Video Acquisition Measurement Methods

Homeland Security

DHS-TR-PSC-07-02

Department of Homeland Security

Public Safety Communications

Technical Report

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Command, Control and Interoperability: Communication, Interoperability and Compatibility

Homeland Security
Science and Technology

Defining the Problem

Emergency responders—police officers, fire personnel, emergency medical services-need to share vital voice and data information across disciplines and jurisdictions to successfully respond to day-to-day incidents and large-scale emergencies. Unfortunately, for decades, inadequate and unreliable communications have compromised their ability to perform mission-critical duties. Responders often have difficulty communicating when adjacent agencies are assigned to different radio bands, use incompatible proprietary systems and infrastructure, and lack adequate standard operating procedures and effective multi-jurisdictional, multi-disciplinary governance structures.

OIC Background

The Department of Homeland Security (DHS) established the Office for Interoperability and Compatibility (OIC) in 2004 to strengthen and integrate interoperability and compatibility efforts to improve local, tribal, state, and Federal emergency response and preparedness. Managed by the Science and Technology Directorate, and housed within the Communication, Interoperability and Compatibility thrust area, OIC helps coordinate interoperability efforts across DHS. OIC programs and initiatives address critical interoperability and compatibility issues. Priority areas include communications, equipment, and training.

OIC Programs

OIC programs, which are the majority of Communication, Interoperability and Compatibility programs, address both voice and data interoperability. OIC is creating the capacity for increased levels of interoperability by developing tools, best practices, technologies, and methodologies that emergency response agencies can immediately put into effect. OIC is also improving incident response and recovery by developing tools, technologies, and messaging standards that help emergency responders manage incidents and exchange information in real time.

Practitioner-Driven Approach

OIC is committed to working in partnership with local, tribal, state, and Federal officials to serve critical emergency response needs. OIC's programs are unique in that they advocate a "bottom-up" approach. OIC's practitioner-driven governance structure gains from the valuable input of the emergency response community and from local, tribal, state, and Federal policy makers and leaders.

Long-Term Goals

- Strengthen and integrate homeland security activities related to research and development, testing and evaluation, standards, technical assistance, training, and grant funding.
- Provide a single resource for information about and assistance with voice and data interoperability and compatibility issues.
- Reduce unnecessary duplication in emergency response programs and unneeded spending on interoperability issues.
- Identify and promote interoperability and compatibility best practices in the emergency response arena.

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Abstract

Several sets of standards exist for measuring digital camera performance. Two sources of particular interest are the International Standards Organization (ISO) [1], and the Standard Mobile Imaging Architecture (SMIA), which publishes a camera characterization specification [2].

The camera performance measurements described here have been designed to be performed at moderate cost with moderately skilled operators. They generally involve photographing simple or standard targets under controlled lighting conditions and then analyzing the resulting images on a computer. The tests do not require expensive or highly specialized equipment.

Within the video transmission system, the tests measure the quality of the video acquisition subsystem (i.e., the video camera). In general, video acquisition quality may be divided into two aspects: still image and motion properties. Motion quality factors are difficult to measure. The most serious arise from image compression artifacts due to video coders. The tests described here are not intended to specify performance parameters for video coders, which may be an integral part of some video acquisition subsystems. Instead, performance parameters for video coders (e.g., frame rate) are considered as part of the video transmission subsystem.

The techniques for determining the video performance requirements given in Section 4 of the Public Safety Statement of Requirements (PS SoR) Volume II [22] are based on the camera performance measurements described here.

Key words: measure capture gama, measure color accuracy, measure dynamic range, measure exposure accuracy, measure flare light (spatial crosstalk or veiling glare), measure image sharpness, measure lens distortion, measure Modulation Transfer Function (MTF), measure reduced light and dim light, measure spatial and temporal variation, measure video acquisition quality, measure video camera acquisition performance, measure vignetting

1 Introduction

This report focuses on important video acquisition (i.e., camera) performance parameters for public safety applications [22]. Most of the tests that will be described were originally designed for still cameras and adapted for use with video cameras. All the tests require that one or more still frames be captured from the video camera. One major difference between still and video frames is low light performance. With video, there is little choice of shutter speeds and long exposure times cannot be used to compensate for dim lighting conditions. Dim lighting performance must therefore be characterized by exposure accuracy and noise.

Video acquisition quality is primarily affected by two factors that arise at different stages of the imaging process:

- Capture—Image quality factors affected by the sensor and lens. These include sharpness, noise (total, fixed pattern, and dynamic), dynamic range, exposure uniformity (vignetting), and color quality. Exposure, which is set at capture time, is also important. There is a tradeoff between pixel size and quality: small pixels provide greater image resolution but suffer more from diffraction and photon shot noise, which are fundamental effects of the wave and particle nature of light.
- Post-capture image processing—Factors include white balance, sharpness (as affected by sharpening), color saturation, and tonal response. These factors are not intrinsic to the camera

sensor and lens, but they can be important in real-time video systems, where there may be little or no opportunity to enhance the image after capture.

2 Lighting Conditions Terminology

The definitions in Table 1 are associated with specifying lighting conditions to be used for the parameter measurements.

Table 1: Lighting Terminology

Term	Description
Standard Lighting Intensity	Approximately 200 to 500 lux (a lux is equal to one lumen per square meter) with ± 10% uniformity over the test chart.
Reduced Lighting Intensity	Approximately 30 to 60 lux with ± 10% uniformity over the test chart.
Dim Lighting Intensity	Approximately 5 to 10 lux with ± 10% uniformity over the test chart.
Color Temperature	The color of the illuminating lamp, defined as the temperature (in degrees Kelvin (K)) at which a heated, black-body radiator matches the hue of the lamp. One key issue involving color temperature is the ability of the camera's white balance algorithm to adapt to light with different color temperatures.
Tungsten Light	Light that has a color temperature between 2,800 and 3,200K.
Daylight Light	Light that has a color temperature between 5,500 and 7,500K.
Neutral Density (ND) Filters	Uncolored filters specified by their density (-$\log_{10}$(light absorption)). These are placed in front of the light sources or camera lens to achieve reduced or dim lighting. Typical values are D = 0.3 (2x; 1 f-stop), 0.6 (4x; 2 f-stops), and 0.9 (8x; 3 f-stops). When filters are stacked, the density is summed. For example, if two SoLux Task Lamps located 1 meter from the target provide approximately 250 lux at the target, 0.6 + 0.9 ND filters (for a density of 1.5, which produces a decrease in lighting intensity by a factor of $2^{(1.5/0.3)} = 2^5 = 32$) can reduce the illumination to 250/32 = 7.8 lux, which is in the range of dim lighting. You can make fine adjustments by moving the lamps.

Table 1: Lighting Terminology (Continued)

<table>
<tr><th>Term</th><th>Description</th></tr>
<tr><td>Color Correction (CC) Filters</td><td>
Filters that alter the color temperature of light reaching the camera. These are placed in front of the lens or the light source. Filter degradation from heat can be a problem near strong light sources.

The best-known CC filters are the Wratten series 80 (strong cooling), 81 (subtle warming), 82 (subtle cooling), or 85 (strong warming). “Warming” means decreasing color temperature and “cooling” means increasing color temperature. Several filters correspond to each number in the series, e.g., 80A, 80B, 80C, etc., each of which alters color temperature by a different amount. (See table below.)

CC filters alter color temperature by a fixed number of mireds (micro-reciprocal degrees), where 1 Mired = 10^6/(degrees K). Example: The Wratten 80A filter (the strongest standard cooling filter) changes color by -131 mireds, equivalent to increasing color temperature from 3,200K to 5,500K. It also reduces light by 2 f-stops.
<table>
<tr><th colspan="4">Blue Filters</th><th colspan="4">Amber Filters</th></tr>
<tr><th>Filter</th><th>Exposure Increase</th><th>Conversion</th><th>Mired</th><th>Filter</th><th>Exposure Increase</th><th>Conversion</th><th>Mired</th></tr>
<tr><td>80A</td><td>2</td><td>3,200–5,500K</td><td>-131</td><td>81</td><td>1/3</td><td>3,300–3,200K</td><td>+9</td></tr>
<tr><td>80B</td><td>1 1/3</td><td>3,400–5,500K</td><td>-112</td><td>81A</td><td>1/3</td><td>3,400–3,200K</td><td>+18</td></tr>
<tr><td>80C</td><td>1</td><td>3,800–5,500K</td><td>-81</td><td>81B</td><td>1/3</td><td>3,500–3,200K</td><td>+27</td></tr>
<tr><td>80D</td><td>2/3</td><td>4,200–5,500K</td><td>-56</td><td>81C</td><td>1/3</td><td>3,600–3,200K</td><td>+35</td></tr>
<tr><td>82C</td><td>2/3</td><td>2,800–3,200K</td><td>-45</td><td>81D</td><td>1/3</td><td>3,700–3,200K</td><td>+42</td></tr>
<tr><td>82B</td><td>2/3</td><td>2,900–3,200K</td><td>-32</td><td>81EF</td><td>1/3</td><td>3,850–3,200K</td><td>+53</td></tr>
<tr><td>82A</td><td>1/3</td><td>3,000–3,200K</td><td>-21</td><td>85C</td><td>2/3</td><td>5,500–3,800K</td><td>+81</td></tr>
<tr><td>82</td><td>1/3</td><td>3,100–3,200K</td><td>-10</td><td>85</td><td>2/3</td><td>5,500–3,400K</td><td>+112</td></tr>
<tr><td></td><td></td><td></td><td></td><td>85B</td><td>2/3</td><td>5,500–3,200K</td><td>+131</td></tr>
</table>
</td></tr>
<tr><td>Middle Gray Surface</td><td>A neutral gray-colored surface with approximately 18 percent reflectance. A middle gray surface provides a useful background for test charts since it influences the auto-exposure algorithm and helps to obtain a good exposure. For the tests presented here, it is sufficient to have a good visual match with a surface of approximately middle gray, which includes patch M (7) on the Kodak Q-13 or Q-14 Gray Scale or patch 22 (4th from left on the bottom row) in the GretagMacbeth ColorChecker (see Figure 2, fourth from left on the bottom row). Examples of middle gray surfaces that can be used include Crescent mat board 1074 (Gibraltar Gray), 935 (Copley Gray), and 976 (Bar Harbor Gray).</td></tr>
</table>

3 Standard Test Chart Setup

Mount all of the test charts described in Section 3.1on a flat background, preferably a half-inch foam board, because this is lightweight and stays flatter than standard-thickness foam boards (both foam board types are widely available at art supply stores). Follow the procedures in Section 3.2 to ensure charts are uniformly illuminated.

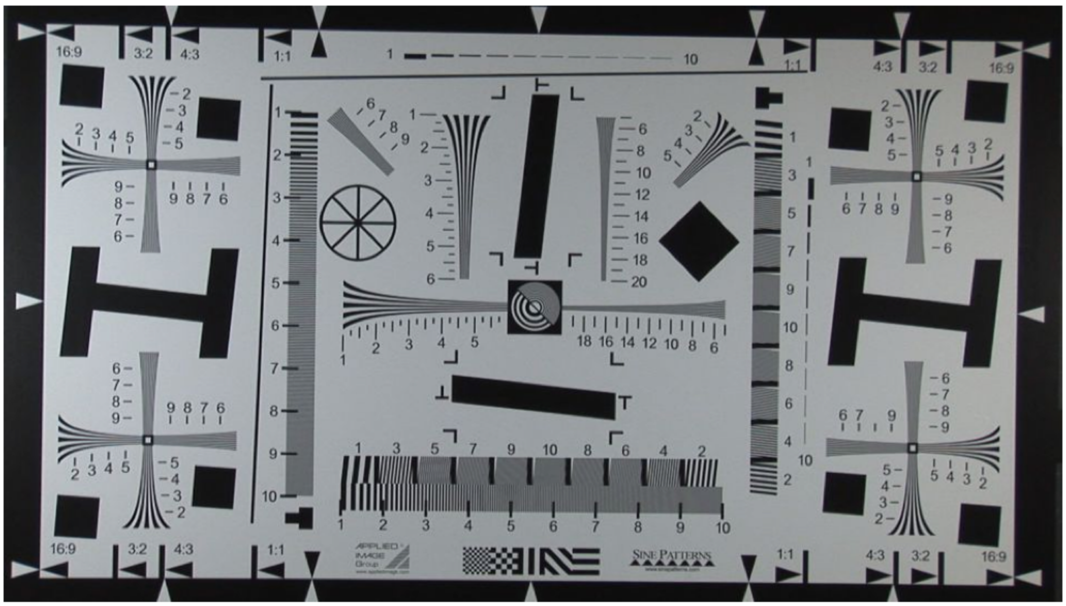
3.1 Standard Test Charts

Use the standard test charts in this section to measure resolution, noise, dynamic range (indirect method), color accuracy (and white balance), and lens distortion. Later sections describe specialized test patterns and methods for directly measuring dynamic range (see Section 4.3) and for measuring flare light distortion (see Section 4.10).

