ANALYZER

by DXOMARK

Analyzer 8.1

The leading image quality evaluation solution

User Manual

Analyzer solution includes everything you need to reliably measure and analyze the imaging performance of any type of image capture device: testing protocols and methodologies, laboratory specifications and installation guidelines, data management and analysis software.

Analyzer is the only solution that can fully measure not just the quality of captured images, but also artifacts from electronic shutters, the effectiveness of 6-axis image stabilization systems, the geometry of dual-module cameras for 3D or stereoscopic vision, and the dynamic response of imaging devices to changing scenes and light levels. Coupled with Analyzer's ability to measure images the way consumers see them, it is possible to fully evaluate cameras and lenses in a way that predicts how they will perform in real world situations.

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1 – Introduction

Thank you for choosing Analyzer, the most reliable and comprehensive solution for testing and characterizing any digital camera. Analyzer is the culmination of years of advanced research in applied mathematics, image processing and measurement techniques conducted by DXOMARK IMAGE LABS scientists and imaging system experts.

Analyzer is designed to enable measurement of any kind of camera, from high-end D-SLRs with top-quality fixed focal or zoom lenses to tiny camera-modules for camera phones.

Analyzer lets you objectively measure the performance of digital cameras for all key optical and imaging characteristics: distortion, lateral and longitudinal chromatic aberrations, vignetting, noise, defective pixels, dark signal, ISO sensitivity, perceived blur, spatial frequency response, resolution, effective focal length, dynamic range, tonal range, white balance, and color fidelity.

You can now quantitatively measure lens optical quality with an accuracy never achieved before, and without any subjective bias. Comparisons between different pieces of equipment or between different settings are simple and rigorous, and performed against strictly identical criteria, making comparisons possible even when tests are carried out in different labs.

Using data from Analyzer, it is possible to both quantify a digital camera's key image quality attributes (such as colorfulness, sharpness, graininess, tone reproduction and scene geometry) and perform a precise diagnosis of the shortcomings of the camera's components (such as lens optics and image processing).

The Analyzer solution includes all the charts necessary for testing different types of cameras or lenses. Analyzer can evaluate any imaging system: camera phones, webcams, digital still cameras or DSLRs, from fixed focal length to auto-focus zoom lenses, provided you use the right charts for each camera and lens.

Although measuring image quality is complex, Analyzer makes it quite straightforward. One of the purposes of this guide is to provide all the necessary explanations to help you perform reliable measurements using simple operations. In particular, the documentation details the complete experimental protocols that you must follow to perform repeatable and accurate measurements for all characteristics.

More precisely, this documentation contains:

- The list of hardware and software required to perform data acquisition and measurement.
- Complete instructions on how to set up the test lab.
- The list of charts provided with Analyzer by DXOMARK IMAGE LABS, and for each chart:

  - The measurements for which it is used.
  - The types of cameras and lenses for which it is suitable.
  - The protocol to follow to ensure optimal shooting conditions.
- The list of all the measurements Analyzer can deliver; and for each measurement, full details are given for:
  - The origin of the physical phenomenon to be measured.
  - The different factors that influence the phenomenon, and its measurement.
  - What Analyzer actually measures.
  - The added value of the measurement in raw format.
  - How to navigate the software user interface.
  - How to interpret the measurements, with illustrations from actual measurements performed on various cameras.
  - How to compare two different cameras.
  - Shooting protocols.

When the instructions in this document are properly followed, the measurements performed by Analyzer are not only easy to perform and to interpret, but are also highly reproducible.

2 – Initial installation

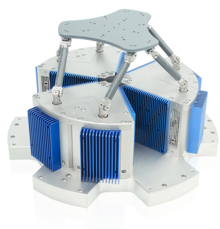
2.1 Required equipment

a) The Analyzer system comprises three distinct physical elements:

- the software installation CD-ROM or a digital link to download an archive with the same content,
- a USB HASP® dongle,
- a set of test targets.

b) The following equipment and products are necessary for installing and using Analyzer solution. DXOMARK IMAGE LABS can supply all or any part of the required equipment. The test shots must be taken in a studio, the specifications and installation of which are described in Sections 3 and 5.

