Image quality factors

Overview and Imatest measurements

Image quality is one of those concepts that's greater than the sum of its parts. But you can't ignore the parts if your goal is to produce images of the highest quality. Every image quality factor counts.

This page introduces the key image quality factors and briefly describes how Imatest™ measures them — with links to detailed pages. It is a guide to Imatest organized by image quality factor. Other guides include the Tour (organized by module) and Imatest documentation (the Table of Contents).

To illustrate the quality factors, we use this early morning image of Monument Valley from Hunt's Mesa, near the Arizona-Utah border. A 13x19 print (available for purchase) is breathtaking, though it can't capture the experience of grabbing the camera gear and running for the truck as the storm broke. Hunt's Mesa isn't public land; you need a Navajo guide to get there. Tom Phillips does an excellent job.

Image quality measurements are affected by the

- **Lens** — Imatest cannot measure lenses by themselves, but lenses can be effectively compared to one another using a single camera body with consistent image processing settings.
- **Sensor** — Imatest can measure the performance of the Lens+sensor from minimally-processed RAW images if they are available. Sharpness, distortion, vignetting, Lateral

Chromatic Aberration, noise, and dynamic range are the principal factors that can be measured at this stage. Most of these measurements can be clearly classified as good/bad.

- **Image processing pipeline**— typically includes demosaicing, color correction, white balance, application of gamma and tonal response curves, sharpening, and noise reduction. Measured from the image delivered to the user (such as in-camera JPEG images). Additional image quality factors include tonal response (contrast, etc.), color response, and many others. The output of the pipeline may be compared to the minimally-processed lens+sensor measurements.

The effect of the pipeline on subjective image quality can be highly scene and application-dependent, making it difficult to assign "good" or "bad" rankings. Imatest results for these factors need to be interpreted carefully. Examples:

Summary table

This table summarizes the image quality factors described in detail below. Most of the charts are available from Imatest Store.

Quality factor	Chart	Module	Comments
Camera, lens			
Blemishes, Sensor defects	plain, uniformly-illuminated surface	Blemish	Can be displayed on flat screen monitor with Screen Patterns. Opal diffusing glass recommended. Note [1]
Color accuracy	X-Rite ColorChecker (24-patch)	Colorcheck, Multicharts	
	IT8.7	Multicharts	
	ColorChecker SG, general *mxn* grids, and many other charts	Multicharts	Note [1]
Dynamic range, Tonal response, Contrast	Step charts	Stepchart	Transmission charts such as the Stouffer T4110 recommended for DR. Algorithm

	Reflective step charts	Dynamic Range	More convenient for measuring DR than Stepchart because it doesn't require a transmission chart.
	Special charts: **ISO-16067-1**, **QA-62**, **EIA Grayscale**, **ISO-14524 OECF**, **ISO-15739 Noise**	Stepchart	Note [1]. Many are available from the Imatest Store.
	ColorChecker, ColorChecker SG, IT8.7, Step Charts	Multicharts	
	SFRplus	SFRplus	Does not measure DR. Highly automated. Measures several factors. Available from the Imatest Store.
Exposure accuracy	Step charts (reflective)	Stepchart	
	X-Rite ColorChecker	Colorcheck	
ISO Sensitivity (closely related to Exposure Index)	Step charts	Stepchart	Two ISO sensitivity measurements are displayed when incident light (lux) is entered. Details in ISO Sensitivity and Exposure Index
	Various color and step charts	Multicharts	
	SFRplus	SFRplus	
	X-Rite ColorChecker	Colorcheck	
Lateral chromatic aberration	Slanted edge, ISO 12233 charts	SFR	Available from the Imatest Store. Note [2]
	SFRplus		Available from the Imatest Store. Note [2]
	Dot pattern	Dot Pattern	Available from the Imatest Store. Note [2]