3.1.1 The ISO 12233 Test Chart

Figure 1 is a sample video frame of the ISO 12233 test chart that was captured using a high-definition (HD) video camcorder. This chart can be used for measuring resolution.

Figure 1: ISO 12233 Resolution Test Chart Captured Using an HD Video Camcorder



3.1.2 Combination Kodak Q-14 and GretagMacbeth ColorChecker Test Chart

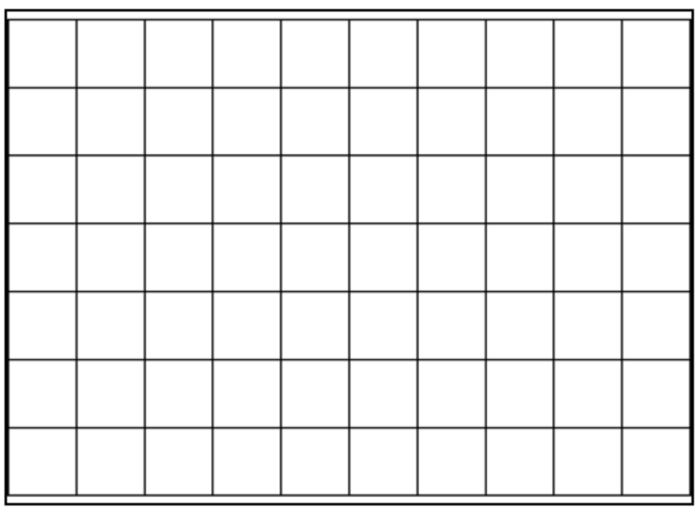
Figure 2 is a sample video frame of the combination Kodak Q-14 (top strip) and GretagMacbeth ColorChecker (bottom checkerboard) test chart that was captured using an HD video camcorder. You can use this combination test chart for measuring noise, color accuracy, and dynamic range (indirect method). Mount the two charts on a middle gray surface mat board between 11 by 14 inches and 12 by 16 inches in size. Mount the flimsy Q-14 test chart with adhesive spray to keep it flat. You can mount the more rigid ColorChecker chart by any means. Since you might need to photograph the gray mat board-mounted targets against dark and white backgrounds (e.g., a white background will be required for testing lens flare), back-affix the mat board with "hook and loop" material that allows easy attachment and removal.

Figure 2: Q-14 and ColorChecker Test Charts Captured Using an HD Video Camcorder

3.1.3 Rectilinear Grid Test Chart

Figure 3 presents a simple rectilinear test chart for testing barrel and pincushion distortion of video cameras.

Figure 3: Rectilinear Grid Test Chart for Testing Lens Distortion



3.1.4 Plain White or Gray Background

Use a very evenly lit white or gray background for performing vignetting measurements. A special device, called an integrating sphere, is advantageous for producing uniform lighting. This is especially true for testing wide-angle lenses, where even illumination over a large area may be difficult to achieve.

3.2 Lighting Setup for Test Charts

Ensure that the lighting on test charts is uniform and glare-free. To achieve this goal, illuminate reflective test charts by at least two lamps, one on each side of the target, oriented at angles between 30 and 45 degrees, as illustrated in Figure 4. To minimize glare on the test chart, ensure no significant lighting comes from behind the camera. Check that the optical axis of the camera is perpendicular to the test chart and intersects the center of the test chart. This will minimize perspective distortion. Lamp position and angle strongly affect the evenness of illumination across the test chart. To maximize uniformity of the light on the test chart, ensure that the lamps and camera all lie in the same horizontal plane, which also intersects the center of the test chart.

Figure 4: Lighting Setup for Test Charts

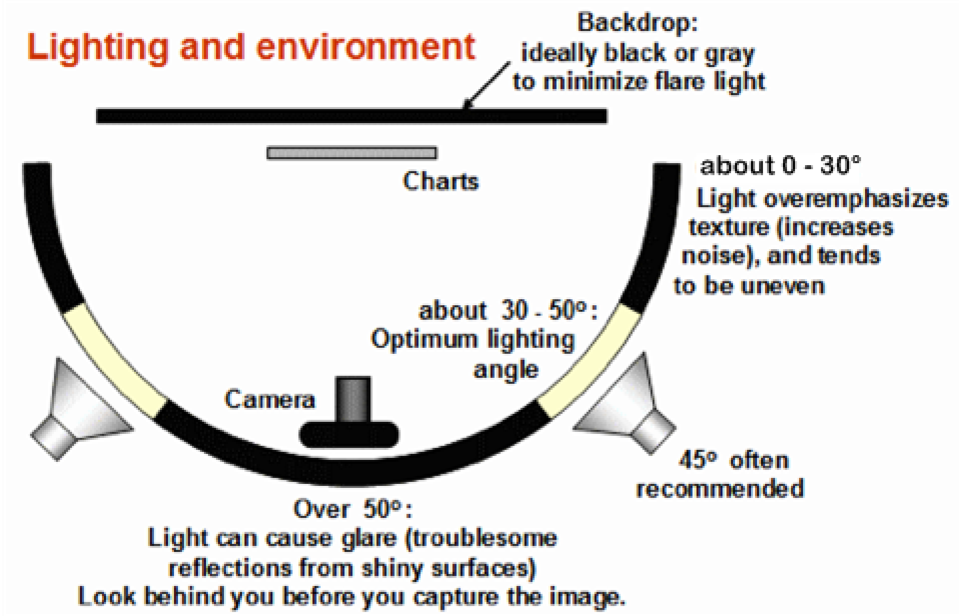


Figure 4 is similar to the default dark room illustration in the SMIA Camera Characterization Specification [3], which you can use for guidance in setting up the lighting. The SMIA-recommended 45º-angle is not optimal for wide-angle lenses. The angle may need to be reduced to 30º or less to reduce glare near the sides of the test chart, which can be particularly serious in the dark zones of the Kodak Q-14 gray scale step chart, which has a semi-gloss surface.

Uneven lighting on the test chart tends to be less noticeable in the original scene but more obvious in the captured image, so examine the post-exposure images carefully for signs of uneven lighting. If, for example, the gray areas on either side of the ColorChecker (i.e., the background gray mat upon which the ColorChecker is mounted) appear to have the same intensity values, then the lighting is sufficiently uniform from left to right. Use similar examinations to determine the top to bottom uniformity of the lighting.

Unless otherwise specified, conduct all performance measurements under standard lighting intensities (see "Standard Lighting Intensity" in Table 1) of approximately daylight color temperature (see "Daylight Light" in Table 1).

3.3 Lamps

Many illuminating lamp options are available to fulfill the lighting needs that Figure 4 illustrates. Select lamps that have native color temperatures between 4,000K and 7,000K with a color rendering index (CRI) of at least 90 percent. Placing two lamps roughly 1 meter from an 18-inch wide target should, with careful adjustment, provide at least 200 lux of even light (no more than ±10 percent variation) on the target.

Smaller lamps producing less heat are well-suited for adjusting color temperature using Wratten color correction filters (series 80, 81, 82, or 85) placed in front of the camera lens or the lamp.

Following are a few lamps covering a range of intensity, color temperature, and uniform lighting accuracy.

- **SoLux Task Lamp**. A halogen lamp with a built-in dichroic filter for 4,700K color temperature. Two SoLux lamps at 0.8 to 0.9 meters from the test chart produce approximately 250 lux of incident light [4].
- **GretagMacbeth Sol-Source Daylight Desk Lamp with Weighted Base**. This is a halogen lamp with a Wratten color-correction filter. You can choose the filter for color temperatures of 5,000K, 6,500K, or 7,500K [5].
- **North Light Ceramic High Intensity Discharge (HID) Copy Light**. A 4,200K color temperature lamp that is available in different wattage ratings (300, 600, and 900 watts) and useful for achieving even illumination [6].
- **Dedolight DLH200D Sundance Halogen Metal Iodide (HMI)**. A very high intensity 5,600K color temperature halogen light [7].

3.4 Modifications for Changing Color Temperature and Lighting Intensity

You can modify lamp heads to accept filters for use in reduced and dim light testing (see "Reduced Lighting Intensity" and "Dim Lighting Intensity" in Table 1), color temperature correction, and polarization for glare removal. For illustration purposes, Figure 5 shows the head of the SoLux Task Lamp.

Figure 5: SoLux Task Lamp Head

The modification involves inserting a lens shade that can accept filters over the lamp head. Figure 6, for example, shows a double-threaded rubber lens hood you could use to accept filters.

Figure 6: Example Lens Shade to Mount Filters

You can use epoxy or cyanoacrylate (Super Glue) to attach the lens shade to the metal rim of the lamp (just outside the bulb). Before attaching the lens shade, ensure there is sufficient clearance so the filters do not contact the lamp head diffuser, and that bulb replacements can occur freely without interference. Due to heat from the lamp, it might be preferable to mount the filters in front of the camera lens.

Use the following filters to adjust the lighting from the SoLux Task Lamp for different color temperatures and lighting intensities. Remember that a mired is 10^6 divided by the color temperature in degrees K.

- 85B warming (yellow) filter. +131 mireds. Changes 4,700K to 2,900K, typical of ordinary incandescent bulbs.
- 80C cooling (blue) filter. –81 mireds. Changes 4,700K to 7,500K, characteristic of cool daylight.
- Neutral Density (ND) filters with D = 0.3 (2x; 1 f-stop), 0.6 (4x; 2 f-stops), and 0.9 (8x; 3 f-stops). Filters can be stacked to obtain densities up to 1.8 (64x; 6 f-stops). For example, if two SoLux Task Lamps located 1 meter from the target provide approximately 250 lux at the target, 0.6 + 0.9 ND filters (for a density of 1.5, which produces a decrease in lighting intensity by a factor of $2^{(1.5/0.3)} = 2^5 = 32$) can reduce the illumination to 250/32 = 7.8 lux, which is in the range of dim light testing. You can make fine adjustments by moving the lamps.

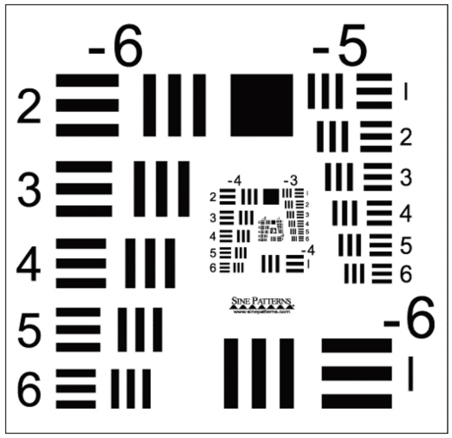
4 Methods of Measurement for Performance Parameters

4.1 Resolution

Resolution is one of the most important image quality factors; it is closely related to the amount of visible detail in an image. The camera's lens quality, sensor design, signal processing, and especially the application of sharpening or unsharp masking—which can result in “halos” near edges when overdone—all affect resolution.

