate (Nyquist), a scanner set at 4800 ppi resolution would yield excellent digital capture results.

8 - Bibliography & Further Reading

The data used in Table 4 was pulled from the following:

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Eastman Kodak. Kodak Film: Data Book on Negative Materials. 1939, 55 pp (15¢)

Eastman Kodak. Kodak Film: A Data Book on B&W Negative Materials. 1941, 59 pp (25¢)

Eastman Kodak. Kodak Films. 1947, 4th ed., 72 pp (35¢)
Eastman Kodak. 1956 Kodak Data Book: Kodak Film for B&W Photography. 1956, Pub F-13, 7th ed., 68 pp (50¢)
Eastman Kodak. Kodak Advanced Data Book: Kodak Film in Rolls for B&W Photography. 1965, Pub F-1, 7th ed., 68 pp (75¢)
Eastman Kodak, Kodak Color Dataguide: Exposure/Printing/Processing. 1969, R-19, 44pp ($5.95) [no film resolution data]
Eastman Kodak, Kodak Professional B&W Films, 1976, Pub F-5, 60 pp. ($5.95) [first use of MTF data]
Kodak. Kodak Films Color and B&W. 1978, Pub AF-1, 163 pp ($3.95) [word resolution descriptors]
Kodak, Eastman Professional Motion Picture Films, 1982, Pub H-1, ($9.95) [no film resolution data]
Kodak. Kodak Films Color and B&W. 1985, Pub AF-1, 200 pp ($8.95) [word resolution descriptors]
Kodak. Kodak Films and Papers for Professionals. 1984, Pub F-5, 86 pp. ($8.95) [low & high contrast target data]
Kodak. Kodak Films and Papers for Professionals. 1986, Pub E-77, 132 pp. ($12.95) [MTF data]
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FujiFilm. Professional Data Guide. 1998, Pub AF-3[?], 102106 pp. (Free) [MTF data]
FujiFilm. Professional Data Guide. 2000, Pub AF-3, 118/122 pp. (Free) [MTF data]
FujiFilm. Professional Data Guide. 2002, Pub AF-3, 131 pp. (Free) [MTF data]
FujiFilm. Professional Data Guide. 2003, Pub AF-3, 129 pp. (Free) [MTF data]
Fuji, Professional Products website, film data sheets http://home.fujifilm.com/products/datasheet/.

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Lester, HM. Photo-Lab Index, 1946, 8th ed., many thousand pp. Morgan & Lester Publishers.
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Vitale, TJ. Film Grain, Resolution and Fundamental Film Particles. v23 (2009). http://videopreservation.conservation- us.org/library/film_grain_resolution_and_perception_v24.pdf.
Vitale, TJ. Brief History of Imaging Technology. v 16 (2009) http://videopreservation.conservation-us.org/library/brief_history_of_imaging_technology_v16.pdf.

9 - Appendix

Table 8: Data Table for **Known & Predicted** values for the native resolution of Negatives (film and commercial glass plates). Figure 16 (below) was made from this data table.

Age of Negative Year	Resolution lp/mm*50.8 PPI	Resolution PPI/50.8 lp/mm	Lens Loss 20%	Lens Loss 25%	Lens Loss 30%	Lens Loss 40%	Lens Loss 50%	Lens Loss 60%	Lens Loss 70%	Lens Loss 80%	Lens Loss 90%
2003	6400	126	5120	4800	4480	3840	3200	2560	1920	1280	640
1990	5450	107	4360	4088	3815	3270	2725	2180	1635	1090	545
1975	4525	89	3620	3394	3168	2715	2263	1810	1358	905	453
1960	3735	74	2988	2801	2615	2241	1868	1494	1121	747	374
1945	3100	61	2480	2325	2170	1860	1550	1240	930	620	310
1940	2900	57	2320	2175	2030	1740	1450	1160	870	580	290
1915	2120	42	1696	1590	1484	1272	1060	848	636	424	212
1900	1755	35	1404	1316	1229	1053	878	702	527	351	176
1885	1460	29	1168	1095	1022	876	730	584	438	292	146
1875	1314	26	1051	986	920	788	657	526	394	263	131

Date in red indictes predicted values based on curve fitting, following the pattern set by the known data points in bold black.
Data in Bold Black typeface indicates that thes are the know values based on 11-13 samples avaraged
Use of this cell color Indicates that data in these cells was not plotted on graph.

Table 9: The data table is used for Figures 1 and 15.

