Scanning and Recording of Motion Picture Film:

CRT Film Recording

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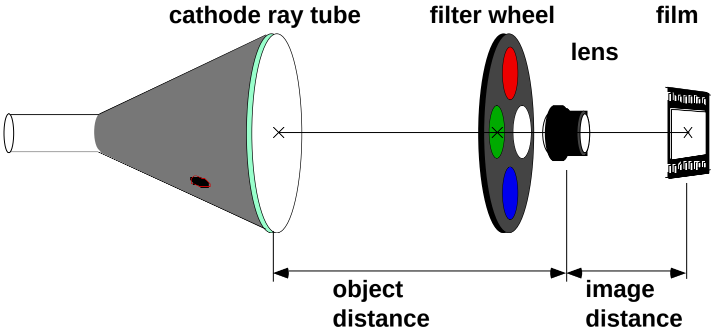
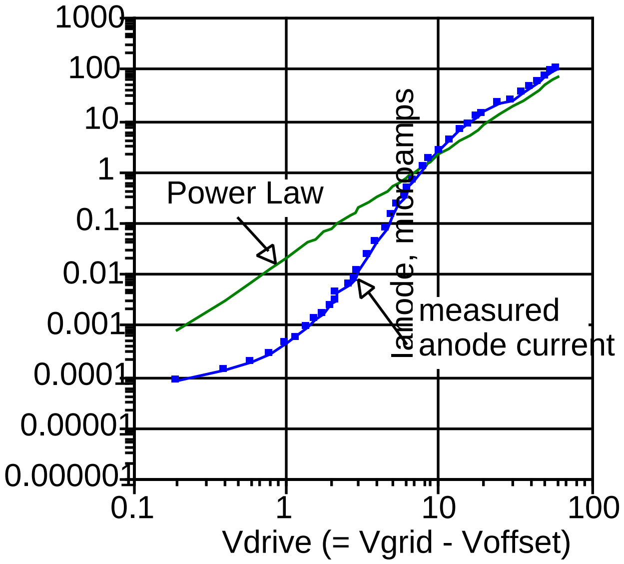


Typical CRT film recorder optical path. A diverse range of technology has been applied to the problem of recording images on film; CRTs are a dominant choice due to their relatively low cost. The four elements illustrated here are present in some form in all CRT-based film recording equipment. The demands on the writing system are high because the media, silver-based film, is so capable and its performance continues to improve.

	Laser	CRT
Deflection	galvo-mirror, polygon mirror	magnetic field
Modulation	crossed polarizers: $\mathbf{e} = \alpha \,\mathbf{sin}^2\, \mathbf{v}$ acousto optic modulators: $\mathbf{e} = \alpha\, \mathbf{v}$	CRT grid drive: $\mathbf{e} = \alpha\, \mathbf{v}^{\gamma}$

Comparison of laser and CRT image recording technology. Different light sources utilize different methods for controlling pixel placement (the raster) and pixel intensity. Lasers are intrinsically bright, but are difficult to scan and modulate. CRTs, using electron beams with essentially no mass, are easy to deflect, and the modulation is entirely electronic. Their lower brightness however, results in a throughput tradeoff.

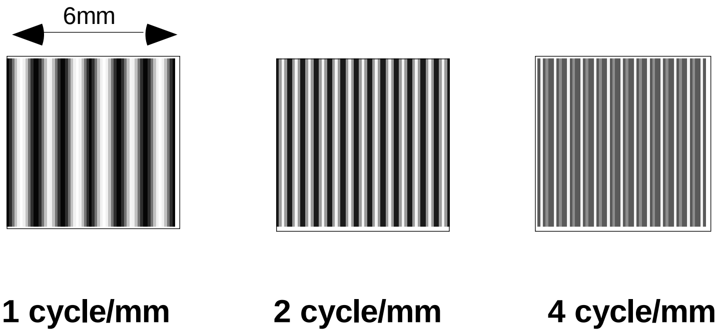


CRT transfer function. Although it is widely believed that CRTs follow a power law with a gamma (exponent) of 2.2, this is really only approximately true. The detailed behavior seems to include a superposition of several different mechanisms, each with its own natural response. This plot compares anode current (light output is linearly proportional to this) as a function of applied drive voltage to a hypothetical device that follows a pure gamma 2.0 power law.

MTF mini-tutorial, spatial frequency samples. Although the concepts of modulation transfer function are well-known, they are not widely known. This introduces the topic of this valuable measuring tool for sharpness. All images can be constructed from basic sinusoidal functions. Here are samples showing an increasing frequency series. The units for measuring spatial frequency are cycles-per-millimeter, sometimes also "line-pairs" per millimeter. Many resolution tests use square waves, but proper mtf measurements are based on sinusoidal amplitudes of intensity.