Lens distortion	Square or rectangular grid or checkerboard,	Distortion	Printable by Test Charts or displayed on LCD flat screen monitor with Screen Patterns.
	SFRplus	SFRplus	Highly automated. Measures several factors. Results in the Image & Geometry display.
	Dot pattern	Dot Pattern	Available from Imatest Store.
Light falloff, vignetting	Plain, uniformly-illuminated surface	Light Falloff	Can be displayed on flat screen monitor with Screen Patterns. Opal diffusing glass recommended.
Noise	Step charts	Stepchart	
	X-Rite ColorChecker	Colorcheck	
	SFRplus	SFRplus	Measures either side of slanted-edges. Works best with low (4:1) contrast charts.
	Wide variety of grayscale stepcharts and color charts	Multicharts	Works with a large variety of grayscale and color charts if patches are large enough. Can measure sensor (raw) noise.
Sharpness (MTF)	Slanted-edge, ISO 12233	SFR, Rescharts	ISO 12233 charts available from Imatest Store. Edges printable by Test Charts. Algorithm
	SFRplus	SFRplus	Highly automated. Measures several factors. Available from Imatest Store.
Veiling glare (lens flare)	Reflective Q-13 or Q-14 step chart with “black hole”	Stepchart	See Veiling Glare. Note [1]
Color moiré	Log Frequency	Log Frequency	
Software	Log F-Contrast	Log F-	Notes [1,2]

[artifacts](#)		[Contrast](#)	
Prints			
[Dmax](#) (deepest black tone)	Custom test chart printed from file, scanned on profiled flatbed scanner	[Print Test](#)	[Gamutvision](#) extracts these properties from ICC profiles.
[Color gamut](#)			

Notes: [1] Not available in Imatest Studio. Available in Master, Image Sensor, etc. [2] can be printed from Test charts, but we recommend purchasing it from the Imatest Store.

Image quality factors for cameras and lenses

Sharpness

Sharpness is arguably the most important single image quality factor: it determines the amount of detail an image can convey. The image on the upper right illustrates the effects of reduced sharpness (from a Picture Window Pro blur operation).

Device or system sharpness is measured as a ***Spatial Frequency Response (SFR)***, also called ***Modulation Transfer Function (MTF)***. MTF is the contrast at a given spatial frequency (measured in cycles or line pairs per distance) relative to low frequencies. The 50% MTF frequency correlates well with perceived sharpness—much better than the old vanishing resolution measurement, which indicated where the detail *wasn't*.

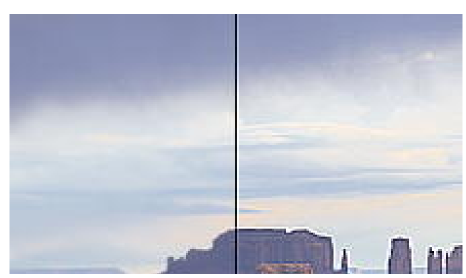
Sharpness and MTF are introduced in Sharpness: What is it and how is it measured?

The perceived sharpness of a print or display is measured by Subjective Quality Factor (SQF) or Acutance, which are derived from MTF, the Contrast Sensitivity Function of the human eye, and viewing conditions.

Imatest's primary sharpness measurement uses slanted-edge patterns analyzed by SFR, Slanted-edge SFR (a part of Rescharts), or SFRplus (highly-automated and strongly recommended), using targets you can purchase or print with the Imatest Test Charts module. Concise instructions are found in How to test lenses with Imatest.

Original | Blurred

Original | Oversharpened



Several alternative patterns, which cause cameras to apply differing amounts of sharpening and noise reduction, can be used for measuring MTF. All require more real estate than the slanted-edge. They include

- Log Frequency, which uses a sine pattern chart that increases in frequency logarithmically. It provides a check on the slanted-edge method. More direct but less accurate,
- Log F-Contrast, excellent for examining loss of detail due to noise reduction,
- Star Chart,
- Random scale-invariant, which minimizes sharpening and maximizes noise reduction. Measures fine texture response.

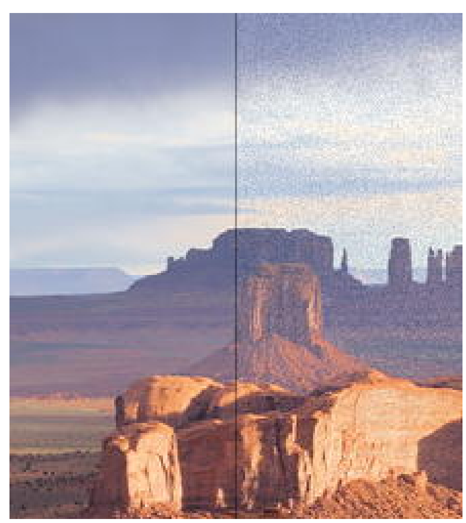
The MTF Measurement Matrix compares the different methods.