58	Cycle for doubling of resolution										
7.35	Step, years per step										
0.9118	Factor (multiplier applied to each step)										
7.9	Steps per Cycle										
2010	Start Year										
Cycle	Resolution	Resolution									
7.35	0.9118	PPI/50.8	Lens Loss	Lens Loss	Lens Loss	Lens Loss	Lens Loss	Lens Loss	Lens Loss	Lens Loss	Lens Loss
Year	PPI	lp/mm	20%	25%	30%	40%	50%	60%	70%	80%	90%
2010	7020	138	5616	5265	4914	4212	3510	2808	2106	1404	702
2003	6401	126	5121	4801	4481	3841	3200	2560	1920	1280	640
1995	5836	115	4669	4377	4085	3502	2918	2335	1751	1167	584
1988	5322	105	4257	3991	3725	3193	2661	2129	1596	1064	532
1981	4852	96	3882	3639	3397	2911	2426	1941	1456	970	485
1973	4424	87	3539	3318	3097	2655	2212	1770	1327	885	442
1966	4034	79	3227	3025	2824	2420	2017	1614	1210	807	403
1959	3678	72	2943	2759	2575	2207	1839	1471	1103	736	368
1951	3354	66	2683	2515	2348	2012	1677	1342	1006	671	335
1944	3058	60	2446	2293	2141	1835	1529	1223	917	612	306
1937	2788	55	2231	2091	1952	1673	1394	1115	836	558	279
1929	2542	50	2034	1907	1780	1525	1271	1017	763	508	254
1922	2318	46	1854	1739	1623	1391	1159	927	695	464	232
1914	2114	42	1691	1585	1480	1268	1057	845	634	423	211
1907	1927	38	1542	1445	1349	1156	964	771	578	385	193
1900	1757	35	1406	1318	1230	1054	879	703	527	351	176
1892	1602	32	1282	1202	1122	961	801	641	481	320	160
1885	1461	29	1169	1096	1023	877	730	584	438	292	146
1878	1332	26	1066	999	932	799	666	533	400	266	133
1870	1215	24	972	911	850	729	607	486	364	243	121
1863	1107	22	886	831	775	664	554	443	332	221	111
1856	1010	20	808	757	707	606	505	404	303	202	101
1848	921	18	737	691	645	552	460	368	276	184	92
1841	840	17	672	630	588	504	420	336	252	168	84
1834	765	15	612	574	536	459	383	306	230	153	77
1826	698	14	558	523	489	419	349	279	209	140	70