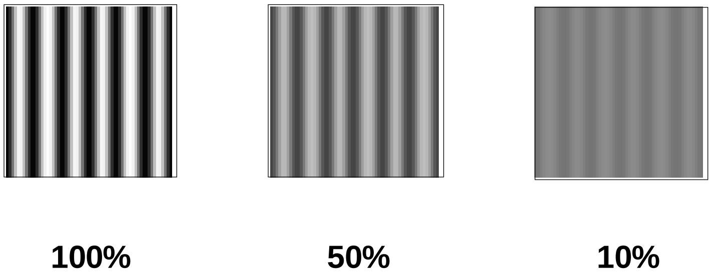
Spatial Frequency Examples

Units are for 35mm slide format renderings

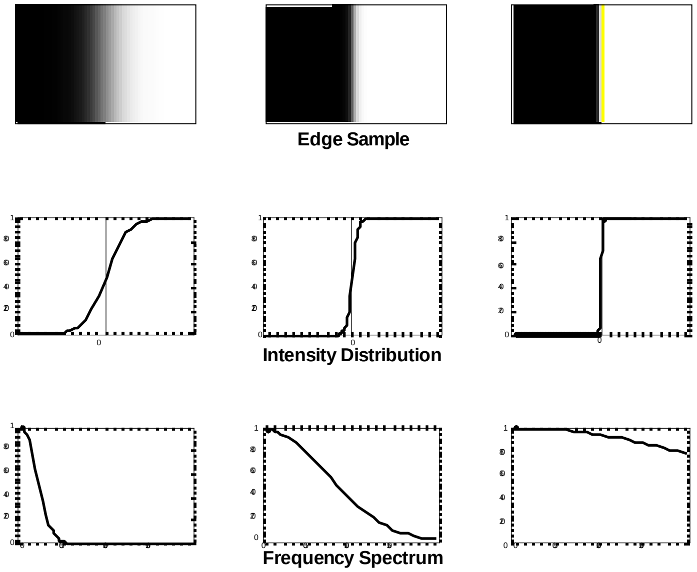


Amplitude modulation samples. At a given frequency, a full range of amplitudes is possible. These illustrate various "depths" of modulation. Full modulation means the amplitude is 100% of a specific reference. As the modulation decreases, the visual effect is a reduction in contrast.

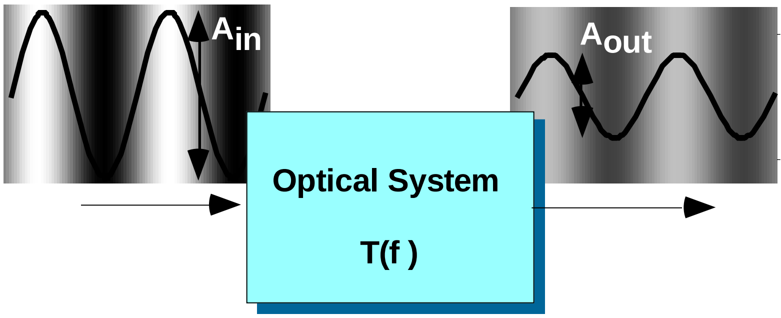
Amplitude Modulation Examples



The frequency content of an edge. To make an edge between black and white requires adding up a series of sin waves of the proper frequency and amplitude. The sharper the edge the more high frequency components it contains. A perfect knife-edge cannot be obtained on physical media. This sequence of charts illustrates the intensity distribution across a set of edges varying from soft to hard. The soft edge does not contain enough high frequency energy to make a rapid transition. This is the essence of the relationship between frequency and perceived sharpness.



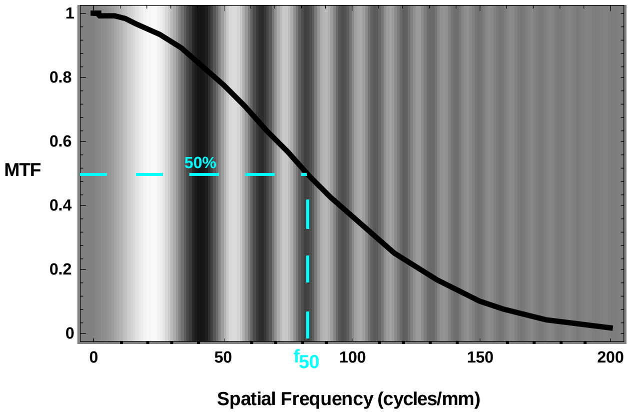
Modulation Transfer Function (MTF)



$$MTF = \frac{A_{out}}{A_{in}}$$

Modulation Transfer Function defined. If one takes a single frequency sin wave and pass it through an optical system, the ratio of the output amplitude to the input amplitude is the modulation transfer function at that frequency. This ratio will vary depending on the frequency and the characteristics of the optical system.

Modulation Transfer Function

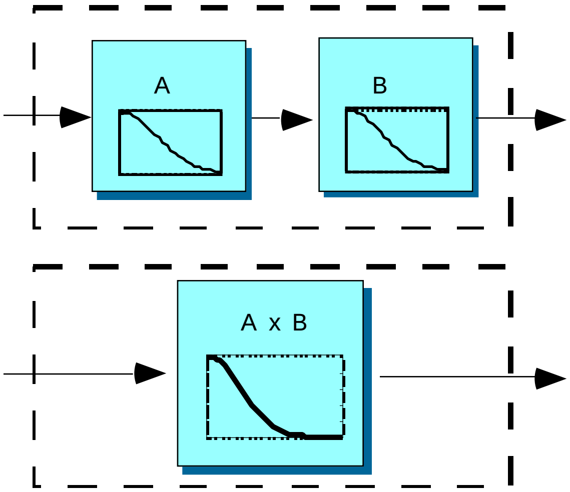


MTF spectrum. The modulation transfer function is a function of frequency. A figure of merit for an optical system is the frequency, f_{50}, where the modulation falls to 50%.

