Low Light Performance of Digital Still Cameras

Dietmar Wueller

Image Engineering, Augustinusstr. 9D, 50226 Frechen, Germany

ABSTRACT

The major difference between a dSLR camera, a consumer camera, and a camera in a mobile device is the sensor size. The sensor size is also related to the over all system size including the lens. With the sensors getting smaller the individual light sensitive areas are also getting smaller leaving less light falling onto each of the pixels.

This effect requires higher signal amplification that leads to higher noise levels or other problems that may occur due to denoising algorithms. These Problems become more visible at low light conditions because of the lower signal levels.

The fact that the sensitivity of cameras decreases makes customers ask for a standardized way to measure low light performance of cameras. The CEA (Consumer Electronics Association) together with ANSI has addressed this for camcorders in the CEA-639 [1] standard. The ISO technical committee 42 (photography) is currently also thinking about a potential standard on this topic for still picture cameras. This paper is part of the preparation work for this standardization activity and addresses the differences compared to camcorders and also potential additional problems with noise reduction that have occurred over the past few years.

The result of this paper is a proposed test procedure with a few open questions that have to be answered in future work.

Keywords: Low light performance, noise, texture, resolution, camera test, sensitivity, dead leaves, exposure

1. INTRODUCTION

Looking at the latest developments in cameras the pixel race is still going on and pixel pitches around 1 micron have become reality. Especially in mobile cameras sensor size and the related module size matters. With shrinking pixel sizes the sensitivity of sensors decreases. Modern technologies try to compensate for this. On the one hand backside illumination increases the quantum efficiency of the sensor itself. On the other hand image processing is used to increase the quality of the amplified signal afterwards.

One major aspect of modern image processing is noise reduction that decreases the amount of noise in the images. Unfortunately the processing algorithms have the problem to differentiate between fine detail in the images and noise. Therefore the denoising also affects low contrast fine detail and reduces resolution in the images. Due to human perception a higher level of noise reduction can be applied to color channels than to the luminance part of the signal without a significant decrease in image quality. But it results in a decrease of color fidelity.

The ANSI standard CEA-639 [1] addresses the issue for camcorders but it does e.g. not take the loss of low contrast fine detail into account.

Therefore the ISO committee TC42 WG18 considers starting work on a new standard. Currently the author conducts several experiments as a preparation for the standards work.

The idea is to look at all 7 affected image quality aspects described below separately and define a quality threshold for each of the aspects before combining them into a single measure for low light performance.

The related image quality aspects are:

Exposure time
In order not to loose detail due to handshake the exposure time needs to be above a threshold that is to be defined. This threshold may vary with optical image stabilization in the camera.

Luminance Level
A way to hide the noise in the image or to prevent blur due to camera shake is to intentionally underexpose the images. That way the bright parts will be visible but the high noise levels may be hidden in the dark areas. But of course the underexposed image looks too dark.

Black level of the output image
In order to compensate for the underexposure the tonal levels may simply be shifted so that the dark areas do not appear black anymore but will become a dark grey.

Noise
If the raw signal is just amplified without any noise reduction applied the result will be a noisy image and from a certain level on the noise will cover the signal in a way that the image gets unacceptable.

Resolution
A simple noise reduction filter basically blurs the image and therefore affects the resolution in a negative way.

Texture
The resolution structures described in ISO 12233 [2] are structures with a relatively high contrast level. A sophisticated noise reduction algorithm detects high contrast structures and therefore should not affect resolution structures in a significant way. Low contrast fine detail however may and will be affected by these algorithms and a method to measure the so called texture loss is still under development.

Color
A smoothing algorithm in the color channels results in a loss of detail for colored objects and for extreme noise reduction may also lead to desaturated colors. Therefore this aspect also needs to be considered.

2.   SUMMARY OF THE ANSI/CEA-639 STANDARD

At a 60Hz frame rate the CEA-639 [1] standard defines how to measure the luminance level by analyzing the video signal for a white patch of an eleven-patch logarithmic grey scale test chart. The light level is decreased and measured (as illumination [lux] on the test chart plane) until the signal level of the white patch reaches 50% (50 IRE, Institute of Radio Engineers [3]) of the maximum output level.