System sharpness is affected by the lens (design and manufacturing quality, position in the image field, aperture, and (for zoom lenses) focal length), and the sensor (pixel count and anti-aliasing filter). In the field, sharpness is affected by camera shake (a good tripod can be helpful), focus accuracy, and atmospheric disturbances (thermal effects and aerosols).

Some lost sharpness can be restored by sharpening, but sharpening has limits. It can't restore detail where MTF is very low (under about 10%). Oversharpening, illustrated on the right, can also degrade image quality (especially at large magnifications) by causing "halos" to appear near contrast boundaries. Images from many compact digital cameras are oversharpened.

Noise

Original | Noise added



Noise is a random variation of image density, visible as grain in film and pixel level variations in digital images. It arises from the effects of basic physics— the photon nature of light and the thermal energy of heat— inside image sensors and amplifiers.

Noise and its measurement are introduced in Noise in photographic images.

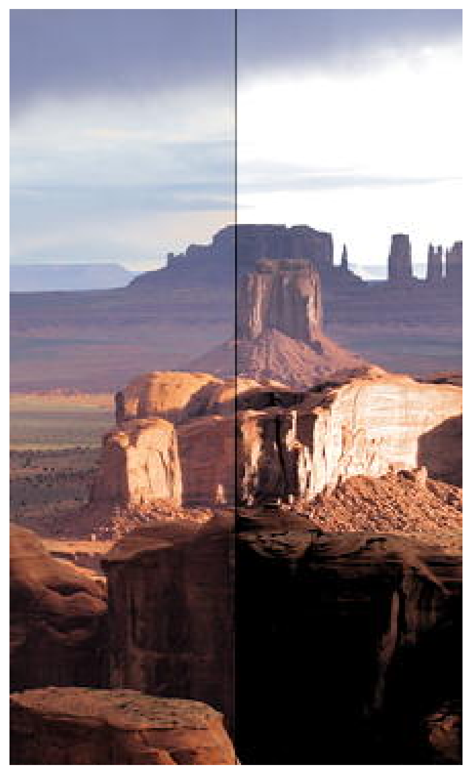
Noise is measured by several Imatest modules. Stepchart and Multicharts produce the most detailed results, but noise is also measured in Colorcheck, SFR, SFRplus, and Light Falloff.

Noise scales strongly with pixel size. It can be very low in digital SLRs, which have pixels at least 4 microns square. But it can get ugly in compact digital cameras and camera phones with tiny sensors, especially at high ISO speeds or in dim light. It is also affected by sensor technology and manufacturing quality.

Software noise reduction (NR) reduces the visibility of noise by smoothing the image, excluding areas near contrasty boundaries. This technique works well, but it can obscure fine, low contrast detail. The Log Frequency-Contrast module clearly measures the effects of software noise reduction. The Random scale-invariant module uses a pattern that tends to maximize noise reduction (it's the worst-case for noise reduction)— in contrast to the slanted-edge (the opposite limiting case), which tends to maximize sharpening and minimize noise reduction.

Dynamic range, tonal response, and contrast

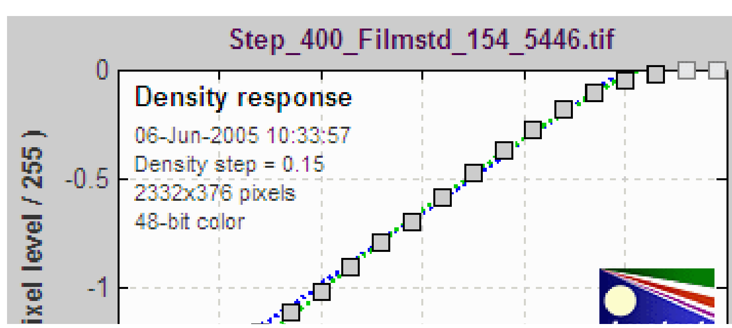
original | clipped



Dynamic range (or exposure range) is the range of light levels a camera can capture, usually measured in f-stops, EV (exposure value), or zones (all factors of two in exposure). It is closely related to noise: high noise implies low dynamic range. It is also related to the tonal response— the relationship between light and pixel level (shown below). Contrast, also known as gamma, is the slope of the tonal response curve. High contrast (shown on the right) usually involves loss of dynamic range— loss of detail, or ***clipping***, in highlights or shadows— when the image is displayed. (The image file often has a greater dynamic range than the displayed image.)