MORE ON NEXT PAGE…

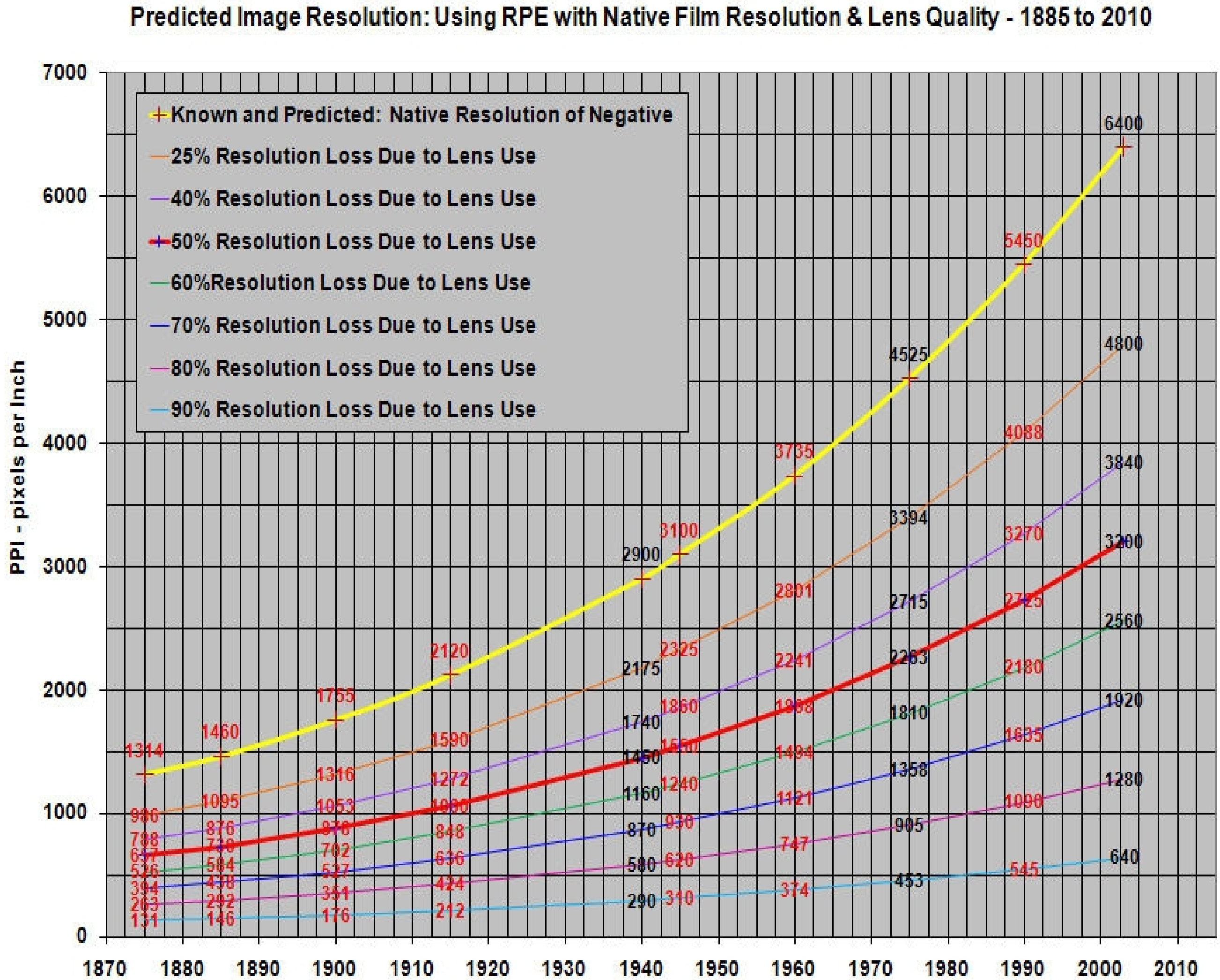

Figure 17: Predicted Image Resolution: Using RPE with Native Film Resolution & Lens Quality - 1885 to 2010. The set of curves predicts image resolution of B&W negatives from 1875 to present (film was introduced by Kodak in 1889; commercial gelatin glass plates use started in 1878). The data labels in bold black are the three known values for native film resolution calculated in Table4 and shown in Table 9 above. The data labels in **bold red** above the yellow curve were fitted to the curve based on the three known points; the data labels on the curves below were calculated from the known and curve-fit values. The yellow curve is the native resolution of the negative; component used for calculating Image Resolution using the RPE. Lens quality is the other component used in the RPE. The series of colored lines below the bold yellow line represent the actual "on-film" image resolution, at various lens qualities. Note that a lens with resolution equal to film will fall along the 50% Resolution Loss Due to Lens Use line (red with blue crosses). The data is reported in PPI (pixels per inch), which is used to facilitate digital scanning; PPI is converted to lp/mm by diving by 50.8 [PPI/50.8 = lp/mm].

Plots from the Film Resolution Database

The following two graphs are quite complex, they contain both raw data point and their individual mean(s), but the curve developed from the selected data shown in Table 4. The plots are snapshots made from an ever-expanding database of published film resolution, using data harvested from the publications shown in bibliography. At present (middle Dec 2009), there are 350 data entries from publications by Kodak, Ansco, DuPont, Defender (DuPont), Fuji and Ilford. As individual data, the points spread widely around the mean (bold curve). Eventually, it was found that averaging all the film resolution data in publications, or, averaging individual film (or plate) data sheets by their year of release, was the best method to tame the wide spreads. This is because the "mean," of the 12 to 20 films published, represents the manufactures full line of film and/or plates at that point in time. Where possible, microfilm data was added judiciously. More microfilm and plate data is being sought. At present, microfilm MTF data only extends back to 1984, while the MTF data on plates extend up to 1965 and not beyond. As out-of-print publications become available, the data will be added to the database. The microfilm data tends to skews the curve higher, while the MTF data on plates is generally lower that the mean for a particular year. The mitigating factor is that the MTF data for the microfilm is more reasonable (conservative) than that from the high contrast 1000:1 (USAF 1951) target or the very low contrast 1.6:1 target.