The black level is monitored and has to stay within a given tolerance range of 7 +/- 3 IRE.

The minimum signal to noise level for an 18% grey chart illuminated at the decreased light level from the luminance level test needs to be 17dB.

The chroma level of a specific red patch (strong red) in the Macbeth Color Checker at this decreased light level needs to stay above 25% of the level reached at bright light conditions of about 1000 lux. This is measured using a waveform monitor that is a standard tool in the video world.

Last but not least the resolution is determined using black and white lines at varying frequencies. The modulation of the video signal for full black to peak white level is determined. With increasing spatial frequency the modulation drops and the frequency where it reaches the 20% threshold is noted. This procedure is performed at 1000 lux and at the decreased light level. The 20% modulation frequency of the decreased light level needs to be at least 70% of the frequency determined at the 1000 lux level.

If one of the described values does not meet the necessary threshold the decreased illumination level needs to be increased until all thresholds are reached. The resulting light level is reported as the camera low light sensitivity.

3.   APPLICATION OF CEA-639 TO STILL CAMERAS

Although the basic principle used for CEA-639 makes sense and should work for still cameras as well, the standard has several downsides when applied to still cameras. First of all it requires video equipment that cannot be used for the analysis of single still image files because it requires a video interface and the 60 frames per second video sequence.

Some of the analysis methods are defined in video signal units that cannot directly be determined from a single sRGB image. And the standard does not address some issues that we see in today's cameras like e.g. texture loss due to noise reduction in images and some that are relevant for still cameras only like max exposure time with and without image stabilization.

4. PROPOSED MODIFIED VERSION FOR APPLICATION TO STILL CAMERAS

4.1 Testchart and illumination

Low light conditions are dominated by tungsten light therefore the lighting condition should be consistent with the tungsten conditions specified in ISO 7589 [4]. The chart should be uniformly illuminated in a way that minimizes stray light and specular reflection. The light source needs to be dimmable without a significant change in color temperature or even better the spectral distribution of the light. Using a set of polarizing filters or using a special spectrally tunable LED light source can achieve this.

Since modern cameras provide scene dependent image processing and in most cases do not provide a live signal for evaluation the ideal approach for a low light test seems to be using a test chart that contains all necessary structures for evaluating the relevant image quality parameters. The TE42 designed and produced by Image Engineering [5] is one example for a chart that can be used. It contains a grey scale, resolution structures, an 18% grey background, the relevant Color Patches and a dead leaves structure for texture evaluation.
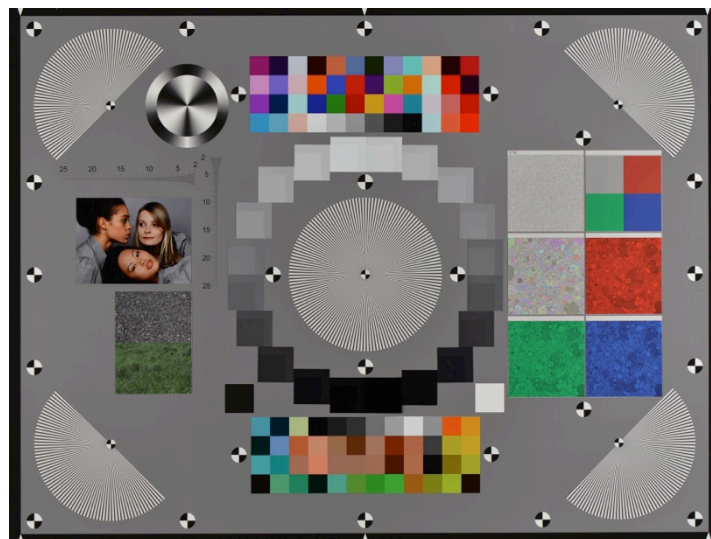

Figure 1: The TE42 is one example for a test chart that can be used to measure the low light performance of a digital still camera.