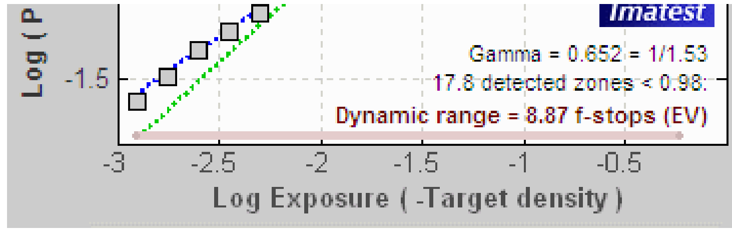
Dynamic range, tonal response, and gamma are measured (A) by Stepchart using a transmission step wedge, preferably one with a maximum density at lest 4.0 (equivalent to 13.3 f-stops), or (B) by Dynamic Range, a postprocessor for Stepchart that uses results from up to four differently-exposed reflective stephart images. The latter technique is often the most convenient because it doesn't require a special light source in a darkened room.

Dynamic range is a strong function of pixel area, which is proportional to the number of electrons a pixel can store. It is invariably better in DSLRs (which have relatively large pixels; at least 5 microns square) than in compact digital cameras. It can be maximized by setting the camera at the lowest ISO speed.



Displaying images with large dynamic

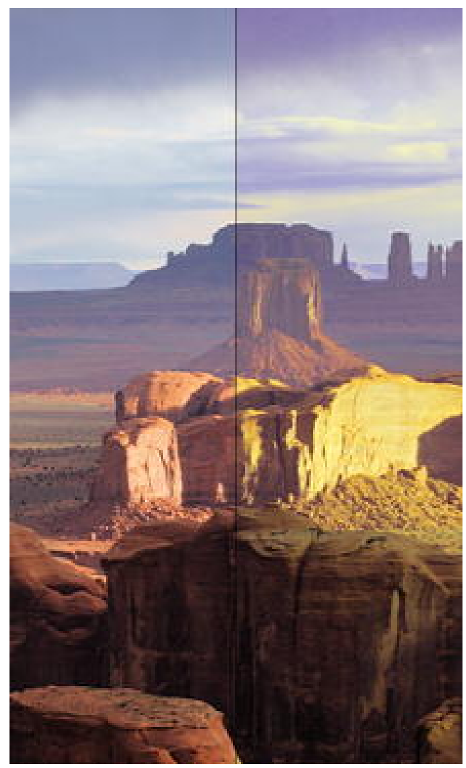
ranges (which can be well over 1000:1; 10 f-stops) can be problematic in printed media, which has a maximum dynamic range of about 100:1 (a little over 6 f-stops; 200:1 at the absolute maximum). Reducing contrast can make the image look flat and dull. Some processing is usually required, like applying an "S" curve or dodging and burning (lightening or darkening) portions of the image. Contrast masking is a particularly effective approach. Tonal quality and dynamic range in digital cameras offers additional tips.



Lenses have an intrinsic contrast— the higher the better— that is primarily limited by flare light— light originating inside and outside the lens's field of view that bounces between lens elements and off the inside of the lens barrel. Flare light tends to fog the image and obscure shadow detail: it reduces dynamic range. Veiling glare is a good measurement of a lens's susceptibility to flare light.

Color accuracy

Original | Color-shifted



Color accuracy is an important but ambiguous image quality factor. It can be critical in medical and technical photography, but less so in pictorial (consumer) photography, where many viewers prefer enhanced color saturation, particularly in "memory colors": foliage, sky, and skin. Accurate color is not the same as "pleasing" color.

Whatever the application, it is important to measure a camera's color response: its color shifts, saturation, and white balance effectiveness.

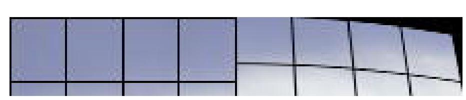
Color response is measured by Colorcheck, using the widely-available 24-patch X-Rite ColorChecker® and by Multicharts using the 24-patch ColorChecker, ColorChecker SG, IT8.7, QPcard, and many other standard and custom charts. These charts may be included in scenes for white balance testing.