- PC-type computer with the following minimum configuration:
  – Intel Pentium IV® processor or higher,
  – One of the version of Windows 10® 64 bits operating system,
  – 2 GB of RAM or more,
  – At least 30 GB of free disk space to operate the software,
  – A video card with 3D driver, compatible with DirectX 12 and OpenGL 3.0 (in Remote Desktop or Virtual Machines you may experience graphical glitches depending on the renderer used),
  – 1024×768 or more VGA monitor, using a maximum of 125% DPI scaling,
  – USB sockets: one for the license dongle, at least one more for a USB hub,
  – Ethernet ports: one for the Hexapod and one for the AMO.
- Diffused studio lighting system (spots fitted with white or silvered umbrellas, or light boxes, tripod stands),
- A very stable tripod with geared center column



- A H811, H840 or H860 PI hexapod (a 6-legged platform allowing the launch of precise user-specified motions). This equipment is available for customers who chose the Stabilization option.

- Customers using the AF measurement option will need to use the specific AF setup with a pair of IR captors, a Digital Trigger, and an integrated USB hub:
- For customers who chose the Timing measurement option, the following equipment is available:

The Touchscreen Probe To electronically simulate a human finger on a capacitive touch screen	
The Digital Trigger To remotely control a Touchscreen Probe	
The Mechanical Trigger To synchronize the pressing of the mechanical button and the sending of the signal to the LED Universal Timer.	

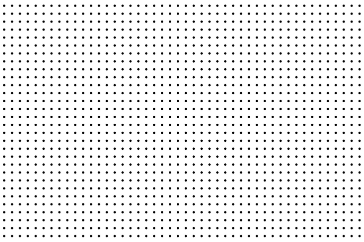
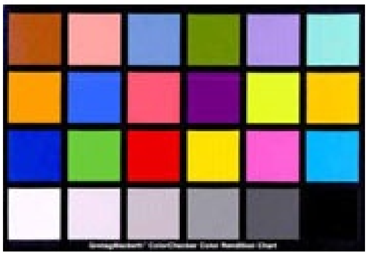
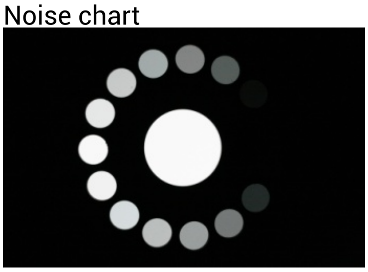
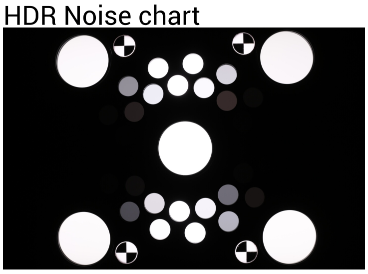
This equipment is described with more details in the Timing measurement section

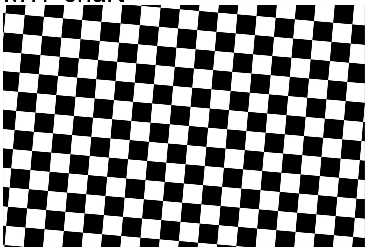
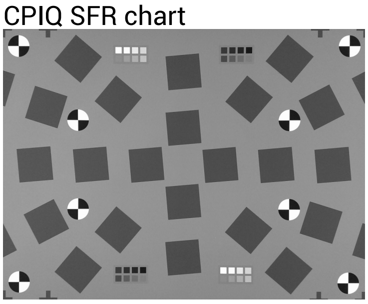
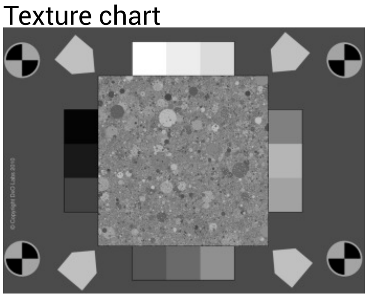
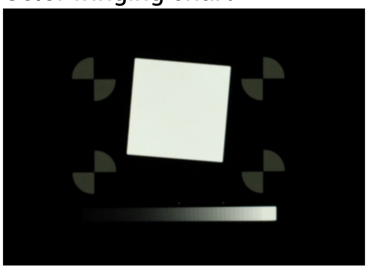
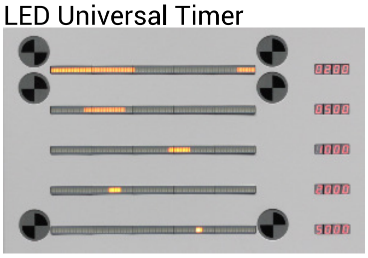
- if test targets have to be removable:
  - Two “Manfrotto®”-type stands and suitable clamps, or