For evaluating cameras that do not provide accurate exposure information it is necessary to monitor the exposure time. Implementing a timing device in the test chart scene can do this.

4.2 Camera settings

The test needs to lead to comparable results over a huge variety of different cameras. The biggest challenge is to combine cameras for which the user has almost no control with cameras that require or at least allow full control over all functions and features.

Cameras should be set to the highest image quality (lowest compression) for output-referred data (not raw). This is typically a mode that creates a final Tiff of JPEG file. Only for those cameras that do not have in camera rendering a post processing of raw data using the standard software provided by the manufacturer shall be allowed.

The same procedure can be applied to raw data but the results will not be comparable to the processed data due to missing noise reduction and a linear tonal curve. But raw data analyses can be compared between the different cameras.

If available the "auto ISO" feature for automatic scene dependent signal amplification shall be used. In case this feature is not available the ISO speed value shall be set to the highest value available that allows to reach all thresholds especially those for noise and color for the chart at a high illumination level value of app. 1000 lux (measured on the chart plane).

The white balance shall be set to auto and the noise reduction to the default level. No flashes or camera build in light sources shall be used or switched on. For cameras where these cannot be switched off this test is generally not applicable. In some cases it may be possible to cover the build in light source and perform the test.

Where available the camera shall be set to shutter-priority mode or auto program mode combined with a maximum exposure time set to the maximum threshold specified for the type of camera in the exposure time section. The exposure shall be determined and set by the camera without any exposure compensation.

4.3 Capture of a Reference image

The test procedure is not designed to judge the over all image quality at any light level. Aspects like for example the resolution of the system are system dependent. Therefore absolute resolution or color reproduction levels cannot be used to define thresholds. For the low light performance some thresholds need to be defined relative to the performance under bright light conditions. In order to do this a reference image needs to be captured at a relatively high illumination level on the chart plane. A value of 1000 lux is used by CEA-639 and seems to be a suitable reference.

From this image all necessary reference values mentioned under the individual image quality aspects can be determined.

4.4 Capture of the test images

Above a chart illumination level of 100 lux most cameras deliver acceptable images. After taking the reference image at 1000 lux the illumination can therefore usually be reduced to 100 lux and then be reduced in steps further down. For each image all of the mentioned image quality criteria need to be evaluated and the lowest illumination level at which all of the thresholds are still in the acceptable range needs to be determined. This level then gets reported as the low light sensitivity of the still camera.

Since the loss in resolution and in texture as well as color are often depending on the amplification specific algorithms a first starting point for the test of cameras with manual control can be to perform a test run at different ISO speed levels for the 1000 lux illumination. That way the max ISO speed setting that leads to acceptable results above the thresholds can be determined.

To estimate the light level and the related exposure it is helpful to know that an illumination of 10 lux is app. an Exposure Value (EV [6][7]) of 2. For doubling the illumination the Exposure Value rises by one.

The Exposure Value and the exposure parameters f-stop, exposure time, and ISO Exposure Index (ISO setting on the camera) are related in the following way:

$$EV = \log_2\left(\frac{100 \cdot k^2}{E \cdot t}\right) \approx 3{,}322 \cdot \log\left(\frac{100 \cdot k^2}{E \cdot t}\right) \qquad (1)$$

with:

k = f-stop

t = exposure time

E = Exposure Index

5.   THE IMAGE QUALITY CRITERIA AND THEIR THRESHOLDS

5.1 Exposure time

The typical use of a still camera is handheld and therefore the exposure time needs to be above a level where handshake starts to blur the image. From the old days of 35mm film photography a rule of thumb says that the reciprocal of the focal length should be the longest hand held exposure time. The origin of this rule of thumb is an old test for human handshake in combination with calculations of the circle of confusion (0,033 mm, visible threshold for a 35mm negative that gets enlarged to 100 x 150mm print). This means the longest exposure time depends on the focal length. For the low light performance the aim is to provide a value that allows to compare cameras. For cameras with a fixed focal length the used focal length usually lies in the range between 28 mm and 45 mm for the 35mm film cameras equivalent focal length. Cameras with a Zoom lens can usually also be set to a 35mm equivalent focal length. These can all be combined and approximated in the maximum exposure threshold of 1/30 second.