Color accuracy may be measured against standard chart reference values or CSV reference files that contain measured color values, which may be altered to reflect customer preferences.

Color accuracy is affected by the Bayer color filter array and by the signal processing and white balance algorithm in the camera or RAW converter. Flare light (veiling glare) in lenses tends to reduce color saturation. Multicharts can calculate a color correction matrix.

Lens distortion

Original | Barrel-distorted



Lens (optical) distortion is an aberration that causes straight lines to curve near the edges of images. It can be troublesome for architectural photography and photogrammetry (measurements derived from images). The simplest approximation is the equation, $r_u = r_d + kr_d^3$ where r_u is the undistorted and r_d is the distorted radius. Depending on the sign of k, it can be either "barrel" (shown on the right) or "pincushion."

Lens distortion and coefficients for correcting it are calculated in Distortion, which also includes 5th order and tangent/arctangent distortion models. Dot Pattern performs an I3A CPIQ-compliant distortion measurement. SFRplus measures distortion in less detail, along with sharpness and several other factors. Distortion results are in the Image & Geometry display.

Distortion is worst in wide angle, telephoto, and zoom lenses. It often worse for close-up images than for images at a distance. It can be easily corrected in software. Picture Window Pro and PTLens have tools for removing it.

Light falloff (vignetting) and sensor nonuniformities

Original | Vignetted

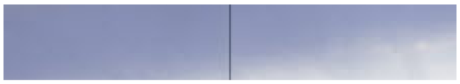
Light falloff (vignetting) darkens images near the corners. It can be particularly strong with wide angle lenses. It is measured by Light Falloff (Uniformity) and Uniformity-Interactive (an interactive module designed to work with the Imatest Image Sensor edition).

Light falloff often improves when lenses are stopped down. It can be easily corrected in software or in the image processing pipeline. Picture Window Pro, PTLens, and several other programs have tools for removing it. Because moderate amounts of light falloff can be pictorially pleasing, it's not always advisable to remove it completely.

Light Falloff (Uniformity) also measures other sensor nonuniformities, including color shading (nonuniformity), stuck pixels, local sensitivity variations, spots (from dust), and noise. It has a particularly rich set of displays in Imatest Master.

Blemishes (visible sensor defects)

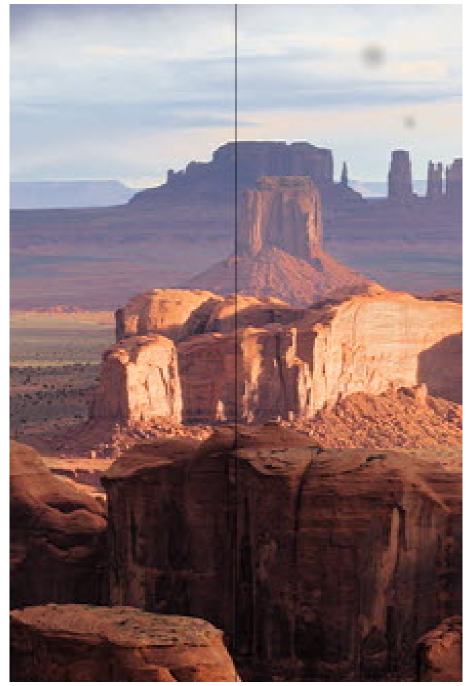
Original | Blemishes



Blemishes are visible spots or marks in the image, caused by sensor defects or by dust in front of the sensor (typically separated by the Bayer, anti-aliasing, and infrared (IR) filters). They are extremely important in manufacturing. They are measured by Blemish Detect (Imatest Master-only).