The other point to note is that the bold black line in Figures 18a and 19a is the data shown in the body of this essay as Figure 1, 15 and 16. The bold red line is the best exponential fit, to that data, of all the data in the Film Resolution Database. The difference between Figure 18a and 19a is that the former has the data massaged to fit the black line, while the latter is uncorrected data from the Database; note title of plot. The uncorrected is a lie as well, because it assumes that resolution data from all sources is identical. This is not so. The MTF data is vastly superior to any of the other data, which was derived from resolution targets such as the (1) USAF 1951 (1000:1 high contrast) target; (2) the 30:1 low contrast target; or the very low contrast 1.6:1 target. Prior to about 1965, (or 1976 when Table 4 was compiled) MTF data did not exist, and, prior to 1965 the "no target specified" designation was found in many publications.

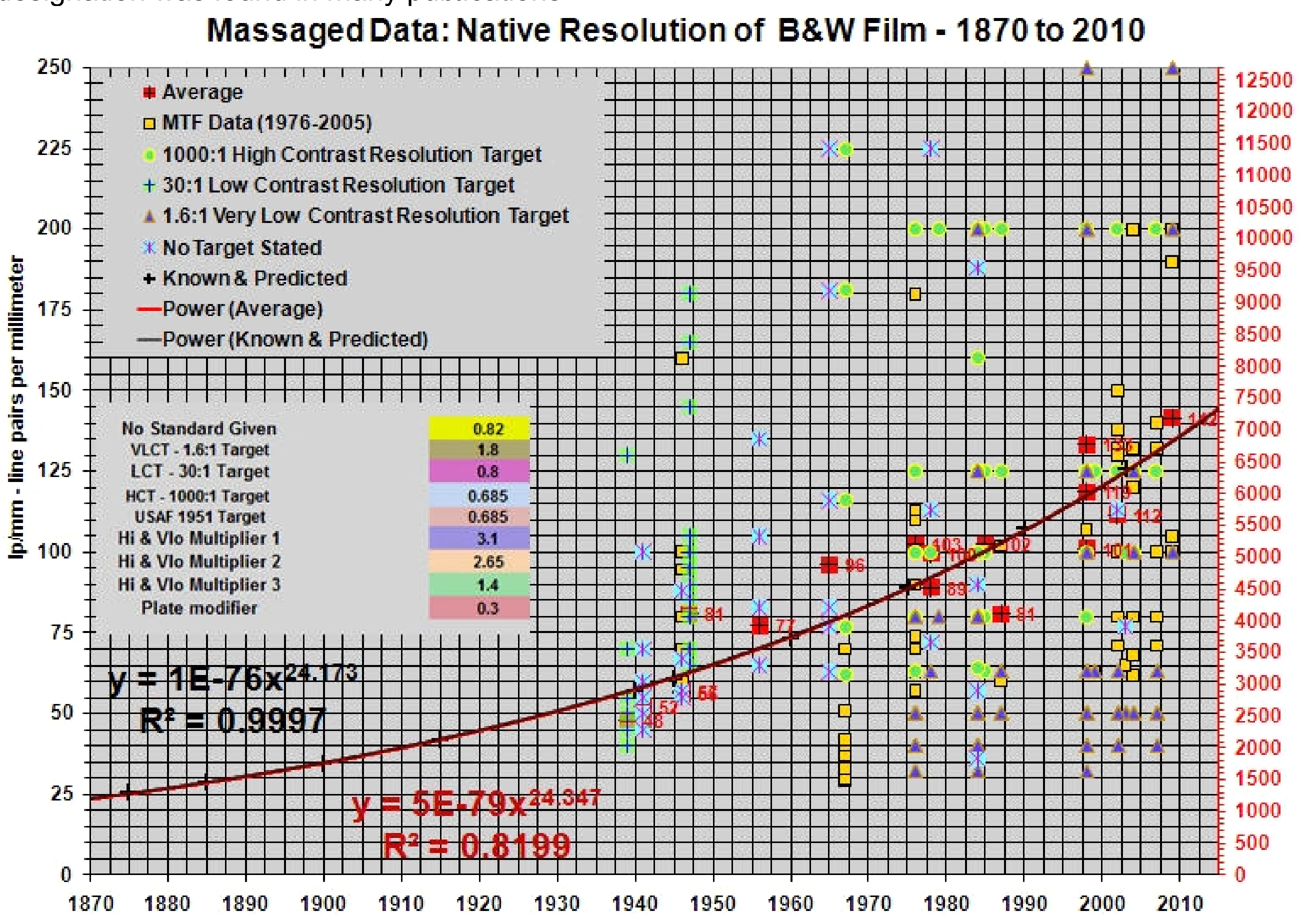

Figure 18a: Massaged Data: Native Resolution of B&W Film: 1870-2010, from plates & film data sheet and data book database. The plot shows an excellent manipulation of the various raw resolution-target data **multipliers** to yield a curve that is almost identical to the plot made from the three average groups (1940, 1975 & 2003/5) that was projected backwards in time using Moore's Law. It also shows the profusion of film resolution data (300+ items) contained in the database of historic films, ranging in date from 1935 to 2009. The red square with black cross symbol locates the average of a particular data group, which is defined by the source of the data such a Kodak, DuPont, Ansco or Ilford film data books. The **bold black line** shows the unaltered native film resolution plot found in Figures 1, 15 & 16; using Moore's Law to predict data regression. The **bold red line** represents the best fit through the data group averages, using