The unanswered question for exposure time currently is the impact of image stabilization. Our lab tests show that by using optical image stabilization the user can gain between two and four f-stops. Our experience shows that software only based stabilization does not work to the user's satisfaction. So what shall be done to the threshold for cameras with sensor or lens based stabilization?

It seems to be fair to increase the exposure time threshold and there are two ways to proceed. One is to go with a fixed threshold of e.g. 1/8 second for these cameras. The other is to measure the stabilization quality according to the CIPA Standard [8] and use the result of that test to specify a camera specific threshold.

5.2 Luminance Level

The reference image shall be converted from a color to a luminance image using the channel weighting described in ISO 12232 [10] ($Y = 2125/10000\ R + 7154/10000\ G + 721/10000\ B$). From this image the mean output level for the brightest patch in the grey scale shall be determined and used as the reference value. The threshold for the mean value of this patch at low light conditions should be an output level that is 20% below the reference value. (e.g. reference value is 255. the threshold = 255 – 51 = 204).

For example camera A uses about 1/15 second as the longest exposure time. If the illuminance of the scene is decreased beyond the level where amplification and exposure time can compensate for it the scene is underexposed and the images get too dark.
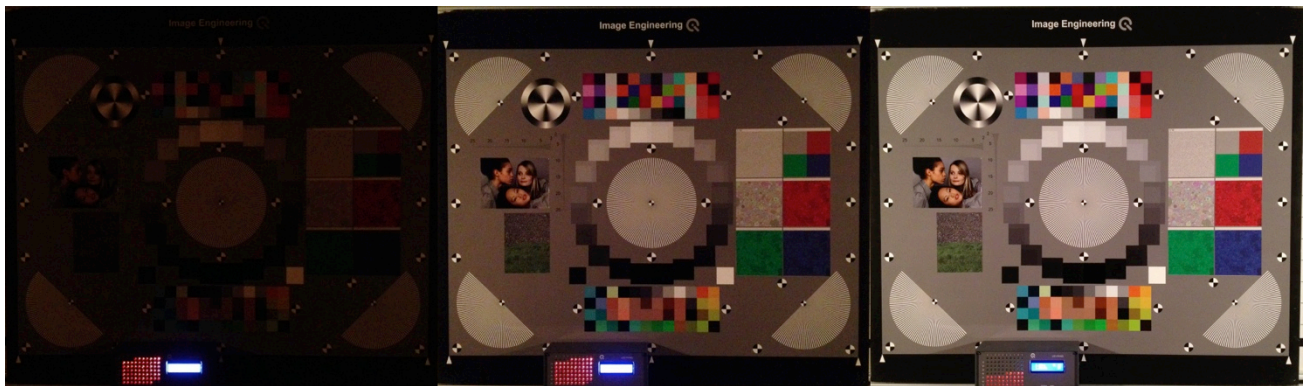

Figure 2: One of the most used cellphones keeps the maximum exposure time at about 1/15 seconds. When the light level is decreased and this exposure time and the maximum amplification is reached the images are underexposed and therefore appear darker (left 2.5 lux, center 10 lux, right 65 lux).

5.3 Black level of the output image

In order to compensate for the underexposure the tonal levels may simply be shifted so that the dark areas do not appear black anymore but will become a dark grey. Therefore the dark level needs to be monitored by using the darkest patch of the grey scale in the low light images and if the black value rises above 20% of the maximum possible output signal (e.g. 20% of 255 = 51) the threshold is reached.