The traditional method of measuring sharpness uses a resolution test chart. First, you capture an image of a resolution test chart such as the USAF 1951 chart (see Figure 7), which consists of a set of bar patterns. Next, you examine the captured image to determine the finest bar pattern that is discernable as black-and-white (B&W) lines. Finally, you make measurements of the horizontal and vertical resolution by using bars orientated in the vertical and horizontal directions, respectively. Unfortunately, this procedure presents problems because it is manual and its results have a strong dependence on the observer’s perception, which can deliver resolution results that correlate poorly with perceived sharpness.

Figure 7: USAF 1951 Chart



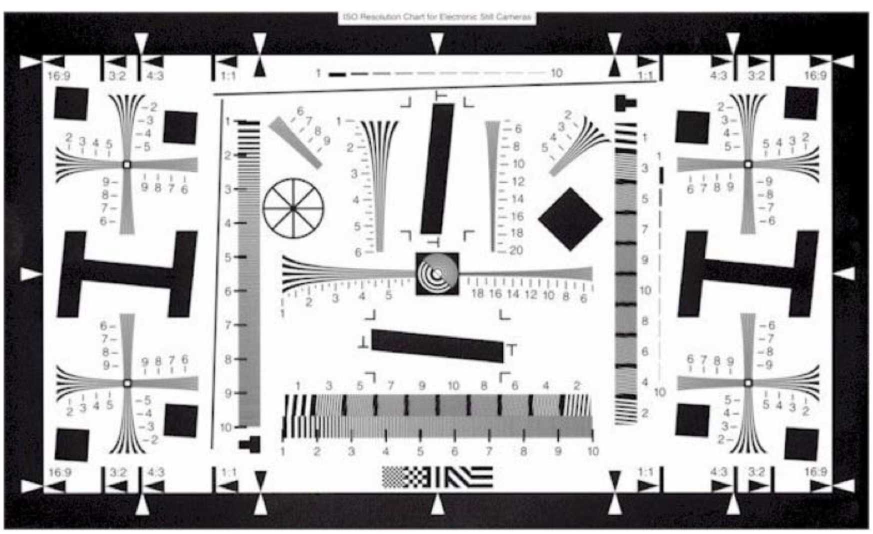
A more contemporary approach is to measure the Modulation Transfer Function (MTF) of the camera system. MTF is the name given by optical engineers to Spatial Frequency Response (SFR). The more extended the MTF response, the sharper the image. The ISO 12233 standard contains a powerful technique for measuring MTF from a simple, slanted-edge target image that is present in the ISO 12233 resolution test chart (see Figure 8).

The International Imaging Industry Association (i3a) offers two free application downloads [8] that implement the ISO standard:

- Slant Edge Analysis Tool sfrwin 1.0 (Windows®-executable for most users)
- Slant Edge Analysis Tool sfrmat 2.0 (MATLAB® must be installed)

Both downloads include printable user guides and both provide SFR plots, but offer little numerical output.

Figure 8: ISO 12233 Resolution Chart



To give accurate results, the sfrmat and sfrwin applications require you to load a tonal response curve, or Opto-Electronic Conversion Function (OECF) file. If the file is omitted, the applications assume gamma = 1, which is atypical of still and video cameras that actually tend to have a capture gamma of around 0.5.

Without the proper OECF file, a measurement error of about 10 to 15 percent will result. Since the sfrmat and sfrwin applications do not come with an OECF file for a gamma of 0.5, Section 5 contains a MATLAB script (makeoecf.m) for creating OECF files.

4.1.1 Example Procedure for Measuring Sharpness

The following example uses the sfrwin application to measure sharpness.

1. Download the sfrwin application mentioned in Section 4.1 for analyzing the slanted-edge pattern in the ISO 12233 resolution chart.

   Extract the sfrwin.zip file into a folder of your choice. (The steps that follow assume the sfrwin application is installed in C:\programs\sfrwin.) Use the makeoecf.m MATLAB program to create an appropriate OECF Look Up Table (LUT) file for the camera system being tested (e.g., a gamma of 0.5 for B&W would produce the OECF file "lut_0.5_1.dat"; a gamma of 0.5 for color would produce the OECF file "lut_0.5_3.dat"). Copy this file into C:\programs\sfrwin\data.

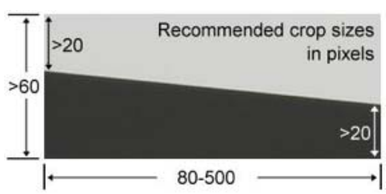
2. Mount the ISO 12233 test chart on a sheet of foam board (1/2-inch thick preferred), using a spray adhesive to keep it flat. Alternatively, use a test chart consisting of high-quality laser prints of slanted edges, tilted roughly 5 degrees from horizontal and vertical.

3. Set up the test chart according to the instructions in Section 3.2. Frame the test chart within the video picture according to the appropriate aspect ratio markings on the chart (e.g., Figure 1 shows proper test chart framing for an HDTV—high-definition television—camera with a 16:9 aspect ratio).

4. Save a sample video clip from the camera and convert one video frame from this file into a standard still image format. Use TIFF or BMP image formats. You can convert a file to TIFF by opening it with an editor such as Irfanview [9] and saving it as a TIFF file.

5. Run the sfrwin application for slanted vertical and horizontal edges near the center of the image and in the far corner of the image (e.g., one of the edges on the lower-right or upper-left of the ISO 12233 chart in Figure 8). For some cameras, the resolution may vary significantly, depending upon the location in the image (i.e., center vs. edge) and the direction (i.e., horizontal vs. vertical).

Figure 9: Best Minimum Cropped Region Pixel Dimensions

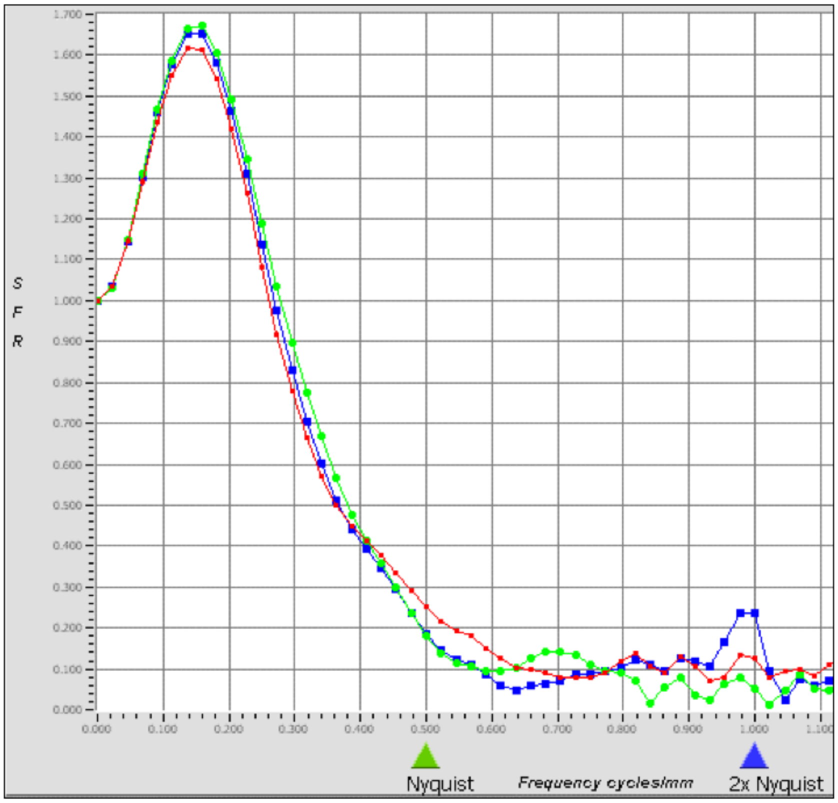


Although the cropped region can be as small as 20 by 20 pixels, ensure the cropped region is at least 60 pixels wide and 80 pixels long to attain the most accurate and consistent results. (Note that the edge is approximately centered in the cropped image.) The horizontal slant edge in Figure 9 is used for measuring the resolution in the vertical direction, while a vertical slant edge (from another part of the ISO 12233 chart) is used for measuring the resolution in the horizontal direction.

In the sfrwin application, leave both **LUT** boxes unchecked for the first run. Leave **Pitch in mm** at **1.0000** to get the output X-axis scaled in cycles per mm. Click **Acquire Image**. Select the input file. Select the region of interest to analyze by clicking and dragging the mouse. In the **Please select the ROI…** window, which might be behind the image window, click **Continue**. Now enter the OECF file name (e.g., lut_0.5_3.dat).

Figure 10 shows example MTF results from the sfrwin application for one slant edge (red, green, and blue channels plotted separately).

Figure 10: Example MTF Results from sfrwin Application



The frequency at which MTF drops to 50 percent (MTF50) of its low frequency value is a widely used sharpness metric. But this metric has a serious weakness because it is strongly affected by sharpening applied by software inside the camera. All digital images benefit from some degree of sharpening, but some cameras over-sharpen, resulting in unrealistically high MTF50 values and annoying halo effects near edges.

A better metric for video systems that works in the presence of over-sharpening is MTF50P, the frequency where MTF is half (50 percent) of its peak value. In Figure 10, the peak MTF is 1.65. MTF50P is the spatial frequency where MTF is half that value, in this case 0.82. For this edge, MTF50P = 0.301 cycles per pixel. This example is for horizontal resolution measured using a vertical edge. MTF50P is identical to MTF50 for images that have little or no sharpening, where MTF(0) = MTF(fpeak).

There are several units for measuring MTF50P. While cycles per pixel are produced directly by the sfrwin application, this measures performance on the pixel level. To obtain a measure of the total image resolution, MTF50P is converted into line widths per picture height (LW per PH, where one cycle equals two line widths), using the following equation:

$$\text{LW per PH} = 2 \times \text{cycles per pixel} \times \text{total pixels}$$

For the example in Figure 10, this would produce a horizontal image resolution value of $2 \times 0.301 \times 640$ (i.e., VGA image), or 385 LW per PH.

4.1.2 Algorithm for Calculating MTF

A description follows of the MTF calculation, as derived from ISO 12233 standard slant edges and as implemented by the sfrmat and sfrwin applications. The essential algorithm described here determines the Fourier transform of the impulse response, which is in turn estimated from the derivative of the unit step response:

1. The pixel values in the cropped image are linearized, i.e., the pixel levels are adjusted to remove the transfer curve (also known as the OECF or gamma encoding) applied by the camera.
2. The edge location centers for the Red, Green, Blue, and luminance channels (Y = 0.299 × Red + 0.587 × Green + 0.114 × Blue) are determined for each line (e.g., for measuring resolution in the vertical direction, the vertical lines in the cropped image with a horizontal slant are used). The edge location centers in each line are determined by differencing successive pixel values in the line, and then finding the location of the maximum absolute value.
3. A first- or second-order least-squares fit is calculated for each channel using polynomial regression, where y denotes the edge location centers (from step 2), and x represents the associated pixel locations of each line. For the cropped image, the second-order equation would have the form, $y = a_0 + a_1 x + a_2 x^2$. The a_i coefficients can be found using the MATLAB polyfit function; the fitted y can be determined using the MATLAB polyval function. The fitted y provides an improved estimate for the true edge location centers. A second-order least-squares fit may be required when lens distortion creates a curved rather than straight slant edge.
4. Depending on the value of the fractional part $fp = y_i - \mathrm{int}(y_i)$ of the second-order least-squares fit for each line, four average lines are produced, one line for each of the following: $0 \le fp < 0.\dot{2}5$, $0 \le fp < 0.\dot{5}$, $0.5 \le fp < 0.\dot{7}5$, and $0.75 \le fp < 1$. The averaging process centers the edge locations of each line within the averaging buffers. Each of the four average lines forms an estimate of the unit step response, each shifted by ¼ pixels.
5. The four average lines from step 4 are interleaved to produce a 4x oversampled line. This allows analysis of spatial frequencies beyond the normal Nyquist frequency.
6. The derivative (*d/dx*) of the averaged 4x oversampled edge is calculated by differencing adjacent pixels. A Hamming windowing function is applied to force the derivative to zero at the endpoints.
7. MTF is the absolute value of the fast Fourier transform (FFT) of the windowed derivative from step 6.