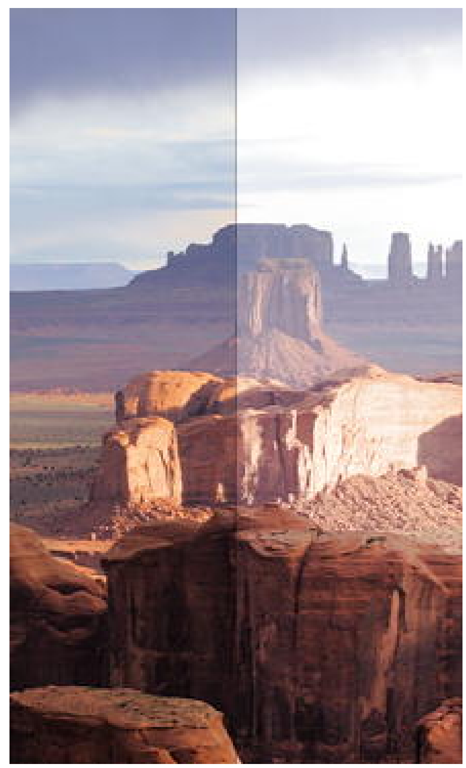
Blemish Detect filters the image using a transfer function derived from the Contrast Sensitivity Function of the Human Visual System. Because of this, when filter parameters are set up properly, visible blemishes will be flagged and blemishes beneath the threshold of visibility will be ignored. ***This can significantly improve manufacturing yields.***

Blemish Detect also measures hot and dead pixels.



Exposure accuracy and ISO Sensitivity

Original | Overexposed



Exposure accuracy is not much of a problem with manually-adjustable cameras. You can usually determine it quickly (with the help of the histogram), and if you don't like it, you can change the exposure compensation or the way you meter.

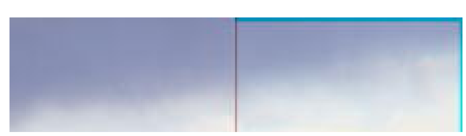
But exposure accuracy can be an issue with fully automatic cameras and with video cameras that offer little or no opportunity for post-exposure tonal adjustment.

Exposure accuracy can be measured by photographing a scene that includes any test chart with a grayscale pattern and analyzing it with Stepchart (for grayscale stepchart-only patterns such as the Q-13/Q-14), Colorcheck (for the X-Rite Colorchecker) or Multicharts (for *any* chart with a grayscale pattern).

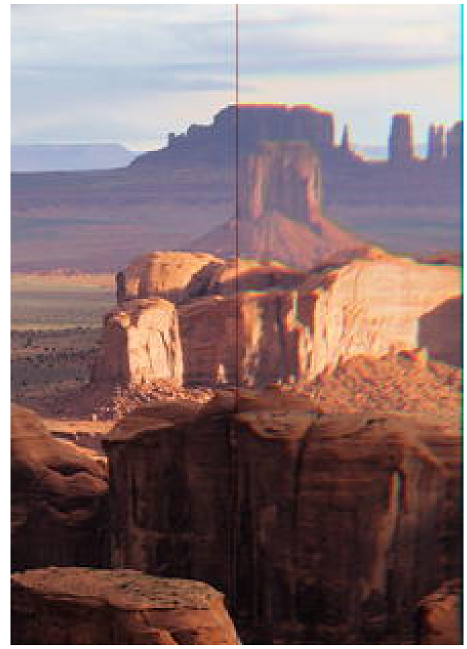
ISO Sensitivity (closely related to exposure accuracy) is a measure of a camera's sensitivity to light. Imatest modules that analyze step charts (which may be included in color charts) display two measures of sensitivity when the incident light in Lux is entered. Details in ISO Sensitivity and Exposure Index

Lateral chromatic aberration

Original | Color-fringed



Lateral chromatic aberration (LCA), also called "color fringing" is a lens aberration that causes colors to focus at different distances from the image center. It is most visible near corners of images. It is explained in [Chromatic aberration].



LCA is measured by SFR and SFRplus using (mostly) tangential edges near the image boundaries. Dot Pattern uses a grid of dots to make an I3A CPIQ-compliant LCA measurement.

LCA is worst with asymmetrical lenses, including ultrawides, true telephotos and zooms. It is strongly affected by demosaicing. It can be fully corrected in software prior to demosaicing, but only partially corrected afterwards. Picture Window Pro has a fairly effective transformation. In the future, information provided by Imatest (detailed LCA profiles) may improve the degree of correction.

Veiling glare (lens flare)

Original | Veiling glare

Veiling glare is stray light in lenses and optical systems caused by reflections between lens elements and the inside barrel of the lens. It predicts the severity of ***lens flare***— image fogging (loss of shadow detail and color) as well as "ghost" images— that can occur in the presence of bright light sources in or near the field of view. (It does not measure the ghosts in detail.)