5.4 Noise

The amplification of the raw signal results in a noisy image and from a certain level the noise will cover the signal in a way that the image gets unacceptable. CEA-639 specifies the threshold using a signal to noise ratio of 17 dB, which is equal to a Signal to noise ratio of 7 according to ISO 15739 [9] for an 18% neutral grey patch. In our case it would be the 18% grey background of the chart.

$$SNR[dB] = 20\log\left[\frac{output\ Signal}{s\tan dard\ deviation}\right]$$

$$SNR = \left[\frac{output\ Signal}{s\tan dard\ deviation}\right]$$

(2)

In order to be consistent with ISO 12232 [10] that uses a SNR of 10 for the first acceptable image the threshold for still cameras should be set to 20 dB or the equivalent value of 10.

Another approach for a low light performance standard could be to use the visual noise measurement described in ISO 15739 [9] that is based on the human visual system and specify a maximum value for the visual noise at a given viewing condition (e.g. 100% viewing on a monitor). At a value of 10 for example the noise starts to cover the signal. So this value can be seen as a proposal for a standard.
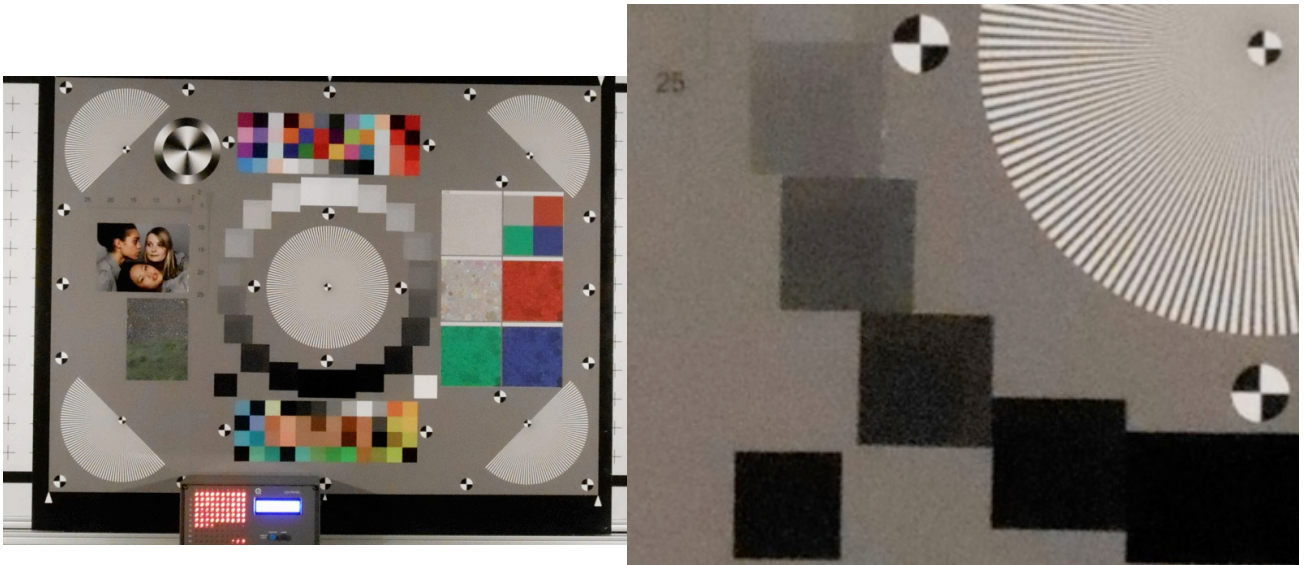

Figure 3: The peak visual noise level for this image reaches a value of almost 10. In the enlarged part the noise is clearly visible and almost covers the 25 at the top left.

5.5 Resolution

To measure resolution - which by definition is the ability of the camera to reproduce fine detail – for a camera that heavily processes the images, a slanted edge cannot be used. Algorithms like sharpening or compression affect edges in a different way than they affect other structures in the images and therefore the analysis of an edge after image processing is not representative for the resolution of the camera anymore. Therefore the resolution analysis needs to be performed on a structure that provides information for each frequency separately and that is not that much affected by those algorithms. A suitable structure that will be part of the upcoming revision of the ISO12233 [2] resolution standard is a sinusoidal Siemens star.