Most optical systems have low-pass behavior, the modulation capability falls off at higher frequencies. It is also common that the low frequencies are passed without attennuation. For these systems the MTF is the same as the "contrast index" defined as:

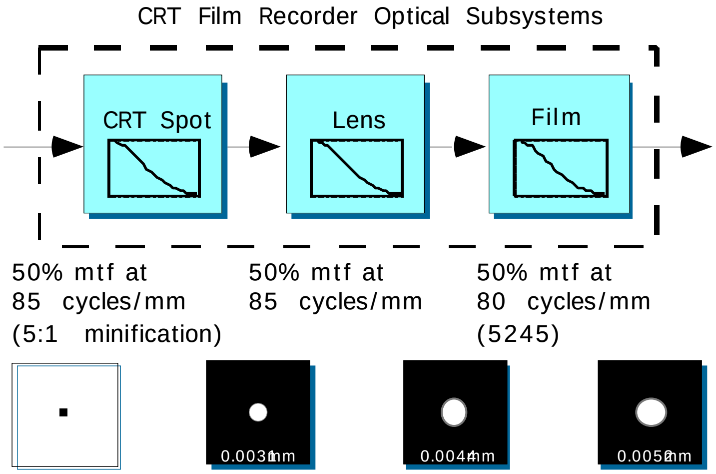
$C = (A_{max}-A_{min})/(A_{max}+A_{min})$

Cascaded Subsystems



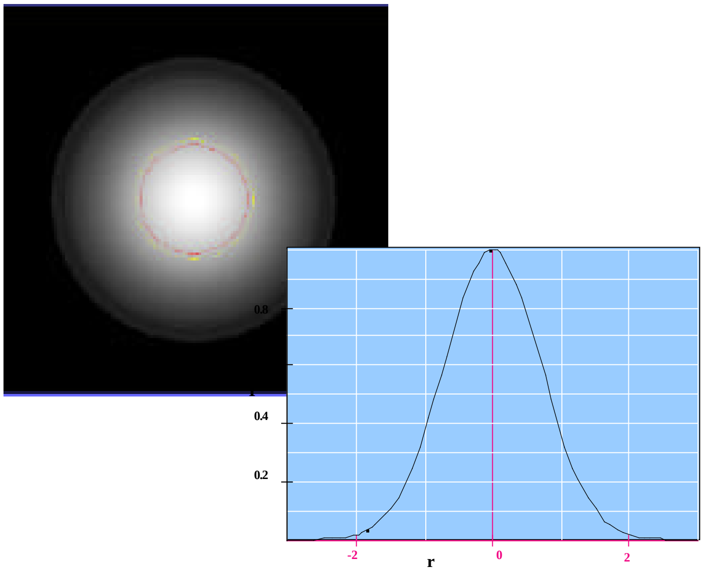
The MTF of cascaded subsystems. A very nice feature of MTF is that it allows us to calculate the sharpness (MTF) of a system if we know the MTF of its components; the spectra just multiply. Conversely, if we know what we want to see as an overall system sharpness, we can determine what the individual MTFs must be.

Subsystems in a film recorder. Here are the main optical components in a CRT film recorder. Each has a characteristic MTF. The net sharpness of the film image is the product of the three components. The equivalent writing spot, shown schematically at the bottom, increases in size at each stage