Veiling glare is measured by Stepchart using a standard Kodak Q-13 or Q-14 step chart mounted beside a "black hole," i.e., a box lined with black behind a small opening, mounted on a large white board, as described in detail in Veiling glare.

Veiling glare can only be measured reliably with RAW images, preferably decoded with gamma = 1, because image processing (especially conversion to sRGB color space) can affect the "toe" region of the tonal response curve, which is critical to veiling glare measurements.

Color moiré

Color moiré

Color moiré is artificial color banding that can appear in images with repetitive patterns of high spatial frequencies, like fabrics or picket fences. The example on the right is a detail of a shirt captured by the Canon Rebel XT with its excellent kit lens. The usual image wasn't used because it doesn't contain a repetitive pattern and because color moiré is difficult to simulate.

Color moiré is the result of aliasing (image energy above the Nyquist frequency) in image sensors that employ Bayer color filter arrays, as explained here. It is affected by lens sharpness, the sensor's anti-aliasing (lowpass) filter (which softens the image), and demosaicing software. It tends to be worst with the sharpest lenses.

Color moiré is measured by Rescharts Log Frequency, which uses a sine chart of logarithmically increasing spatial frequency.

Software artifacts: noise reduction and sharpening

Original | NR+Sharpening

Software (especially operations performed during RAW conversion) can cause significant visual artifacts, including oversharpening "halos" and loss of fine, low-contrast detail. These artifacts result from ***nonlinear (nonuniform) signal processing*** (so-called because it varies with the signal). Images may be sharpened (MTF boosted) in the proximity of contrasty features like edges and blurred (lowpass filtered) in their absence. This generally improves ***measured*** performance (both sharpness from slanted-edges and noise/Signal-to-Noise Ratio (SNR) from chart patches), but it may result in a degradation of perceived image quality, for example, a "plasticy" cartoon-like appearance of skin even though edges are strongly sharpened. This loss of detail cannot be measured with SFR.

These artifacts can be measured by the Log F-Contrast module in Rescharts, which analyzes the chart shown on the right, which varies logarithmically in spatial frequency on the horizontal axis and in contrast on the vertical axis.

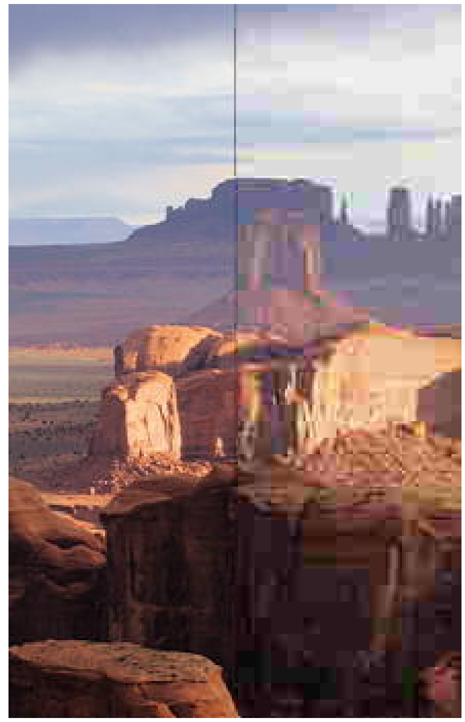
Data compression and transmission losses

Original | Low-quality JPEG

Data compression and transmission losses can have a significant effect on image quality. The right side of the image on the left has been saved as a low quality JPEG. Banding, loss of low-contrast detail, and “waviness” near edges are visible.

> *A full analysis of data compression and transmission losses is not yet available in Imatest.*

Some of these losses, especially the loss of low-contrast detail, can be analyzed with the Log F-contrast module in Rescharts. A more detailed analysis of compression losses is under development.



Quality factors for printers

Print Dmax

Original | Reduced Dmax

Dmax = -$\log_{10}$(minimum print reflectivity) is a measure of the deepest black tone a printer/ink/paper combination can reproduce. It is an extremely important print quality factor. Prints with poor Dmax look pale and weak. Dmax = 1.7 is a good value for matte prints; 2.0 is a good value for glossy, semigloss, and luster prints. There have been reports that Epson Ultrachrome K3 printers have Dmax as high as 2.3 with Premium Luster paper. That would be ***outstanding***.