From the analysis of the star the modulation or contrast can be plotted as a function of the frequency. The frequency where the contrast threshold of 10% is reached is typically called the limiting resolution.

The basis for this threshold is the Rayleigh criterion found by Lord Rayleigh in the late 1800 hundreds [16] that tells that two points in an image can be determined if the intensity between the two circles falls below 0.81 of the peak intensity. With this value introduced in the modulation formula we get the 10% modulation threshold:

$$Modulation = \frac{I_{max} - I_{min}}{I_{max} + I_{min}} = \frac{1 - 0.81}{1 + 0.81} = \frac{0,19}{1,81} = 0,10 \tag{3}$$

This limiting resolution needs to be determined for the reference image and for the low light images. For consistency with CEA-639 the threshold level for resolution could be 70% of the resolution from the reference image.
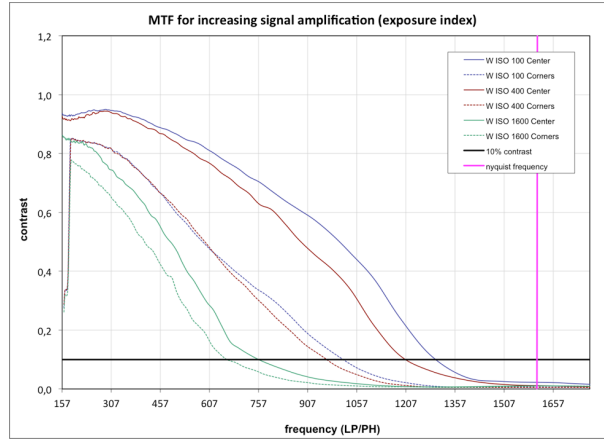

Figure 4: An example MTF set showing the decrease in resolution for increasing signal amplification. Combined tests with raw images show that most of the visible effect is caused by denoising in the image processing chain.

5.6 Color

Denoising in older cameras often resulted in a loss of color fidelity and mainly in a loss of chroma. Nowadays, small colored details still get lost due to the smoothing algorithms used at low light conditions but the chroma in bigger color patches is usually preserved. Only at the borders of the patches the smoothing gets visible. But still this aspect requires to be monitored and the approach by the CEA-639 standard is not suitable for still cameras.

For still cameras a set of color patches equal or similar to the x-rite color checker SG shall be captured in the reference image as well as in the low light image. If nothing else is specified the images from the camera under test shall be treated as sRGB images according to IEC 61966-2-1 and converted into CIELAB space. Otherwise an appropriate way to convert the image into CIELAB space shall be use e.g. ICC color management. The chroma value for each patch shall be determined as:

$$C* = \sqrt{a*^2 + b*^2}$$

<div align="right">(4)</div>

As a proposal the chroma value for all patches in the low light images need to be above 50% of the chroma value in the reference image.

5.7 Texture

Modern denoising algorithms preserve regular structures in images. Therefore the processing does not destroy edges and structures like the ones in the siemens star. This is the reason why we still measure reasonably good resolution values in images of some cameras although the low contrast fine detail often referred to as texture is already gone. Currently there is an ongoing test in the ISO committee on how to measure the texture loss in images and the standard coming out of this activity will most likely be the basis for the evaluation in the low light performance.

A dead leaves approach that has been the topic of several papers at the Electronic Imaging Conference over the past years ([11] [12] [13] [14] [15]) is considered as a potential candidate to measure the loss of texture in images.
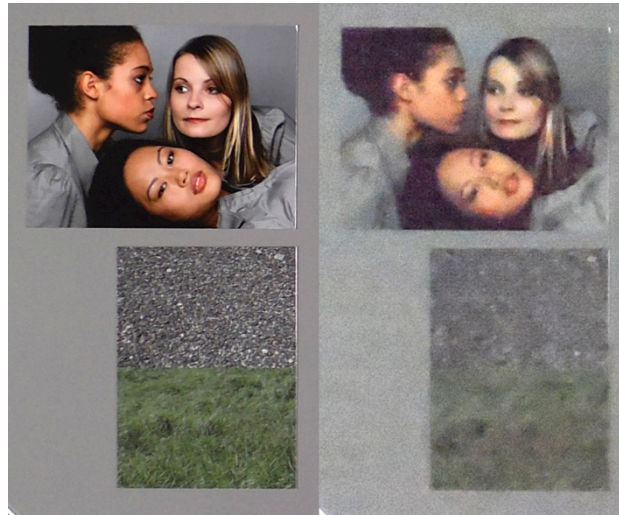