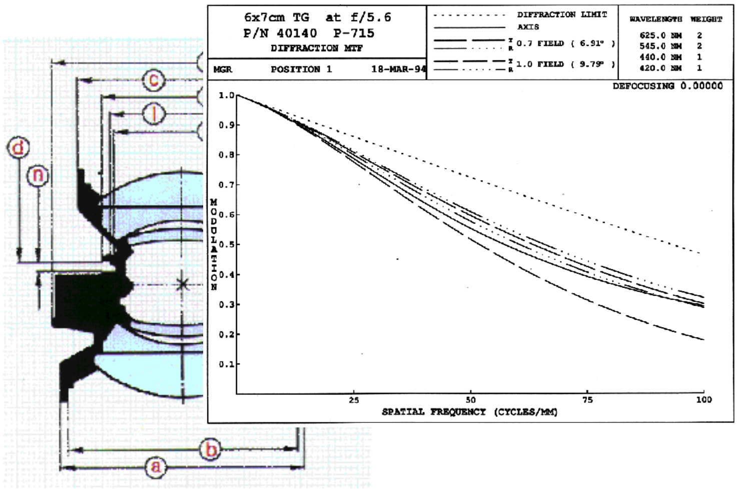


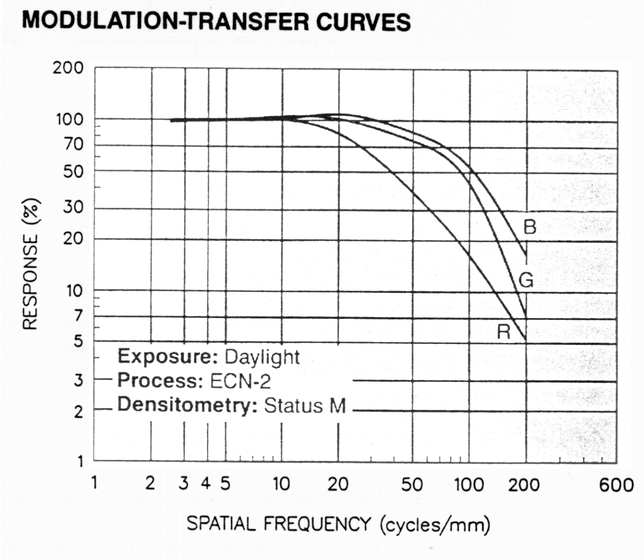
CRT spot. The writing spot starts out at the CRT screen. It can be approximated as a gaussian intensity distribution. The 50% amplitude diameter of the spot is often used as a measure of its size. Another useful measure is the "gaussian radius" where the intensity falls to 1/e of its peak value. The two are related by:

$$R_g = 0.6D_{50}$$

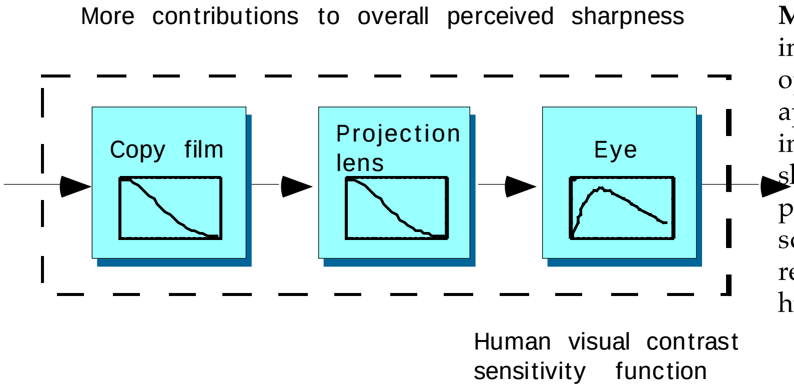


Lens design. The CRT spot is imaged by a lens onto the film. Typically the image of the spot is reduced onto the film, but the MTF of the lens prevents it from being a perfect reduction. Here is a characteristic MTF plot for a lens design. The dotted line represents the upper limit on lens performance; it is the diffraction limit of a finite aperture.

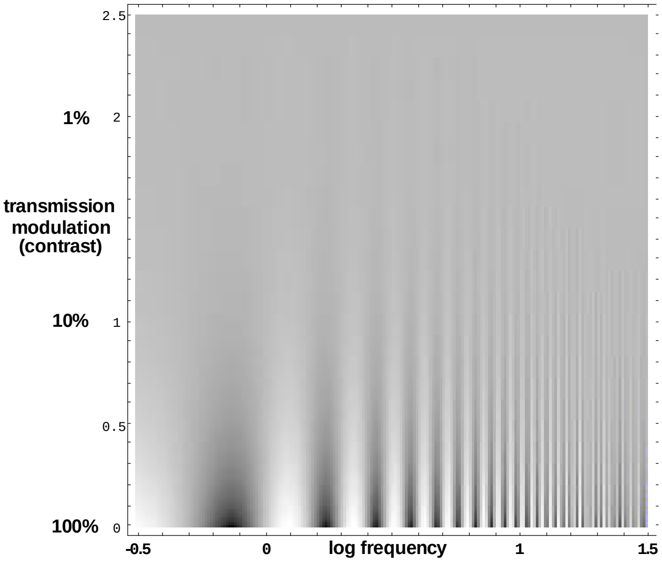




Film resolving power. The film itself limits the resolution that can be recorded. This is the MTF chart for 5245 film. Nearly all color films will show differences in the resolution between color channels. This is partly responsible for colored edge and fringe artifacts.



More factors to sharpness. After an image is recorded on film, further operations influence its final appearance. The process of making internegatives and prints reduce the sharpness; the performance of the projection lens and its focus on the screen are also factors. Finally, the resolution and visual response of the human eye must be included.



Human visual contrast sensitivity function. The human response is much more difficult to quantify than most optical systems, but this illustrates that contrast is a function of frequency. This chart shows a sinwave of increasing frequency whose amplitude changes from 100% to zero. There will be a range in the middle where the wave apparently extends highest. This is the point of maximum sensitivity, the peak of the human mtf curve.

Digital resolution, pixel packing for smooth shading. This shows the result of placing gaussian shaped pixels too far apart. These are separated by 1.5 gaussian radii. In order to make a solid, flat field, the pixels (scanlines) must be positioned to within $1.2R_g$ of each other.

How many pixels do I need? In order to assure raster artifact-free images, you need to provide a minimum number of pixels. The number depends on the effective spot size in the system: a smaller spot will require a higher pixel density. Here is a three step method to estimate the number of pixels required.

The number is higher than many people use for their image resolution. To compensate, the film recorder must replicate pixels in order to avoid raster line artifacts.

1. Obtain the equivalent spot radius. For a gaussian spot this will be at 0.265 / f_{50}, the 50% mtf frequency.

2. Multiply R_g by 1.2 to obtain the maximum pixel spacing. Beyond this, raster line artifacts will be visible.

3. Divide the format width by this spacing to obtain the total number of pixels in a scanline.

Example: MGI Solitaire Cine-2, 5245, Academy Offset

f_{50} (50% mtf)	48 cyc/mm
$R_g = 0.265 / f50$	0.0055 mm
$s = 1.2 R_g$	0.0066 mm
Format width	22 mm
Digital resolution required to make smooth raster field	3320 pixels

How many pixels can I use? After a certain number, additional pixels will not improve image sharpness. That upper limit depends on the effective writing spot size as well as your ability to discriminate high frequency information. The maximum useful number of pixels is higher than most people think.