4.2 Noise

Noise is the unwanted random spatial and temporal variations (e.g., snow) in the video picture. It has a strong effect on a camera's dynamic range.

One method of measuring noise is to capture and analyze images of a step chart consisting of patches of uniform density, such as the Kodak Q-14 Gray Scale (Figure 2, top). The Q-14 Gray Scale consists of 20 patches with densities from 0.05 to 1.95 in steps of 0.1. Noise and signal-to-noise ratio (SNR) can be measured for each patch. SNR tends to be worst in the darkest patches and for dim lighting. Several lighting conditions with various intensities (e.g., standard, reduced, dim) and color temperatures (e.g., tungsten, daylight) may be required to adequately characterize noise and SNR.

Follow these steps to measure noise and SNR within a patch:

1. Select a rectangular region that contains most of the patch. The edges of the selected region should be far enough from the patch boundaries to eliminate edge effects. The selected region typically comprises 50 to 70 percent of the total patch area. The pixel values will be represented by *P*(*x*,*y*), where $1 \le x \le m$ and $1 \le y \le n$. The mean pixel level of the region is:

$$\mathrm{mean}(P) = \frac{1}{mn}\sum_{x=1}^{m}\sum_{y=1}^{n} P(x,y)$$

2. A useful approximation of the noise in the region is the standard deviation σ of:

$$P{:}N_P = \sigma(P) = (\Sigma(P(x,y) - \mathrm{mean}(P))^2/(mn-1))^{1/2}$$

   However, lighting nonuniformity reduces the accuracy of the simple standard deviation in many practical situations. To obtain a good noise measurement, the signal variation due to lighting nonuniformity must be removed, as the following procedure describes:

   a. Find the horizontal and vertical mean values of the signal.

$$P_{Ymean}(x) = \frac{1}{n}\sum_{y=1}^{n} P(x,y) \qquad P_{Xmean}(y) = \frac{1}{m}\sum_{x=1}^{m} P(x,y)$$

   b. Find the second-order polynomial fits to these means.

$$F_Y(x) = f_{y1}x^2 + f_{y2}x + f_{y3} \qquad F_X(y) = f_{x1}y^2 + f_{x2}y + f_{x3}$$

   The f_{xi} and f_{yi} coefficients can be found using the MATLAB polyfit function; the fitted $F_Y(x)$ and $F_X(y)$ can be determined using the MATLAB polyval function. These values represent the slowly varying illumination within the patch.

   c. Subtract the nonuniformity terms of F_Y and F_X from *P*(*x*,*y*) to obtain the uniformly illuminated signal:

$$P_U(x,y) = P(x,y) - f_{y1}x^2 - f_{y2}x - f_{x1}y^2 - f_{x2}y$$

   d. Pixel noise is the standard deviation of P_U for the region $(1 \le x \le m, 1 \le y \le n)$:

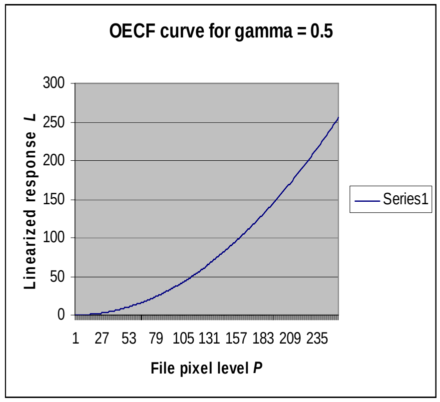
$$N_P = \sigma(P_U) = (\Sigma(P_U(x,y) - \mathrm{mean}(P_U))^2/(mn-1))^{1/2}$$

   e. Note that the constant terms, f_{y3} and f_{x3}, have no effect on N_P; using the equation $P_U(x,y) = P(x,y) - F_Y(x) - F_X(y)$ instead of the equation in step c, results in the same value of N_P.

3. The *pixel* SNR (P/N_P) for the region is equal to $\mathrm{mean}(P_U)/N_P$.

4. In imaging literature, *S*/*N* often refers to the scene-referenced or sensor SNR, S/N_S, prior to the conversion to an image file. The conversion is characterized by a transfer function called the OECF (Opto-Electronic Conversion Function), which is represented as a table with pixel level *P* as the independent variable and Luminance (linearized response) *L* as the dependent variable. Figure 11 shows an OECF curve for camera gamma = 0.5.

Figure 11: OECF Table Plot for Camera Gamma



5. The OECF can be calculated from the image of the Q-14 chart using the knowledge that the chart has density steps of 0.1, where *density* = $-\log_{10}$(exposure).

6. The OECF is often approximated as an exponential function, though in practice an "S" curve is frequently superimposed on top of the exponential. The exponential transformation from the sensor to the image file is called gamma encoding; it is the inverse function of the OECF, since luminance is transformed to pixel level (see Figure 12). The equation for gamma encoding is $\text{Pixel level} = P = L^{\Delta}$, where L is luminance. Camera gamma γ is typically around 0.5 for standard image files [10] designed for display gamma = 2.2.

   Camera/Capture Gamma Nomenclature

   Display (i.e., monitor) gamma is always described by the equation, $L = P^{\gamma}$. But camera (or capture) gamma can be defined in either of two ways: 1) It can be defined under the assumption that $\text{output} = \text{input}^{\gamma}$, in which case, $P = L^{\gamma}$; or 2) it can be defined under the assumption that $L = P^{\gamma}$ for both the input and the output, in which case, $P = L^{\frac{1}{\gamma}}$. The former assumption is used in standard film response curves. The latter assumption appears in some imaging literature, for example, in Charles Poynton's well-known Gamma FAQ.[1]

   In this document we use the first formula, $P = L^{\gamma}$. With this nomenclature, camera and display gamma have the same units, so that total system gamma is the product of the camera and display gamma.

7. Gamma (γ) is a measure of perceived image contrast. It can be determined by plotting $\log_{10}(P)$ as a function of *density*, ($-\log_{10}$(exposure)). γ is the average slope of the relatively linear region of the plot, i.e., where the slope is at least 20 percent of its maximum value. This requirement ensures that a relatively linear portion of the response curve is used. Portions of the image where the slope is lower, typically located in the toe and knee (deep shadow and extreme highlight regions) of the response curve, contribute little to the pictorial content of the image. Strobel, Compton, Current, and Zakia provide justification for this criterion [11]. Gamma can be measured at the same time as noise using the method described in Section 4.5.

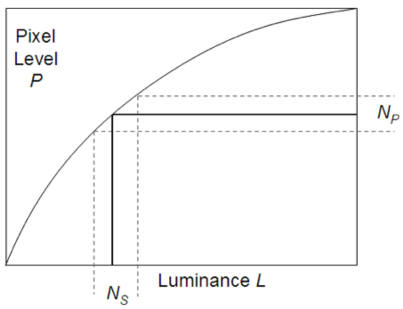
8. The scene or luminance noise, scaled according to Figure 12 (the inverse of the OECF chart), is

1. For NTSC video systems, camera gamma is equal to 0.45.

$$N_S = N_P \frac{dL}{dP}$$

where *dL/dP* is the derivative of the OECF.

Figure 12: Scaled Luminance Noise



9. The scene-referenced SNR is:

$$S/N_S = \frac{L}{N_S} = \frac{L}{N_P \frac{dL}{dP}}$$

10. For an OECF that is approximated by the inverse function of the gamma correction curve, $P = L^{\gamma}$, and

$$\frac{dP}{dL} = \gamma L^{\gamma - 1} \qquad \frac{dL}{dP} = \frac{P^{1/\gamma - 1}}{\gamma}$$

The scene-referenced SNR is approximated by:

$$S/N_S = \frac{L}{N_S} = \frac{\gamma P^{1/\gamma}}{N_P P^{1/\gamma - 1}} = \frac{\gamma P}{N_P}$$

where γ is the factor that converts pixel SNR, which is easy to measure, into scene SNR. This approximation holds true only when the OECF resembles an exponential curve.

These equations provide the basis for measuring noise and SNR in individual patches of any of several test charts. It is possible to specify maximum values of noise, or minimum values of SNR, for one or more patches in a chart. An example is patches 2 (light gray) and 10 (dark gray) of the Kodak Q-14 Gray Scale. Noise is generally invisible in white areas, and difficult to see in dark areas (although SNR can be poor in dark areas). Noise tends to be worse in dim light, where amplifier gain in video cameras has to be boosted to recover the signal.

4.3 Dynamic Range

Dynamic range (DR) is an important video acquisition performance specification in many public safety applications, especially where lighting is poorly controlled or where video images contain multiple objects under vastly different lighting conditions. An example is nighttime objects illuminated by a spotlight together with objects not illuminated by the spotlight.

The measurement of DR in this section is for instantaneous DR, in that the camera's aperture and shutter speed are assumed to be fixed for the duration of the measurement. This is different than tunable dynamic range, where the camera aperture can be opened and closed over time. Instantaneous DR is a measure of the total range of unique luminance levels that can be output by the camera in any given video frame.

A camera's effective dynamic range depends primarily on two factors:

- Intrinsic dynamic range of the camera's image sensor—or the range of unique luminance levels that can be captured by the sensor. In video cameras, where the frame rate does not allow long exposures and where low light performance is achieved by increasing the amplifier gain, versus opening up the lens aperture, effective dynamic range will be limited by reduced SNR.
- Flare light—also called "veiling glare." Light that bounces between lens elements and off the interior barrel of the lens can limit the effective dynamic range by fogging shadows and causing ghost images in the proximity to bright light sources.

DR is usually measured in f-stops (factors of two in luminance), but it can also be measured in exposure density units, where one density unit = 3.32 f-stops. You can measure DR by photographing a transmission or reflection step chart consisting of patches with a wide range of densities. Most step charts have uniform density steps of 0.1 or 0.15 (1/3 or 1/2 f-stop). The logarithm to the base 10 of the pixel level ($\log_{10}(P)$) and the scene-referred SNR is calculated for each patch.

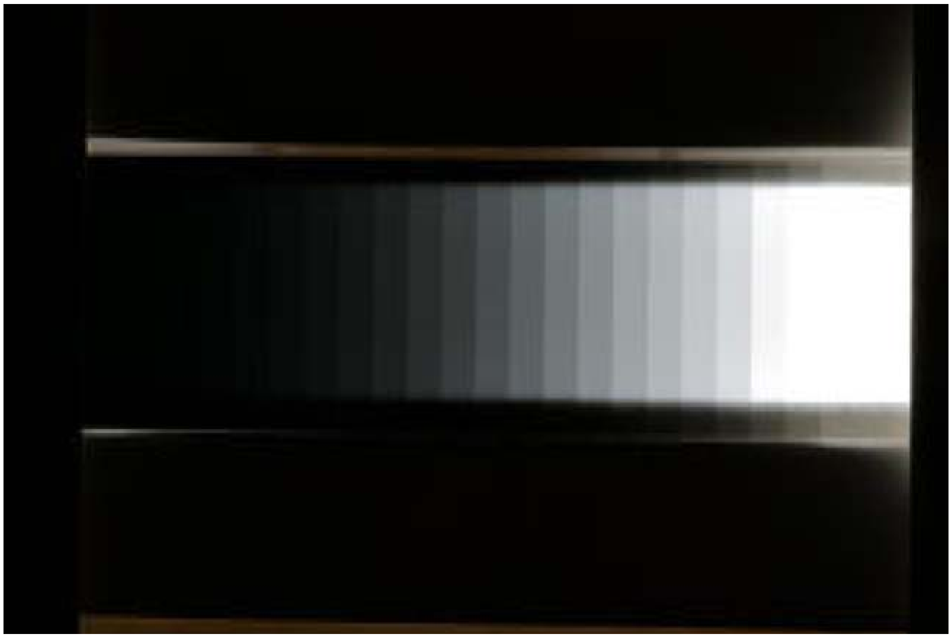
The camera's dynamic range is then defined as the range of step chart densities (or equivalently, f-stops) where the following criteria are met:

1. The difference in $\log_{10}(P)$ between patches for charts with uniform density steps (or $\Delta(\log_{10}(P))/\Delta(\text{density})$ for charts with non-uniform density steps) is greater than a specified fraction (typically 0.2 to 0.3) of the maximum difference. The difference refers to the maximum difference observed over all the steps. This difference is called the contrast step.
2. The scene-referenced SNR (see Section 4.2) is greater than a specified level, typically 1, which corresponds to the intent of the ISO 15739 specification [21], which defines the ISO digital still camera (DSC) dynamic range measurement. The higher the specified level of the scene-referenced SNR, the smaller the resulting dynamic range. This dynamic range will still have a higher effective SNR.