an exponent-based equation ($y=2E-78x^{24.174}$); the formula is seen in the **bold red text** below the **bold red trendline**. The two lines are on top of each other, and are difficult to differentiate (in color it is a black line with a red halo). Note that the units used for the y-axis on the left are lp/mm (where lp/mm x 50.8 = ppi), while the units on the right side y-axis are pixels per inch (ppi), where ppi ÷ 50.8 = lp/mm (line-pairs per millimeters). The data multipliers used to modify the various target source are shown in Figure 18b below, and also in the legend of the chart in Figure 18a.

No Standard Given	0.82
VLCT - 1.6:1 Target	1.8
LCT - 30:1 Target	0.8
HCT - 1000:1 Target	0.685
USAF 1951 Target	0.685
Hi & Vlo Multiplier 1	3.1
Hi & Vlo Multiplier 2	2.65
Hi & Vlo Multiplier 3	1.4
Plate modifier	0.3

Figure 18b: In the column on the right are the multipliers used to modify the raw film resolution data extracted from various sources, which used a variety of resolution targets and MTF-plots harvested from film data books (and Plate & Film) and individual published film data sheets. There are five versions of the film resolution targets along with the **preferred** MTF data (determined at 30% contrast) or the terminal point for the plot line published in the MTF chart, which can range from 85% to 35% residual contrast, rather than extend down to at least 30% residual contrast. Where there are both High Contrast (1000:1) and Low Contrast (1.6:1) target data given for each film [but no MTF data given], a modifier is used to balance the target data to a more average datum. In most cases, the **Hi & Lo Modifier #1** is used, but for the earlier publications, the **Hi & Lo Modifier #2** works best. This is determined in the instances where the preferred MTF at 30% is also included for some or all the individual films [generally the MTF data is reported, unless less than a third of the films have MTF data].