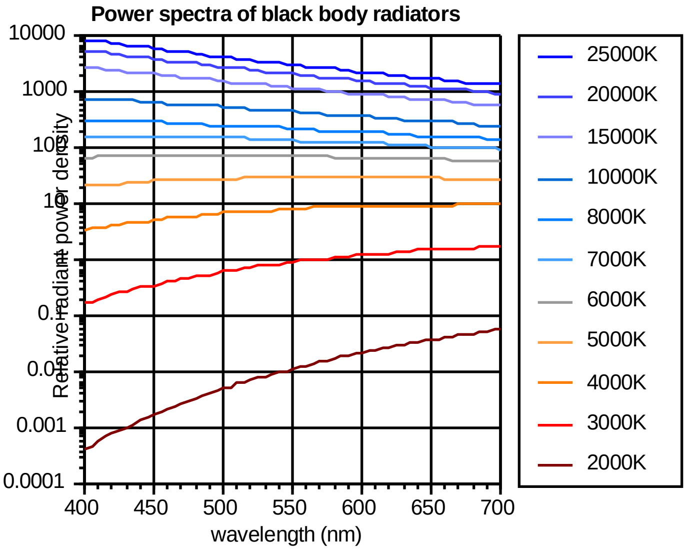
1. Obtain the frequency, f_{005}, where the mtf is around 0.5%. This is about the highest frequency we care about visually. For a gaussian spot this will be at 2.76 x f_{50}, the 50% mtf frequency.

2. Multiply f_{005} by two to obtain the Nyquist sampling rate required. Below this sampling density aliasing (jaggies) will be visible.

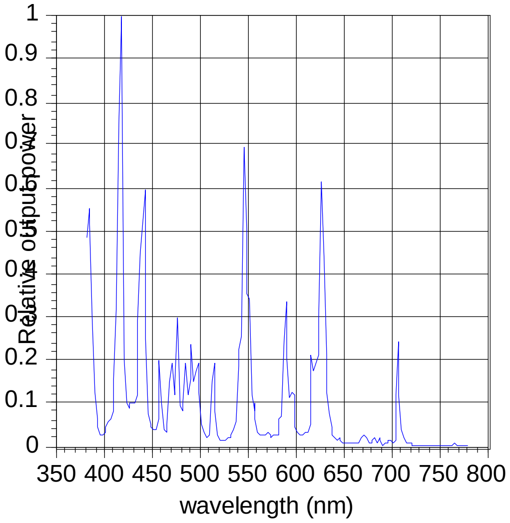
3. Multiply by the format width to obtain the total number of pixels in a scanline.

Example: MGI Solitaire Cine-2, 5245, Academy Offset

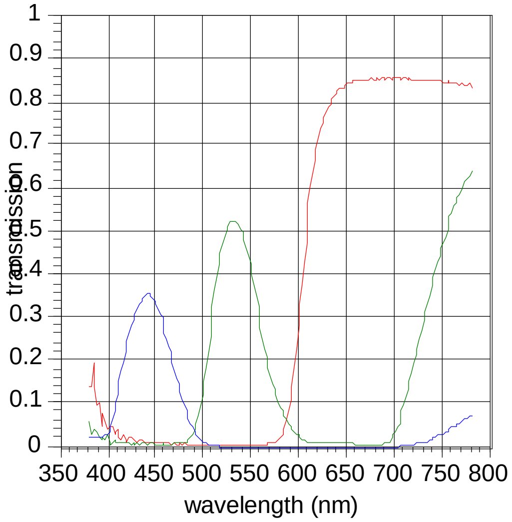
f_{50} (50% mtf)	48 cyc/mm
$f_{005} = 2.76 f_{50}$	133 cyc/mm
$f_{Nyquist} = 2 f_{005}$	266 samples/mm
Format width	22 mm
Digital resolution required to match optical sharpness	5852 pixels



Light source spectrum Each light source has its own distinct spectral power distribution. All objects radiate a continuous spectrum of power. If they are hot enough, the power spectrum enters the wavelength region where it becomes visible. The shape of the spectrum and the relative amounts of power in the short, medium, and long wavelength regions determine the color that will be percieved at that temperature. Incandescent lighting is limited to the 3000K region where the filament is hot enough to radiate well, but not so hot as to melt itself.