Significant differences exist between DR measurements of still and video cameras. Still cameras, especially digital SLRs with large pixel sizes, often have extremely large dynamic ranges, 10 or more f-stops, which can be realized via post-processing of raw sensor files. This is more than can be easily displayed in prints, so a certain amount of post-processing image manipulation is required to make the full dynamic range useful (e.g., to bring out information hidden in the shadows). On the other hand, users can only access processed sensor information from video cameras that have much less dynamic range.

Because still cameras can have such large dynamic ranges, their DR is best tested using transmission step charts (e.g., Figure 13) such as the Stouffer T4110, which has an exposure density range of 4.0. Measuring DR with a transmission chart takes considerably more care and effort: the chart must be evenly illuminated from behind and photographed in total darkness. Stray room light must be avoided.

Figure 13: Example Transmission Step Chart Image



On the other hand, you can photograph the Kodak Q-13 or Q-14 reflection step chart (top strip chart in Figure 2) using the standard lighting setup described in Section 3.2. But its exposure density range is only 1.9, which is equivalent to 1.9 × 3.32 = 6.3 f-stops. This is well below the DR of many digital still and video cameras, but it may be sufficient for specifying whether a video camera has sufficient DR for public safety requirements. You can measure a camera's DR using a chart with a DR less than that of the camera under test by specifying both criteria 1 and 2 described above (i.e., the minimum value of $\Delta(\log_{10}(P))$ and the minimum SNR) in such a manner so as to ensure that the camera has excellent performance within the 6.3 f-stop range of the reflective chart (with high SNR) as well as acceptable performance beyond the 6.3 f-stops (with reduced SNR).

In summary, a camera's dynamic range can be measured by one of two methods:

- **Direct Method.** Uses a transmission step chart with a density range that equals or exceeds the camera's DR. Direct measurements are more difficult to perform than indirect measurements, but they are more accurate and can be used as checks on indirect measurements.
- **Indirect Method.** Uses a reflection test chart, such as the Kodak Q-13 or Q-14, whose DR may be less than that of the camera under test. Rather than estimating the camera's total DR, minimum acceptable values are set for both the contrast step $(\Delta(\log_{10}(P))/\Delta(\text{density}))$ and the minimum SNR. This ensures that the camera's effective DR exceeds the density range of the reflective chart by an acceptable margin. The indirect method is much more convenient than direct method.

4.3.1 DR Direct Method

Table 2 lists several transmission step charts, all of which have a density range of at least 3 (10 f-stops). Kodak and Stouffer photographic step tablets can be purchased calibrated or uncalibrated. Calibrated charts, which have individual density measurements for each patch, offer an assurance of quality but little practical improvement in accuracy.

Table 2: Transmission Step Charts for Measuring Dynamic Range with the Direct Method

Product	Steps	Density Increment	Dmax	Size
Kodak Photographic Step Tablet No. 2 or 3	21	0.15 (1/2 f-stop)	3.05	1 by 5.5 inches (#2) larger (#3)
Stouffer Transmission Step Wedge T2115	21	0.15 (1/2 f-stop)	3.05	0.5 by 5 inches
Stouffer Transmission Step Wedge T3110	31	0.10 (1/3 f-stop)	3.05	3/4 by 8 inches
Stouffer Transmission Step Wedge T4110	41	0.10 (1/3 f-stop)	4.05	1 by 9 inches
Danes-Picta TS28D (on its Digital Imaging page)	28	0.15 (1/2 f-stop)	4.2	10 by 230 mm (0.49 inches)

Follow these steps to manually measure DR using the direct method:

1. Prepare a fixture for mounting the transmission step chart. Ensure it is large enough to keep stray light out of the camera.

   Note: Stray light can reduce the measured dynamic range; avoid it at all costs. You can make fixtures from simple materials such as scrap mat board.

2. Place the fixture with the step chart on top of a light box or any other source of uniform diffuse light. Standard light boxes are fine. If some non-uniformity is visible in the light box, orient the chart to minimize its effects; that is, if there is a linear fluorescent lamp behind the diffuser, place the chart above the lamp, along its length.

3. Photograph the step chart in a darkened room. Ensure no stray light reaches the front of the target, as this will distort the results. Keep the surroundings of the chart relatively dark to minimize flare light, as Figure 13 shows. The density difference between the darker zones is not very visible in the figure, but it shows up clearly in the measurements.

   - If possible, set the camera exposure manually. The indirect method, which Section 4.3.2 describes, is more suitable for cameras that cannot be set manually because a reflection chart can easily be surrounded with a neutral (approximately 18 percent reflectance) gray background to influence the auto-exposure setting. If your camera displays a histogram, use it to determine the exposure that just saturates the lightest region of the chart. Overexposure (or underexposure) will reduce the measured dynamic range. The lightest region should have a relative pixel level of at least 0.98 (pixel level 250 of 255). Otherwise, the full dynamic range of the camera will not be measured.

   - You can photograph the chart slightly out of focus to minimize noise measurement errors due to texture in the test chart patches. We emphasize the word “slightly” because the boundaries between the patches must remain distinct.

   - The distance to the test chart is not overly critical. For an accurate noise analysis, ensure the chart fills most of the image width for cameras with VGA (640 pixels wide) or lower resolution. Increasing the size improves the accuracy of the noise measurement, although in some cases it might increase light falloff (vignetting), which can affect the accuracy of the measurement.

   - Capture the image from the camera in the highest quality format. If the camera employs data compression, use the highest quality (lowest compression) setting.

4. Determine the mean pixel level and scene-referenced SNR of each patch in the chart image. (These are defined in Section 4.2.)

5. Visualize the results by plotting the logarithm of the normalized mean pixel level (e.g., $\log_{10}(\text{mean}(P)/255)$ for systems with 8-bits per color) against $\log_{10}(\text{exposure})$. This can be derived from the known density steps of the chart, most often 0.10 or 0.15. $\log_{10}(\text{exposure}) = -density + k$, where k is an arbitrary constant. This is a standard plot that is similar to traditional characteristic curves for film.

6. The dynamic range is the range of densities, or the density step multiplied by the number of steps, where 1) the contrast step $(\Delta(\log_{10}(\text{mean}(P)/255))/\Delta(\text{density}))$ is larger than 0.2 of the maximum contrast step; and 2) the scene referenced SNR (S/N_S, defined in Section 4.2) is larger than a specified minimum level, typically 1 or larger. If you choose a scene referenced SNR level other than 1, include this level with the DR specification. Convert dynamic range in density to f-stops by multiplying by 3.32.

The following steps use the Imatest application [12] as an example to illustrate the direct method of measurement for DR:

1. Download and install the Imatest application.

2. Start the Imatest application, and click the **Stepchart** button in the main Imatest window.

3. Open the input image file.

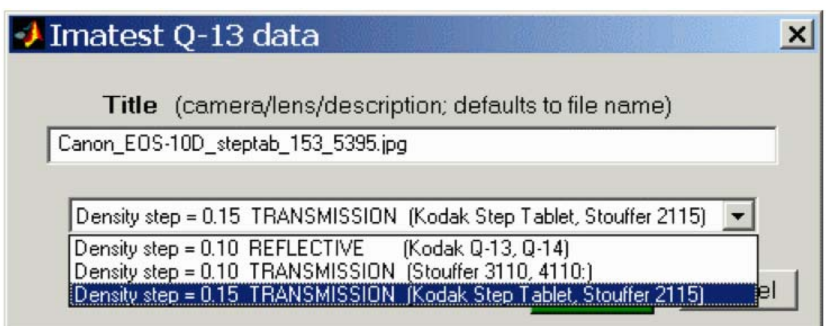
4. Crop the image to minimize edge effects.

   The red rectangle in Figure 14 shows a typical crop.

Figure 14: Example Crop of a Stouffer T4110 Chart

5. Make any necessary changes in the step chart input window (see Figure 15).

Figure 15: Example Step Chart Input Selection



   The default selection is a reflective target with density steps of 0.10 (i.e., the Kodak Q-13 or Q-14). If you are using a transmission target (see Table 2), choose the correct target type from the drop-down list.

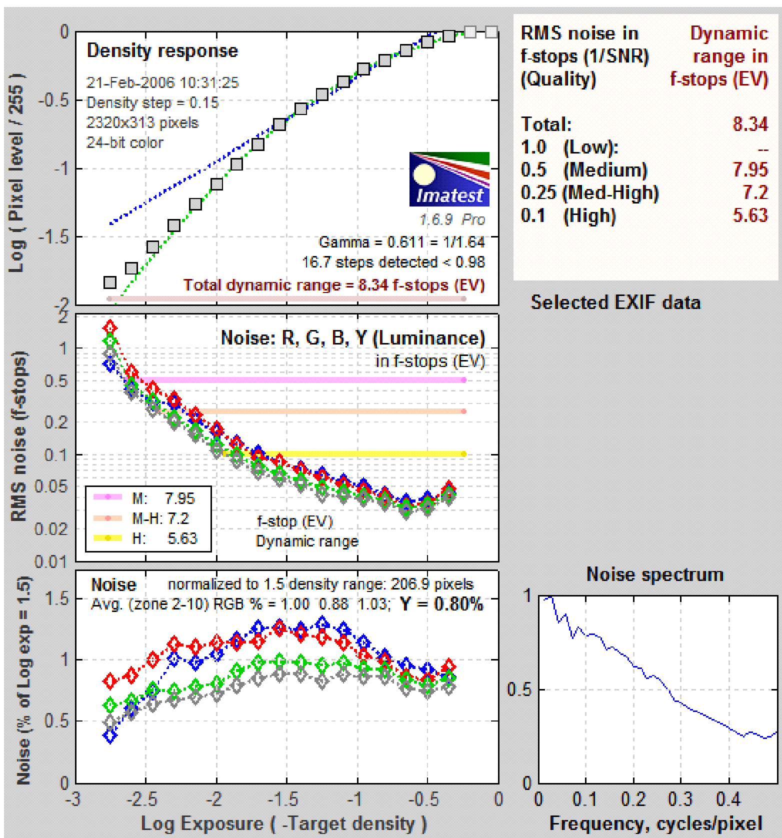
6. Click **OK** to continue.

Figure 16 shows the strip chart image of Figure 14 after step chart processing.

Figure 16: Strip Chart Image of Figure 14 After Step Chart Processing

Imatest detects the chart zones using the smallest density step that results in uniformly spaced detected zones. For smaller steps, noise can be mistaken for zone boundaries. For larger steps, fewer zones are detected. The dynamic range is the difference in density between the zone where the pixel level is 98 percent of its maximum value (250 for 8-bits per color, where the maximum is 255), estimated by interpolation, and the darkest zone that meets the measurement criterion in step 5 of the preceding list of steps for manually measuring DR using the direct method. Figure 17 presents example DR results from the Imatest application. The measured DR is 8.34 f-stops.