Dmax is measured by Print Test, along with the Printer’s tonal response curve and the color factors described below. Print test requires a decent flatbed scanner, and for best accuracy, a Step chart.

Dmax is affected by the printer, paper, and ink. The response curve is also affected by the ICC profile. Print Test can help with the selection of supplies and diagnosis of printing problems.

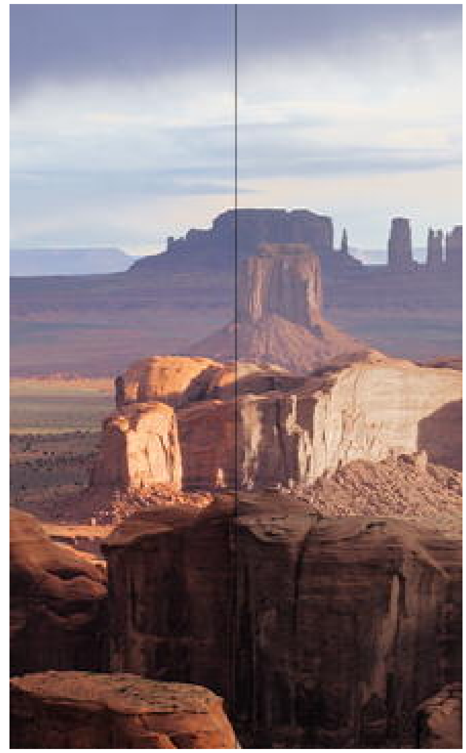
Print color gamut

Original | Reduced gamut

Print color gamut is the range of colors a printer/ink/paper combination can reproduce. It is an important quality factor, though its importance may be somewhat overrated. (This statement is bound to generate controversy.) Relatively unsaturated colors such as skin tones dominate our impression of print quality. Such colors must be reproduced accurately. Gamut affects only highly saturated colors. Overall color response, especially for low to moderately saturated colors, is more important than gamut.

Print color gamut and overall color response are measured by Print Test, along with the density factors described above.

Print gamut is affected by the printer, paper, ink, and working color space. Color response is also affected by the ICC profile and rendering intent. Print Test can help with the selection of profiles, software settings, and the diagnosis of color problems.



Links

Bror Hultgren (ImagIntegration.com), an imaging scientist with 27 years experience at Polaroid, has developed algorithms and software that relates image quality factors (especially MTF, noise spectrum, white balance, and memory colors) to perceived image quality. Bror is available for consulting.

Direct Digital Image Capture of Cultural Heritage from RIT is a gold mine of information. Links to a number of reports on image quality targeted at museums and cultural institutions. The 78-page Final Project Report by Berns, Frey, Rosen, Smoyer and Taplin, July 2005, is probably the best summary unless you have time for Erin P (Murphy) Smoyer's 345 page Master's thesis (about twice the length of the average Ph.D. thesis).

The Research Library Group (RLG) has published an excellent series of articles, Guides to Quality in Visual Resource Imaging (2000). These articles are the predecessors to the above-mentioned RIT Direct Digital Image Capture work.

The European Broadcasting Union (EBU) has a library of technical papers (the EBU Tech 3000 series), some related to TV image quality, for example, T3249, Measurement and Analysis of the Performance of Film and Television Camera Lenses (1995), and T3281, Methods for the Measurement of Characteristics of CCD Cameras (1995).

Volker Gilbert has written an excellent French language description of Imatest. (PDF version)

SMIA (Standard Mobile Imaging Architecture), a consortium founded by Nokia and STMicroelectronics, has published a Camera Characterization Specification for image quality measurements in camera phones. To obtain the spec you must join SMIA. It’s free; all you need to do is answer a brief questionnaire.

Paul van Walree has an excellent page on Optics, covering several sources of degradation.

The University of Texas Laboratory for Image & Video Engineering is doing some interesting work on image and video quality assessment, which approaches the problem using information theory, natural scene statistics, wavelets, etc. Challenging material!

Details of several Imatest algorithms are included in Appendix C, Video Acquisition Measurement Methods (pp. 91-125), of the Public Safety SoR (Statement of Requirements) volume II v 1.0, released by SAFECOM, prepared by ITS (a division of NTIA, U.S. Department of Commerce). No credit is given, but the style and illustrations will be recognizable.