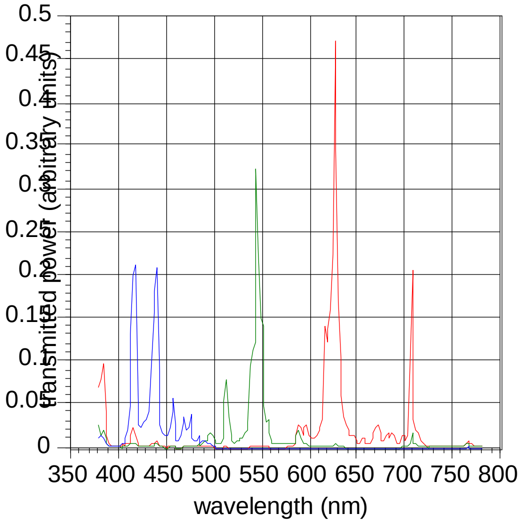


Phosphor spectrum. Sources which have energy in each of the long, medium, and short wavelength regions of the spectrum can be perceived as "white" even though not all wavelengths are present. This is the spectrum of a phosphor used in CRT film recording. It is called a "line spectrum" because most of its energy is confined to the wavelengths near specific wavelengths. It has some strong short (blue) wavelength lines, while the long (red) wavelength lines have less energy. The visual appearance of this phosphor is a pale purple.



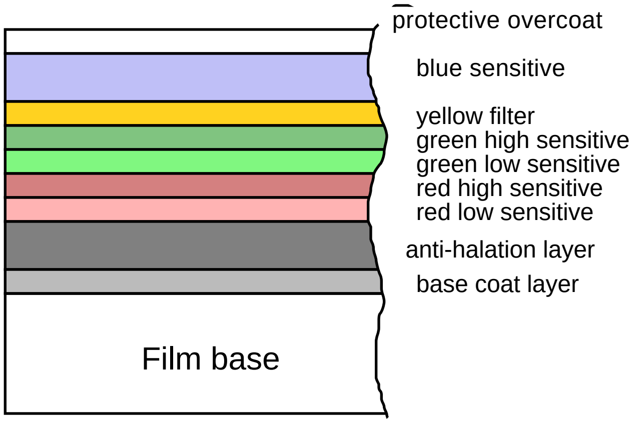
Color separation filters. In order to control the energy delivered from each band, separate exposures are made, each from an isolated part of the spectrum. To block the unwanted part of the spectrum, color filters are placed between the source and the film.

Filtered CRT spectrum. The degree of color saturation that can be achieved depends in part on how pure the three wavelength bands of the exposure can be made. The plot here shows the net energy in each band of the filtered phosphor spectrum. Narrowband sources provide for a wide color gamut, but the tradeoff is in obtaining enough energy to make the exposure in a reasonable time.

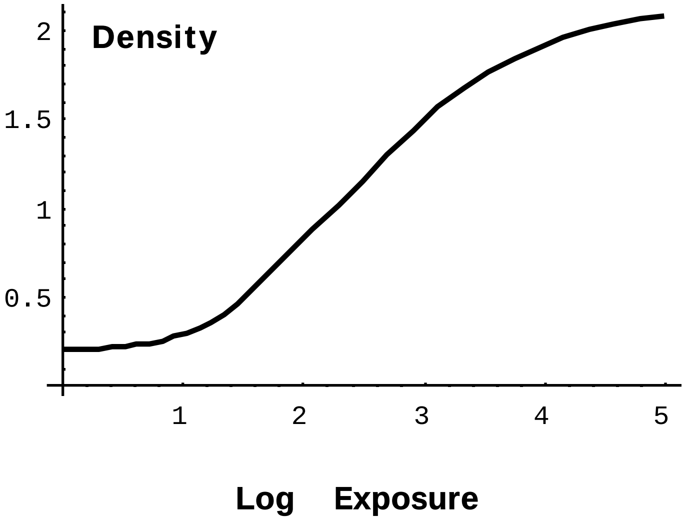


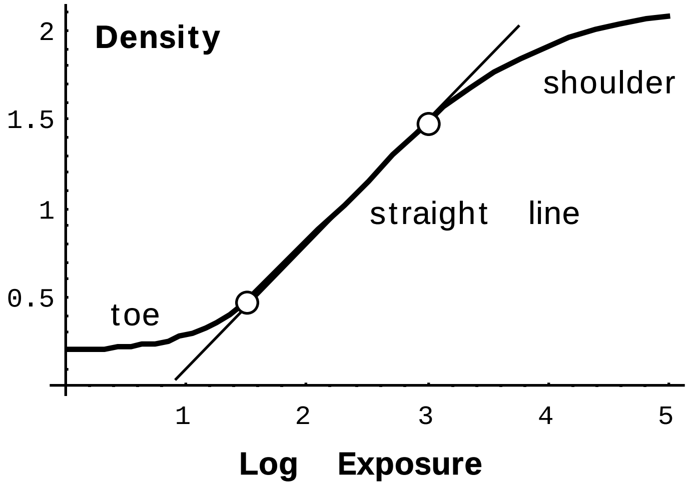
Film construction. Modern photographic film is a complex material. The emulsion layers in color film are all sensitive to blue. To make green-only and red-only sensitive layers, a yellow filter is placed in front (but below the blue-sensitive layer), blocking the blue light from reaching them.

Each color sensitive layer may actually comprise several layers, each with a particular response range to extend the film's latitude. Additional layers are needed to control halation and to aid in the manufacturing process.