Figure 17: Example DR Measurement Results



4.3.2 DR Indirect Method

The indirect dynamic range measurement is easier to perform than the direct measurement because it takes advantage of the same lighting setup used in the sharpness and color measurements (see Section 3.2). It is based on a minimum detectable contrast step with a specified SNR in an image of a reflective step chart with a density range of 1.9: somewhat less than the expected total dynamic range, but very practical nonetheless.

Some of the following steps for the indirect dynamic range measurement are identical to the direct method in Section 4.3.1.

1. Photograph the Q-14 (or similar) reflective step chart, mounted as described in Section 3.1.2, and light as described in Section 3.2. Check the image carefully to make sure there is no glare or reflections on the target, which would ruin the measurements.
   - You can photograph the chart slightly out of focus to minimize noise measurement errors due to texture in the test chart patches. We emphasize the word “slightly” because the boundaries between the patches must remain distinct.
   - The distance to the test chart is not overly critical. For an accurate noise analysis, ensure the chart fills most of the image width for cameras with VGA (640 pixels wide) or lower resolution. Increasing the size improves the accuracy of the noise measurement, although in some cases it may increase light falloff (vignetting), which may affect the accuracy of the measurement.
   - Capture the image from the camera in the highest quality format. If the camera employs data compression, use the highest quality (lowest compression) setting.
2. Determine the logarithm of the normalized mean pixel level (e.g., $\log_{10}(\text{mean}(P)/255)$ for 8-bit systems) and scene-referenced SNR (S/N_S) of each patch in the chart image. (Section 4.2 describes this process.)
3. Visualize the results by plotting the logarithm of the normalized mean pixel level against $\log_{10}$(exposure), which can be derived from the known density steps of the chart, typically 0.10 or 0.15, using the equation, $\log_{10}(\text{exposure}) = -density + k$, where *density* is the patch density and *k* is an arbitrary constant. This is a standard plot that is similar to traditional characteristic curves for film.
4. The dynamic range is the range of densities (the density step times the number of steps) where: 1) the contrast step $(\Delta(\log_{10}(\text{mean}(P)/255))/\Delta(\text{density}))$ is larger than 0.2 of the maximum contrast step; and 2) the scene referenced SNR (Section 4.2 defines S/N_S) is larger than a specified minimum level, typically 1 or larger. If you choose a scene-referenced SNR level other than 1, include this level with the DR specification. Choosing a scene referenced SNR level that is greater than one for this indirect DR measurement will allow a higher effective DR to be specified, provided all patches still fall within the criteria. Convert dynamic range in density to f-stops by multiplying by 3.32.

4.4 Color Accuracy

Color accuracy is dependent on a camera’s sensor quality and signal processing, particularly its white balance (WB) algorithm. Measure color accuracy under both daylight and tungsten lighting, as Section 2 describes.

Measure color accuracy by photographing the GretagMacbeth ColorChecker (see Section 3.1.2), the widely used standard color chart consisting of 24 patches: 18 color and 6 grayscale. Using the color difference equations in the sections that follow, analyze the individual color patches for color error. These color difference equations are from the *Digital Color Imaging Handbook* [13].

The ideal background for photographing the color chart is gray mat board of approximately 18 percent reflectance (*density* = 0.745): the reflectance of a standard gray card. This corresponds to zone 7 (M) on the Kodak Q-13 or Q-14 gray scale and to patch 22 (bottom row, fourth from the left) on the

GretagMacbeth ColorChecker. The color and reflectance of the gray background does not have to be very accurate, as its only purpose is to influence the camera's automatic exposure and white balance.

4.4.1 Color Accuracy Measurement

Follow these steps to manually measure color accuracy:

1. You can make the measurement for any specified combination of lighting intensity (standard, reduced, or dim) and color temperature (tungsten, or daylight) as Section 2 specifies. Ensure you associate the lighting intensity and color temperature that was used with any measured values. Adjust the lighting and GretagMacbeth ColorChecker chart as Section 3 specifies, and capture one video image from the GretagMacbeth ColorChecker chart.
2. Measure the average color values for each patch in the ColorChecker chart, excluding areas near the boundaries. If the values are Red Green Blue (RGB), go to step 4 below. If they are YC_BC_R (common for many video cameras), use the equation in step 3, below, to convert to RGB.
3. The conversion equation from YC_BC_R to RGB (scaled for maximum values of 255) [14] is:

$$\begin{bmatrix} R \\ G \\ B \end{bmatrix} = \frac{1}{256}\begin{bmatrix} 298.1 & 0 & 408.6 \\ 298.1 & -100.3 & -208.1 \\ 298.1 & 516.4 & 0 \end{bmatrix} \bullet \left(\begin{bmatrix} Y \\ C_B \\ C_R \end{bmatrix} - \begin{bmatrix} 16 \\ 128 \\ 128 \end{bmatrix} \right)$$

   RGB values from this equation that fall outside the range [0, 255] should be clipped at 0 and 255.
4. Convert the RGB color values into L*a*b* color values, using the equations in Section 4.4.2.
5. The standard measurements of color (chroma) error (or color difference) between colors 1 and 2 are ΔE^*_{ab} (which includes both color and luminance) and ΔC^*_{ab} (color only):

$$\Delta E^*_{ab} = \sqrt{(L_2^* - L_1^*)^2 + (a_2^* - a_1^*)^2 + (b_2^* - b_1^*)^2} \qquad \text{chroma and luminance}$$

$$\Delta C^*_{ab} = \sqrt{(a_2^* - a_1^*)^2 + (b_2^* - b_1^*)^2} \qquad \text{chroma only}$$

   ΔC^*_{ab} and ΔE^*_{ab} are the Euclidian distances in the CIE (*Commission Internationale de L'Eclairage*) L*a*b* (CIELAB) color space between the reference values from the table in Section 4.4.2 and the measured sample values.
6. Alternatively, if greater accuracy is required, you can use the more accurate but less familiar CIE 1994 color difference formulas, ΔE^*_{94} and ΔC^*_{94}. These equations account for the eye's reduced sensitivity to chroma differences for highly saturated colors. In the equations that follow, subscript 1 represents the reference values from the table in Section 4.4.2, and subscript 2 represents the measured sample values:

$$\Delta E^*_{94} = \sqrt{\left(\frac{\Delta L}{K_L S_L}\right)^2 + \left(\frac{\Delta C}{K_C S_C}\right)^2 + \left(\frac{\Delta H}{K_H S_H}\right)^2} \qquad \text{chroma and luminance}$$

$$\Delta C^*_{94} = \sqrt{\left(\frac{\Delta C}{K_C S_C}\right)^2 + \left(\frac{\Delta H}{K_H S_H}\right)^2} \qquad \text{chroma only}$$

$$\Delta L = L_1 - L_2 \qquad \Delta C = C_1 - C_2 \qquad \Delta a = a_1 - a_2 \qquad \Delta b = b_1 - b_2$$

$$C_1 = \sqrt{\Delta a_1^{\,2} + \Delta b_2^{\,2}} \qquad C_2 = \sqrt{\Delta a_2^{\,2} + \Delta b_2^{\,2}} \qquad \Delta H = \sqrt{\Delta a^2 + \Delta b^2 + \Delta C^2}$$

$$S_L = K_L = K_C = K_H = 1$$

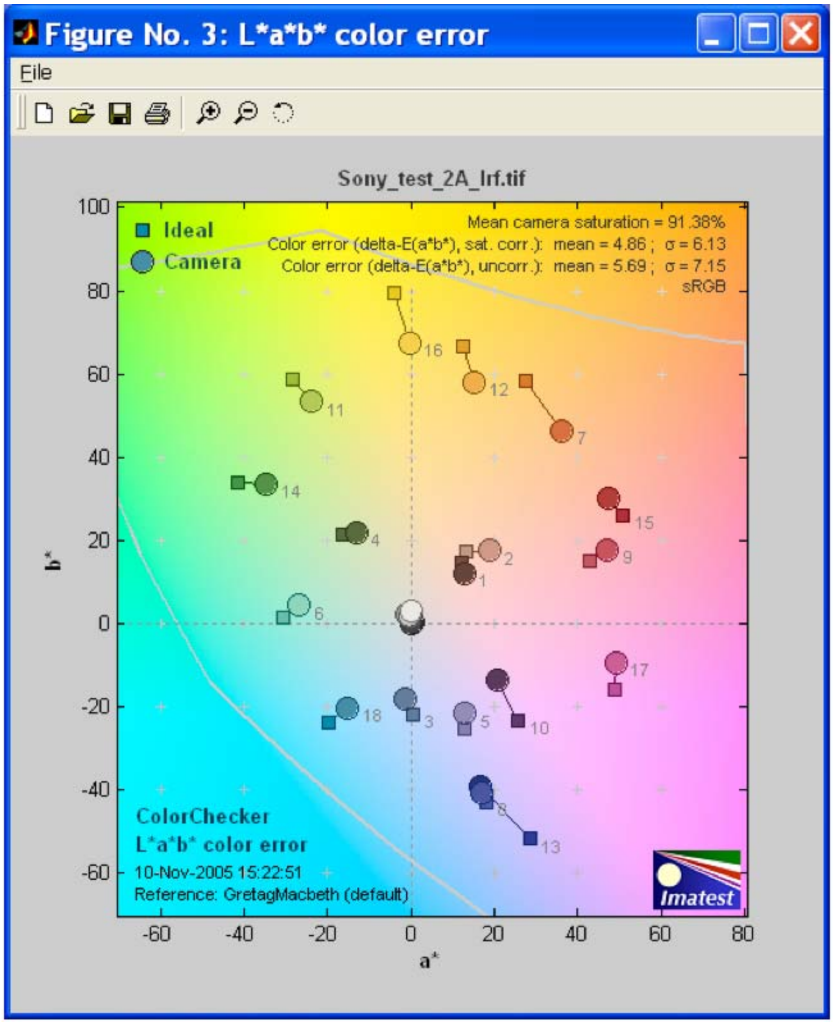
$$S_C = 1 + 0.045C_1 \qquad S_H = 1 + 0.015C_1$$

ΔE^*_{94} and ΔC^*_{94} result in lower numbers than ΔE^*_{ab} E^*_{ab} and ΔC^*_{ab}, especially when strongly saturated colors (large values of C_1 and C_2), are compared.

7. For purposes of determining an overall measurement of color accuracy, the $\text{mean}(\Delta C^*_{ab})$ or $\text{mean}(\Delta C^*_{94})$ is computed over all 24 patches of the ColorChecker chart. ΔC^* is preferred over ΔE^* because it excludes luminance (exposure) error, which is dealt with separately in Section 4.6.

Figure 18 shows example color accuracy measurement results as output by the Imatest application. The axis in this plot (i.e., a* and b*) are defined in step 4 above.

Figure 18: Example Color Accuracy Measurement Results



4.4.2 Converting RGB values to L*a*b*

To obtain ΔE^*_{ab} and related color difference values, it is necessary to convert the system-dependent RGB values into L*a*b* values. This is a two-step process: 1) Convert RGB into XYZ; 2) Convert XYZ to L*a*b*. The following equations and values are from brucelindbloom.com [15]:

1. If the RGB values are in the range [0, 255], divide their values by 255. Given an RGB color whose components are in the nominal range [0.0, 1.0], compute:

   $[\,X\;Y\;Z\,] = [\,r\;g\;b\,]\,[\,M\,]$

   where, [M] is the matrix and, if the RGB system is **not** sRGB (standard RGB[2]):

   $r = R^{\gamma};\quad g = G^{\gamma};\quad b = B^{\gamma}$

   and if it **is** sRGB:

2. A standard RGB color space, known as sRGB, based on a standard for HDTV. sRGB was created to achieve a greater color consistency between hardware devices.

$$
\begin{aligned}
r &= R/12.92 && R \le 0.04045 \\
&= ((R + 0.055)/1.055)^{2.4} && R > 0.04045 \\
g &= G/12.92 && G \le 0.04045 \\
&= ((G + 0.055)/1.055)^{2.4} && G > 0.04045 \\
b &= B/12.92 && B \le 0.04045 \\
&= ((B + 0.055)/1.055)^{2.4} && B > 0.04045
\end{aligned}
$$

sRGB is approximately (but not exactly) gamma $\gamma = 2.2$. Most video color spaces use gamma $\gamma = 2.2$. (See the Info section of brucelindbloom.com for the correct gamma γ values of various RGB color spaces.) For sRGB, the matrix [M] is:

$$
[M] = \begin{bmatrix} 0.412424 & 0.212656 & 0.0193324 \\ 0.357579 & 0.717178 & 0.119193 \\ 0.180464 & 0.0721856 & 0.950444 \end{bmatrix}
$$

(The Math section of brucelindbloom.com provides the matrix [M] for other RGB working spaces.)