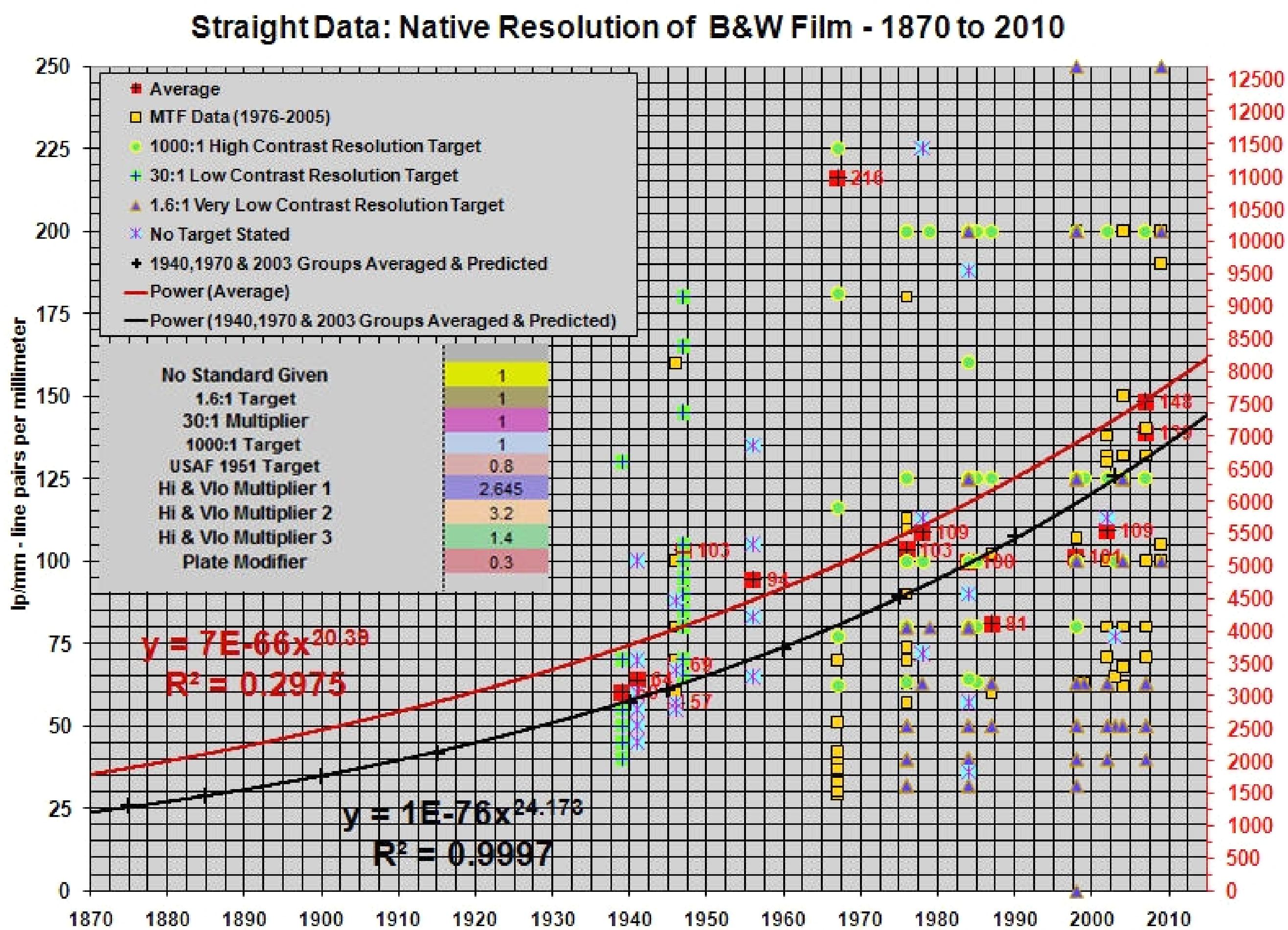

Figure 19a: Straight Data: Native Resolution of B&W Film: 1870-2010from plates & film data sheet and data book database. The plot shows the profusion of film resolution data contained in a database of 300+ historic films, ranging from 1935 to 2009. The red squares with black crosses show the averages of data groups defined by the source of the data such a Kodak, DuPont Ansco or Ilford film data books. The **bold black line** shows the plot found in Figures 1, 15 & 16. The **bold red line** represents the best fit through the averages using an exponent-based equation; the formula is seen in the **bold red**

text below the **bold red trendline**. Note that the units used for the left Y-axis are lp/mm (where lp/mm x 50.8 = ppi) and the right Y-axis uses pixels per inch (ppi), where ppi ÷ 50.8 = lp/mm (line-pairs per millimeters). Note the multipliers used to modify the various forms of data, seen in the lower right corner of the chart legend window (upper left corner). An enlargement of the "multiplier window" can be seen below in Figure 18b

No Standard Given	1
1.6:1 Target	1
30:1 Multiplier	1
1000:1 Target	1
USAF 1951 Target	0.8
Hi & Vlo Multiplier 1	2.645
Hi & Vlo Multiplier 2	3.2
Hi & Vlo Multiplier 3	1.4
Plate Modifier	0.3

Figure 19b: The multipliers used to modify the various forms of data used to compile the data sheet database. There are five versions of the film resolution targets along with the **preferred** MTF data (determined at 30% contrast) or the terminal point for the plot line published in the MTF chart, which can range from 85% to 35% residual contrast, rather than extend down to at least 30% residual contrast. Where there are both High Contrast (1000:1) and Low Contrast (1.6:1) target data given for each film [but no MTF data given], a modifier is used to balance the target data to a more average datum. In most cases, the **Hi & Lo Modifier #1** is used, but for the earlier publications, the **Hi & Lo Modifier #2** works best. This is determined in the instances where the preferred MTF at 30% is also included for some or all the individual films [generally the MTF data is reported, unless less than a third of the films have MTF data].

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Albumen Photography Website in 2000 <http://albumen.conservation-us.org>
VideoPreservation Website in 2007 <http://videopreservation.conservation-us.org>