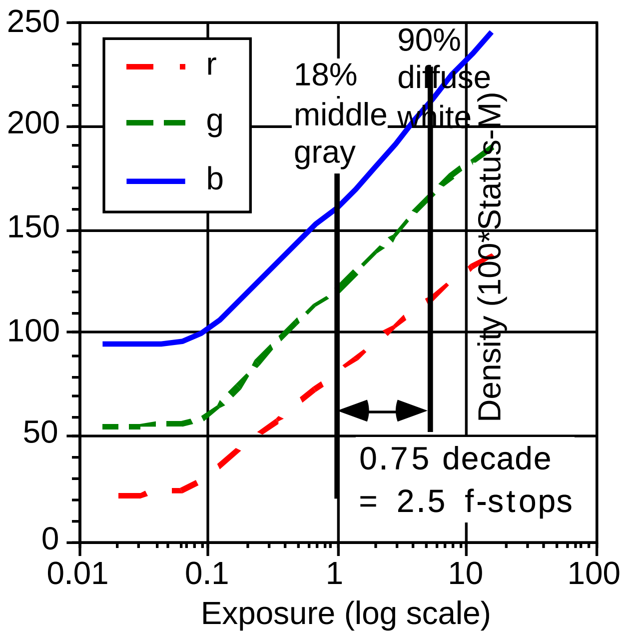


Basic film response, the HD curve. The fundamental behavior of film is based on the interaction between photons and silver ions in the film. The statistics of the spatial distribution of the developed silver grains results in this characteristic curve shape when optical density is plotted against log exposure. Such curves are called DlogE curves, characteristic curves, or HD curves, after Hurter and Driffield, early photographic scientists who pioneered this method of describing film behavior.



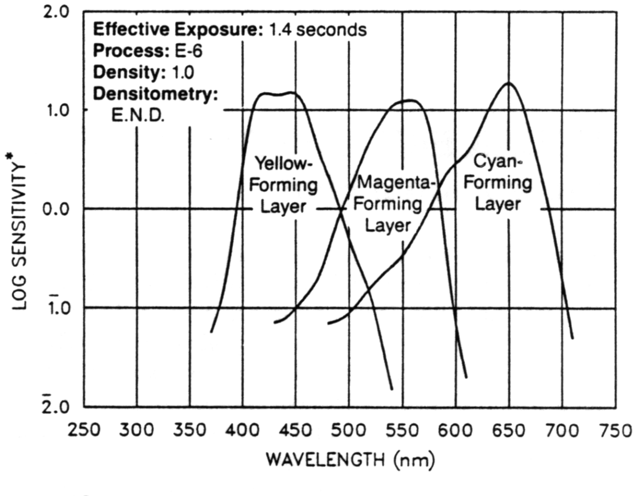


Key features of the characteristic curve. The general appearance of characteristic curves are quite similar. Each starts out at the film base density and then as exposure increases, the density starts to build up. The density response then enters a region where it increases proportionally to the log exposure. The onset and the slope of this straight line region establish the *speed* and *contrast* of the film. Eventually, the developed metallic silver approaches the total amount available in the emulsion and the response saturates.



Color film curves. Color film has the same general behavior, but in three separate response curves, associated with the three bands of the spectrum. They are offset from each other because of *colored couplers* (mask layers) that help compensate for unwanted dye absorptions.

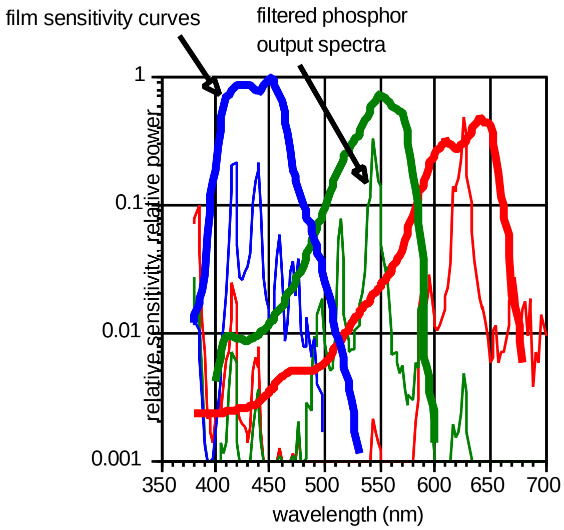
Typically, only the toe and part of the straight line portions of the response curve are used. Overexposure simply translates the scene information up the curve, providing *exposure latitude*. The excess density is compensated by overexposing during the printing step. The low contrast (low slope) of the negative is also compensated by the slope of the print paper response.



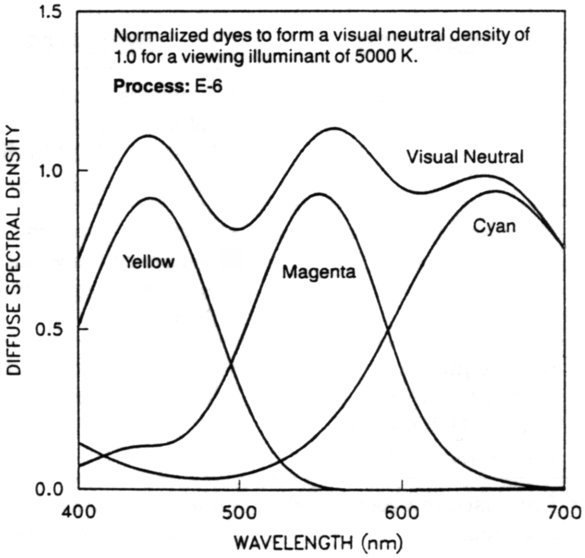
*Sensitivity = reciprocal of exposure (ergs/cm²) required to produce specified density

Exposure and sensitivity. *Exposure* is measured as a light intensity-time product such as "lux-seconds". *Sensitivity* is the reciprocal of the exposure needed to reach a specified target density.