2. Convert XYZ from step 1 to L*a*b*. This conversion requires a reference white X_r, Y_r, Z_r. Since most color spaces in video cameras have a D65 (6,500K) white point, X_r = 0. 9505, Y_r = 1.0, Z_r = 1.0890 are recommended. (Use X_r = 0.9642, Y_r = 1.0, Z_r = 0.8252 for color spaces that use a D50, or 5,000K illuminant.)

$L^* = 116 f_y - 16$; $a^* = 500\,(f_x - f_y)$; $b^* = 200\,(f_y - f_z)$, where:

$$
\begin{aligned}
f_x &= \sqrt[3]{x_r} && x_r > \varepsilon && \varepsilon = 0.008856 \\
&= \frac{\kappa x_r + 16}{116} && x_r \le \varepsilon && \kappa = 903.3 \\
f_y &= \sqrt[3]{y_r} && y_r > \varepsilon \\
&= \frac{\kappa y_r + 16}{116} && y_r \le \varepsilon \\
f_z &= \sqrt[3]{z_r} && z_r > \varepsilon \\
&= \frac{\kappa z_r + 16}{116} && z_r \le \varepsilon
\end{aligned}
$$

and

$$
x_r = \frac{X}{X_r} \qquad y_r = \frac{Y}{Y_r} \qquad z_r = \frac{Z}{Z_r}
$$

Table 3 provides GretagMacbeth ColorChecker CIE L*a*b* reference values, measured with illuminant D65 and D50, 2 degree observer.

Table 3: GretagMacbeth ColorChecker CIE L*a*b* Reference Values

	2 Degree	Illuminant	L*	a*	b*
1	CC1	D65	37.542	12.018	13.33
2	CC2	D65	65.2	14.821	17.545

Table 3: GretagMacbeth ColorChecker CIE L*a*b* Reference Values (Continued)

	2 Degree	Illuminant	L*	a*	b*
3	CC3	D65	50.366	-1.573	-21.431
4	CC4	D65	43.125	-14.63	22.12
5	CC5	D65	55.343	11.449	-25.289
6	CC6	D65	71.36	-32.718	1.636
7	CC7	D65	61.365	32.885	55.155
8	CC8	D65	40.712	16.908	-45.085
9	CC9	D65	49.86	45.934	13.876
10	CC10	D65	30.15	24.915	-22.606
11	CC11	D65	72.438	-27.464	58.469
12	CC12	D65	70.916	15.583	66.543
13	CC13	D65	29.624	21.425	-49.031
14	CC14	D65	55.643	-40.76	33.274
15	CC15	D65	40.554	49.972	25.46
16	CC16	D65	80.982	-1.037	80.03
17	CC17	D65	51.006	49.876	-16.93
18	CC18	D65	52.121	-24.61	-26.176
19	CC19	D65	96.536	-0.694	1.354
20	CC20	D65	81.274	-0.61	-0.24
21	CC21	D65	66.787	-0.647	-0.429
22	CC22	D65	50.872	-0.059	-0.247
23	CC23	D65	35.68	-0.22	-1.205
24	CC24	D65	20.475	0.049	-0.972
1	CC1	D50	37.986	13.555	14.059
2	CC2	D50	65.711	18.13	17.81
3	CC3	D50	49.927	-4.88	-21.925
4	CC4	D50	43.139	-13.095	21.905
5	CC5	D50	55.112	8.844	-25.399
6	CC6	D50	70.719	-33.397	-0.199
7	CC7	D50	62.661	36.067	57.096
8	CC8	D50	40.02	10.41	-45.964
9	CC9	D50	51.124	48.239	16.248
10	CC10	D50	30.325	22.976	-21.587

Table 3: GretagMacbeth ColorChecker CIE L*a*b* Reference Values (Continued)

	2 Degree	Illuminant	L*	a*	b*
11	CC11	D50	72.532	-23.709	57.255
12	CC12	D50	71.941	19.363	67.857
13	CC13	D50	28.778	14.179	-50.297
14	CC14	D50	55.261	-38.342	31.37
15	CC15	D50	42.101	53.378	28.19
16	CC16	D50	81.733	4.039	79.819
17	CC17	D50	51.935	49.986	-14.574
18	CC18	D50	51.038	-28.631	-28.638
19	CC19	D50	96.539	-0.425	1.186
20	CC20	D50	81.257	-0.638	-0.335
21	CC21	D50	66.766	-0.734	-0.504
22	CC22	D50	50.867	-0.153	-0.27
23	CC23	D50	35.656	-0.421	-1.231
24	CC24	D50	20.461	-0.079	-0.973

4.5 Capture Gamma

Charge-coupled device, or CCD, image sensors are linear. But the output of still and video cameras is nonlinearly encoded for several reasons:

- Nonlinear encoding corresponds closely with the eye's response. Linear 8-bit coding would have more levels than necessary in the brightest regions and too few levels for smooth response in the darkest regions, resulting in banding.
- Historically, signals required for driving displays are non-linear.
- The file encoding standards for information interchange require nonlinear response.

A camera's response to light follows the approximate equation:

$$\text{Pixel level} = k\ \text{luminance}^{\gamma}$$

where:

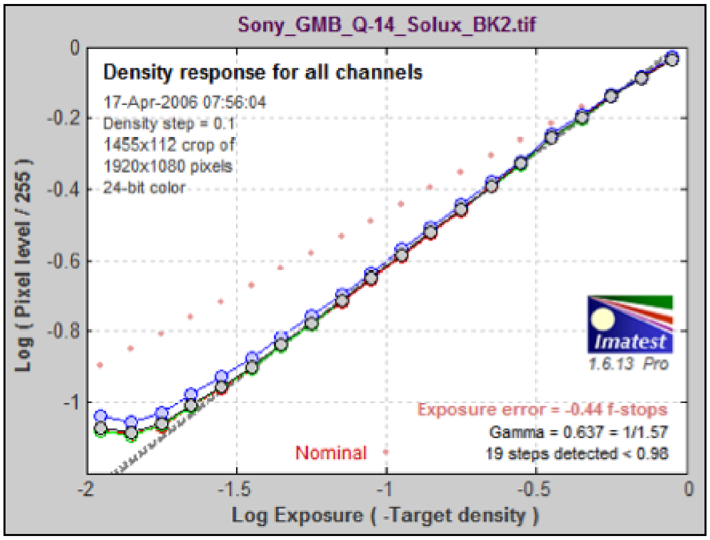
the exponent γ is the camera or capture gamma, and *k* is a constant related to exposure and bit depth.

The standard for video cameras and several still camera color spaces is $\gamma = 1 \div 2.2 = 0.45$. When pixel level vs. luminance is displayed logarithmically, γ is the slope of the curve:

$$\log_{10}(\text{pixel level}) = \gamma \log_{10}(\text{luminance}) + k_1$$

This curve resembles the classic characteristic curve for film, where response (density, in the case of film) is plotted against log exposure. Even when the characteristic curve for camera response deviates from the simple exponential equation, as it often does, the average response can still be fitted to the exponential. Figure 19 shows an example from the Imatest application, which illustrates the deviation from the straight line at Log Exposure < -1.5, which is apparently caused by glare (which can be minimized by careful lighting). As discussed previously, Log Exposure is equal to -1 × *density*.

Figure 19: Density Response Plotted Against Log Exposure



Measuring gamma requires photographing a target with patches of known density, $d = -k \log_{10}(\text{reflectance}) = -k \log_{10}(\text{luminance})$, or luminance $= k\, 10^{-d}$. Since $\text{Pixel level} = k\ \text{luminance}^{\gamma}$ (see *camera's response to light* equation, above), where *k* is a constant with different values in the different equations, then

$$\text{Pixel level} = P = k\, 10^{-d\gamma}$$

Solve for γ by measuring the average pixel level of two patches in the linear region, then solving:

$$P_1 = k10^{-d_1\gamma} \qquad P_2 = k10^{-d_2\gamma}$$

$$\frac{P_1}{P_2} = \frac{10^{-d_1\gamma}}{10^{-d_2\gamma}} = 10^{(d_2 - d_1)\gamma}$$

$$\log_{10}\left(\frac{P_1}{P_2}\right) = (d_2 - d_1)\gamma$$

$$\gamma = \frac{\log_{10}\left(\frac{P_1}{P_2}\right)}{d_2 - d_1}$$

Follow these steps to measure gamma:

1. Photograph a Kodak Q-13 or Q-14 step chart or a GretagMacbeth ColorChecker, illuminated using the standard lighting intensity as described in Section 2 and Section 3.2. Note that you can perform this measurement at the same time as other tests that use these charts.
2. Find the average measured pixel levels P_i of the patches i, excluding regions near boundaries that may not be representative of the interior. If it is convenient, plot $\log_{10}(P_i)$ as a function of $\log_{10}$(luminance), (i.e., -1 × *density*).
3. Select two patches near the ends of the relatively linear region. Typically, this might be patches 4 and 10 of the Kodak Q-13 or Q-14 chart, or patches 2 and 5 on the bottom row of the GretagMacbeth ColorChecker chart. Label the selected patches 1 and 2 for the purpose of using the above equation for calculating γ (step 4 below).
4. As indicated in the above equation, $\gamma = \log_{10}(P_1/P_2)/(d_2 - d_1)$. Values of d_i for the Kodak Q-13 or Q-14 chart and GretagMacbeth ColorChecker chart are given in Section 4.6. Example patches 2 and 5 for the GretagMacbeth ColorChecker chart (bottom row) have specified densities of d_1 = 0.23 and d_2 = 1.05, respectively. If the measured pixel values (from step 2) for these two patches were P_1 = 200 and P_2 = 85, then $\gamma = \log_{10}(200/85)/(1.05 - 0.23) = 0.4532$.

4.6 Exposure Accuracy

For a camera with a nominal capture gamma of γ, the pixel level for a correctly exposed test chart patch with *density* $d_i = -\log_{10}$(exposure) is:

$$P_i = 255\left(\frac{10^{-d_i}}{1.06}\right)^{\gamma}$$

where:

$\gamma = 1/2.2 = 0.4545$ for most video cameras and (approximately) equals this value for the sRGB color space.

For the Kodak Q-13 or Q-14 chart, d_i = {0.05, 0.15, 0.25, 0.35, 0.45, 0.55, 0.65, 0.75, 0.85, 0.95, 1.05} for P_{ri} (patches 1 to 11 out of 20 total). The corresponding reference pixel levels for a camera with $\gamma = 0.4545$ are P_{ri} = {235.7, 212.3, 191.2, 172.2, 155.1, 139.6, 125.8, 113.3, 102.0, 91.9, 82.7}.

Table 4 lists sRGB reference values by GretagMacbeth [16].