Figure 5: The loss of texture with increasing Exposure index. The part of an image on the left was shot with a sample camera at ISO 100 and the one on the right at ISO 6400.

6. SUMMARY

Digital still cameras require a similar but different test procedure for low light performance than camcorders. Variable exposure time combined with image stabilization as well as denoising algorithms are aspects that are not covered by CEA-639 but have to be taken into account. The procedure described in this paper does not try to reinvent the wheel but adds aspects and modifications where necessary.

The whole test is based on thresholds and it is arguable for each individual aspect what threshold should be used and why. Some of these may easily find consensus among experts like the rule of thumb for the exposure time. For others we currently do not even have a reliable method to measure them like for example for texture loss.

This paper is really just an outline and now we need to test at least 30 to 50 cameras and mobile devices to make sure this procedure works according to our expectations.

Proposed thresholds overview:
Exposure time: 1/30 second; 1/8 second or measurement result for cameras with stabilization
Luminance level: 20% below reference
Black level: needs to be below 20% of max possible output level
Noise: peak standard deviation of 10 for visual noise according to ISO 15739
Resolution: 30% below reference
Color: 50% below reference
Texture: to be done

REFERENCES

[1] CEA-639 (ANSI), Consumer Camcorder or Video Camera Low Light Performance
[2] ISO 12233, Photography -- Electronic still-picture cameras -- Resolution measurements
[3] IRE, Institute of Radio Engineers, http://en.wikipedia.org/wiki/IRE_(unit)
[4] ISO 7589, Photography - Illuminants for sensitometry - Specifications for daylight, incandescent tungsten and printer
[5] TE42, http://www.image-engineering.de/index.php?option=com_content&view=article&id=423&Itemid=97
[6] ISO 2720, Photography – General purpose photographic exposure meters (photoelectric type) – Guide to product specification
[7] Exposure Value, http://en.wikipedia.org/wiki/Exposure_value
[8] CIPA DC-011-2012, Measurement and Description Method for Image Stabilization Performance of Digital Cameras (Optical System), http://www.cipa.jp/image-stabilization/index_e.html
[9] ISO 15739, Photography -- Electronic still-picture imaging – Noise measurements
[10] ISO 12232, Photography — Digital still cameras — Determination of exposure index, ISO speed ratings, standard output sensitivity and recommended exposure index
[11] F. Cao, F. Guichard, Hervé Hornung, Measuring texture sharpness of a digital camera, Proc. SPIE. 7250, Digital Photography V (January 18, 2009)
[12] Jonathan B. Phillips, Douglas Christoffel, Validating a texture metric for camera phone images using a texture-based softcopy attribute ruler, Proc. SPIE. 7529, Image Quality and System Performance VII (January 17, 2010)
[13] Frédéric Cao, Frédéric Guichard, Hervé Hornung, Dead leaves model for measuring texture quality on a digital camera, Proc. SPIE. 7537, Digital Photography VI (January 17, 2010)
[14] Jon McElvain, Scott P. Campbell, Jonathan Miller, Elaine W. Jin, Texture-based measurement of spatial frequency response using the dead leaves target: extensions, and application to real camera systems, Proc. SPIE. 7537, Digital Photography VI (January 17, 2010)
[15] Uwe Artmann, Dietmar Wueller, Improving texture loss measurement: spatial frequency response based on a colored target, Proc. SPIE. 8293, Image Quality and System Performance IX (January 22, 2012)
[16] Rayleigh Criterion, Born and Wolf, Principles of Optics, Cambridge University Press, 7th edition, Page 371, ISBN 0521642221