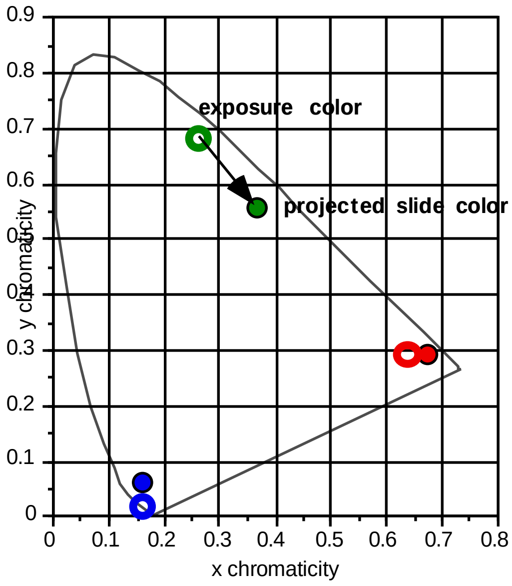
Sensitivity relative to the exposure spectrum. Here are the sensitivity curves superposed on the spectral components of the color separated CRT phosphor. It is desirable to have the exposure energy in each band match the corresponding sensitivity function without influencing the other layers of the film.

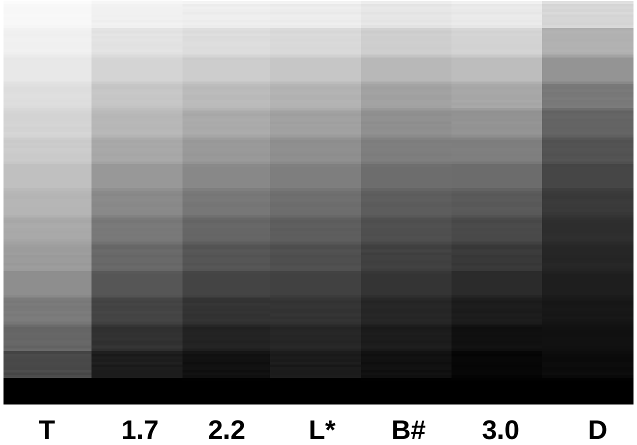


Dye absorption spectra. No matter how pure the exposure however, the resulting film image is the superposition of three dye spectra. The spectral bandwidth and separation of these dyes constrain the saturation and brightness of the final picture. In this plot the individual dye absorption curves are shown. Each *blocks* a portion of the spectrum and is transmissive elsewhere (though not perfectly so). The net result is a spectrum which is blocked partially everywhere. The relative concentrations to make a visual match to a uniform 10% transmission (neutral density 1.0) across the full spectrum are shown.



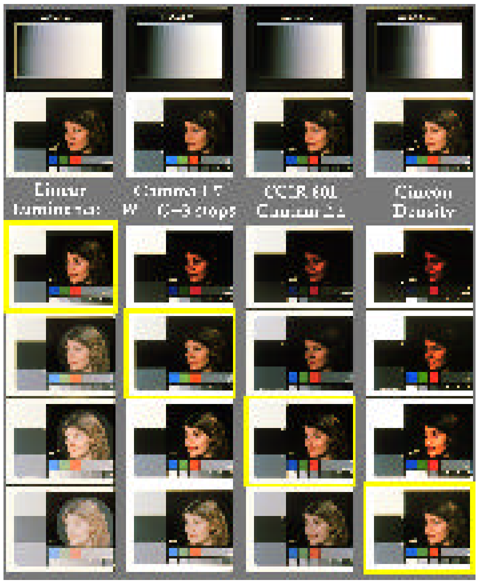
Colorimetry of digitally exposed film. The locations of the projected film primaries are shown on this chromaticity chart, compared to the color of the light that made the exposure. It can be seen that green and blue desaturate, while red actually increases in saturation. The final colors seen in the projected slide depend on the final dye concentrations in the film, and the spectrum of the projector bulb, a light source which has a strong red component.





Common tonal scales used in digital imaging

File format	ext	implicit scale
SGI	.rgb	gamma 1.7
Targa	.tga	unspec, 2.2
Tagged Image File	.tif	various
Cineon, 10-bit	.cin	printing den
Cineon 8-bit	.cin	printing den
Cineon 8-bit	.rgb	linear lum
D1		gamma 2.2
Macintosh		gamma 1.8



Tonal scale match and mismatch. This chart illustrates the importance of using the correct tonal scale lut for a digital image. The digital encoding of the image assumes a specific tonal assignment. If that same relationship is not used when recording the image back to film, the results will be disappointing.

The four columns represent the output lut being used. The top scale is a digital ramp to illustrate the lut. The bottom four rows are images encoded to those tonal scales. Where the image data matched the lut's tonal scale, the resulting image is correct (yellow frames). All others are distorted in tonal rendition.

Other influences on film appearance:

- viewing environment
  - normal (print)
  - dim surround (CRT)
  - dark surround (projected images)
- flare
- halation
- grain