Table 4: GretagMacbeth ColorChecker sRGB Reference Values

Color	Name	R	G	B
1	dark skin	115	82	68
2	light skin	194	150	130
3	blue sky	98	122	157
4	foliage	87	108	67
5	blue flower	133	128	177
6	bluish green	103	189	170

Table 4: GretagMacbeth ColorChecker sRGB Reference Values (Continued)

Color	Name	R	G	B
7	orange	214	126	44
8	purplish blue	80	91	166
9	moderate red	193	90	99
10	purple	94	60	108
11	yellow green	157	188	64
12	orange yellow	224	163	46
13	blue	56	61	150
14	green	70	148	73
15	red	175	54	60
16	yellow	231	199	31
17	magenta	187	86	149
18	cyan	8	133	161
19	white	243	243	242
20	n8	200	200	200
21	n6.5	160	160	160
22	n5	122	122	121
23	n3.5	85	85	85
24	n2	52	52	52

For the GretagMacbeth ColorChecker, the grayscale patch densities on the bottom row have nominal densities of d_i = {0.05, 0.23, 0.44, 0.70, 1.05, 1.50}. The corresponding sRGB reference pixel levels for a camera with $\gamma = 0.4545$ are P_{ri} = {243, 200, 160, 122, 85, 52} [17].

For a set of measured pixel levels P_i, the mean exposure error (Err_{exp}) in f-stops is:

$$Err_{exp} = -3.32 mean(\log(P_i) - \log(P_{ri}))/\gamma$$

where:

γ is the measured camera (capture) gamma, as described in Section 4.5, and P_{ri} are the sRGB reference pixel levels for the patches (given above). For the Kodak Q-13 or Q-14 chart, take the mean over patches 4 to 11, which is the camera's probable linear region, excluding very dark and light regions. For the GretagMacbeth ColorChecker chart, take the mean over grayscale patches 2 to 5 on the bottom row (patches 20 to 23 on the chart as a whole).

The following steps summarize the procedure for measuring exposure error:

1. Photograph a Kodak Q-13 or Q-14 step chart or a GretagMacbeth ColorChecker chart, mounted on a neutral gray background as described in Section 3.1.2, and illuminated with standard lighting intensity as described in Section 2 and Section 3.2.
2. Find the average measured pixel levels P_i of the patches, excluding regions near boundaries that may not be representative of the interior.
3. Apply the above equations, making use of measured capture gamma γ from Section 4.5, to calculate exposure error, Err_{exp}.
4. Exposure may be affected by history. It is worth testing the image after the lens has been covered for a few seconds and after a bright light has been reflected into the camera for a few seconds (long enough for the auto exposure to adapt).
5. Exposure may be affected by light level and color temperature. This test may be repeated for reduced and dim lighting intensities and for light with daylight and tungsten color temperatures (see Section 2 and Section 3.4).

4.7 Vignetting

Vignetting is the falloff of light at the edges of the image. The following steps for measuring relative illumination are from the SMIA Camera Characterization Specification [18]:

1. Photograph a flat, evenly lit surface. The surface can be composed of a mat gray or white material. Check that the surface illumination varies by no more than ±10 percent.
2. Measure the average pixel levels in the center of the image and all four corners of the image, using small rectangular shaped sub-regions (square sub-regions preferred). Ensure the squares or rectangles are no larger than 1 percent of the total image area. That would make them about 10 percent (or slightly less) of the image dimensions on each side.
3. The relative illumination is:

   relative illumination (%) = 100% P_{center} / P_{corner}(worst case)

   where:

   P_{center} is the average pixel level of the center square, and P_{corner}(worst case) is the average pixel level of the darkest corner.

4.8 Lens Distortion

Lens distortion is the deformation of the image due to straight lines in the subject rendered as curved lines in the image from the camera.

Follow these steps to measure lens distortion:

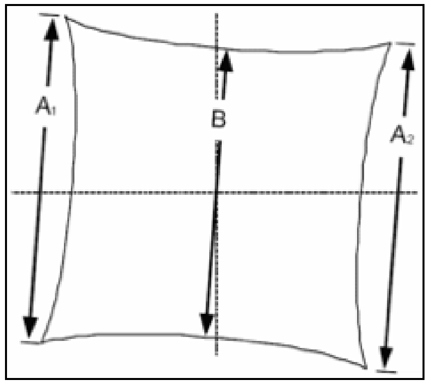
1. Capture a video image of the rectilinear grid test chart (see Section 3.1.3). Ensure that the video image is framed so that A_1 and A_2 (see Figure 20) are approximately 98 percent of the image height. This does not have to be measured precisely but the rectilinear grid test chart should nearly fill the image.
2. Apply the veiling glare formula from the Standard Mobile Imaging Architecture (SMIA) camera characterization specification to the captured image [19]. The distances in the equation below (A_1,

A_2, and B) can be measured electronically using image analysis software, or manually using a printed version of the image:

SMIA TV Distortion = $100(A\text{-}B)/B$; $A = (A_1 + A_2)/2$

3. SMIA TV Distortion > 0 indicates pincushion distortion, while SMIA TV distortion < 0 indicates barrel distortion.

Figure 20: SMIA TV Distortion



4.9 Reduced Light and Dim Light Measurements

Unlike still cameras, long exposures are not an option with video cameras. At low light levels the aperture is opened and the sensor gain is increased, degrading the SNR and dynamic range. Performance at low light levels cannot be inferred from measurements at high light levels. Many public safety applications involve working in reduced lighting conditions (i.e., tactical video, nighttime surveillance video). For these applications, video camera performance should be directly measured under reduced or dim lighting intensities (see “Reduced Lighting Intensity” and “Dim Lighting Intensity” in Table 1).

Select the color temperature of the reduced or dim lighting to match the color temperature that will be encountered (for example, see “Daylight Light” and “Tungsten Light” in Table 1). Section 3.4 presents a method for modifying lamp head assemblies to properly emulate reduced lighting with the proper color temperature. Dimmers cannot in general be used to obtain low light levels with the proper color temperature, since the color temperature drops to very low levels as the light is dimmed—well under 3,000K.

You can achieve reduced light by stacking neutral density and color-correction (CC) filters. For example, the 85B warming (amber) filter, +131 mireds, changes 4,700K to 2,900K, where 2,900K is typical of ordinary incandescent bulbs. The 85B warming filter also decreases exposure level by two thirds f-stop. Add neutral density (ND) filters to the stack to achieve additional light reduction. Typical ND filters have D = 0.3 (2x; 1 f-stop), 0.6 (4x; 2 f-stops), and 0.9 (8x; 3 f-stops). Stacking filters sums density. For example, to achieve dim lighting with two SoLux Task Lamps located 1 meter from the target (approximately 250 lux at the target), 0.6 + 0.9 ND filters (density = 1.5 total) can reduce the illumination to 250/32 = 7.8 lux, well within the definition of dim lighting intensity.

You can perform the following measurements at reduced light levels (30 to 60 lux) and low light levels (5 to 10 lux), as appropriate for the application. The primary measurements are exposure accuracy, dynamic range, and color accuracy. Noise and gamma are measured to determine exposure accuracy and dynamic range:

- **Exposure Accuracy.** Underexposure is a frequent problem at low illumination. Exposure accuracy is important and easy to measure.
- **Dynamic Range.** Degraded at low light levels. A reduced dynamic range may be acceptable at low light levels.
- **Color Accuracy.** Affected by increased noise, changes in signal processing, and the tungsten light balance typical of low illumination. Reduced color accuracy may be acceptable at low light levels.
- **Noise.** Degraded at low light levels. Measured to find the dynamic range.
- **Gamma.** A secondary measurement at low light levels: measured to determine exposure accuracy.

The details of the tests depend on the specific application. Where low light performance is of interest, you would typically test a camera for exposure accuracy, dynamic range, and color accuracy at approximately 2,700 to 3,200K (typical of tungsten lighting), at reduced and dim lighting intensities, as defined in Table 1.

Note: Resolution does not need to be tested at low light levels, unless there is suspicion that low light performance is achieved by techniques such as combining pixels, which reduce resolution.

4.10 Flare Light Distortion (Under Study)

Flare light, also called spatial crosstalk, or veiling glare, is light that bounces between lens elements and off the interior barrel of the lens. Flare light can significantly reduce the dynamic range of a camera under adverse lighting conditions. An example occurs when there is a strong light source, such as a spotlight in the image or near the image frame. Photographers go to considerable lengths to control flare from various sources. For instance, they use lens shades, "barn doors" on studio lights, etc., but flare light may not be controllable in public safety applications. Therefore, it is desirable to have a standard method of measurement for determining the reduction in camera DR due to flare light. This phenomenon is known as flare light distortion.

The International Electrotechnical Commission (IEC) 61966-8 has a standard for spatial crosstalk (somewhat equivalent to flare light) [20]. The IEC standard was designed for scanners, and may be inadequate for cameras, where images can be degraded by light in the proximity of the image frame.

Flare light is called "veiling glare" in section 5.24 of the SMIA Camera Characterization Specification [19]. The SMIA measurement is satisfactory when: 1) a manual exposure setting is available; and 2) access to the raw or unprocessed output of the sensor is available. Unfortunately, these conditions rarely apply to video cameras. Veiling glare is "veiled" by the signal processing in the video camera. A more sensitive measurement is necessary.

There is no widely accepted measurement for flare light distortion at this time. Hence flare is usually described qualitatively in published lens test reports.

Measuring flare involves several difficulties. The assumption cannot be made that cameras respond linearly to light, or linearly with a gamma curve. Many cameras have "S" tonal response curves that improve pictorial quality by boosting contrast ($(\Delta C = \Delta(\log_{10}(P))/\Delta d$, see step 7 of Section 4.2) of the middle tones at the expense of contrast in the shadows and highlights. It is important not to confuse the decrease in contrast near the toe of the "S" curve with flare. Furthermore, some cameras have adaptive signal processing, which means gain may be decreased or increased, depending on the scene contrast. This improves pictorial quality but complicates measurements.

One possible flare light distortion test takes advantage of the fact that flare tends to reduce step chart contrast in shadow areas. The measurement under study involves photographing a standard reflective step chart, such as the Kodak Q-13 or Q-14, against a large black-and-white background, for example, 32 by 40 inch (80 by 100 cm) foam board. The charts can be surrounded by a small neutral gray region, just large enough, and no larger, to influence the auto exposure setting.

5 MAKEOECF.M

The following MATLAB m-file script creates an OECF LUT, or Look Up Table, for use by the sfrwin application. The sfrwin application assumes a gamma of 1.0 if no LUT is provided to it. This will result in the MTF measurement being off by 10 to 20 percent. The output file generated by the makeoecf.m script will either contain a lookup table with one column (for black and white) or three columns (for color), depending upon how the script is called. See the instruction manual (user_guide.pdf) that comes bundled with the sfrwin application for details on how to input a user-generated LUT.

```
function makeoecf(varargin)
% makeoecf (gamma, ncol, filename)
% Create an OECF file for sfrwin.
% First argument is gamma. Default = 0.5
% Second argument is ncol: 1 (for Black & White), 3 (for color). Default = 3
% Third argument is the filename (no blanks). Default = lut_gamma_ncol.dat
%
% Example Calls: makeoecf (‘0.5’,‘3’, ‘Lut_0.5_3.dat’)
%                makeoecf (‘0.5’)

% Set defaults
gamma = 0.5;
ncol = 3;

if (nargin>=1)    % gamma between 0.1 and 10
   gamma = str2num(varargin{1});
   if gamma<.1 | gamma>10
      disp('Gamma must be a number between 0.1 and 10.');  return;
   end
end
if (nargin>=2)    % 1 or 3 for B&W or color
   ncol = str2num(varargin{2});
   if ~(ncol==1 | ncol==3)
      disp('Number of colors (2nd argument) must be 1 or 3.');  return;
   end
end
if (nargin>=3)    % Output file name.
   fileout = varargin{3};
else
   fileout = ['lut_' num2str(gamma,2) '_' num2str(ncol) '.dat'];
end

foecf = 255*linspace(0,1,256).^(1/gamma);

fid = fopen(fileout, 'w');
if ncol==1  % B&W
   fprintf(fid, '%7.2f\n',foecf);
else        % ncol==3: color
   foecf = [foecf; foecf; foecf];  % 3 columns.
   fprintf(fid, '%7.2f %7.2f %7.2f\n',foecf);
end
fclose(fid);
disp(['End makeoecf. File written to ' fileout '.']);
return;
```

6 References

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