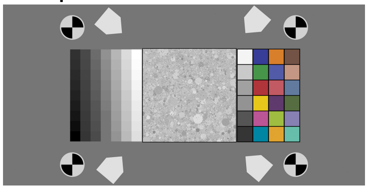
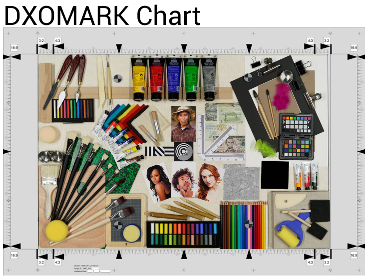
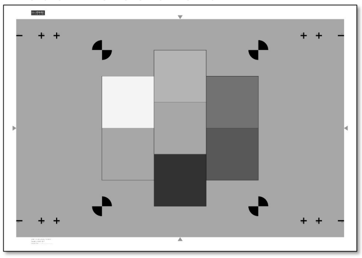
    - An artist's studio easel
- A luxmeter capable of measuring reflected and incident light
- A precise laser telemeter,
- If the camera accepts such accessories, either a cable release of suitable length to avoid shaking the camera at the moment of releasing the shutter, or a USB or FireWire cable suitable for triggering the camera from a computer,
- Other items:
    - Spirit level,
    - Black pencil + a permanent felt-tip pen,
    - Folding rule or tapeline,
    - Plumb-line,
    - Opaque adhesive tape, in a color that contrasts with the studio floor,
    - "Gaffer"-type black tape
    - A sheet of neutral grey paper with similar dimensions to the test target for exposure setting adjustment (see Section 5.3.4); store this sheet either flat, or very loosely rolled (do not fold)
- The following items are required only when setting up the studio and test targets, if test targets are going to be permanently affixed to the studio wall:
    - A means of attaching the test target to the wall (asymmetric channel approximately 1 m (40") long, if possible with locking screws, two mirror clips; or alternatively, two tubular fixings with anchors of a diameter and type appropriate to the type of wall, and screws). The lens test chart is 1 cm (0.4") thick.
    - A builder's straight edge at least 1.5 m (5') long
    - An electric drill and appropriate bits
    - A suitable screwdriver
    - A ball of string or a builder's chalk line
    - Carpet- or mirror-type double-sided adhesive tape (required only if the wall to support the test target is not perfectly vertical, or not flat)
    - Wine corks (or similar) and various thin offcuts of wood (required only if the wall to support the test target is not perfectly vertical, or not flat)
    - Various grades of glass sandpaper and a sanding block
    - A craft knife

2.2 Test targets

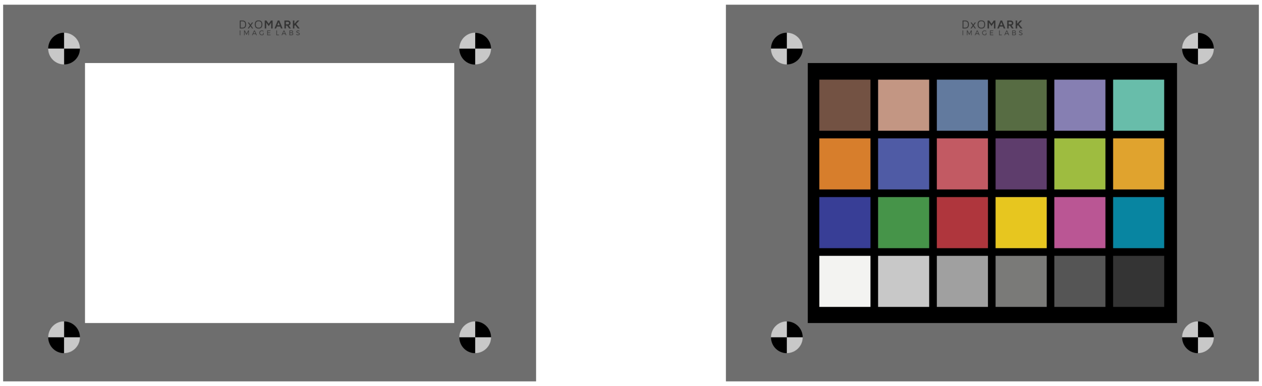
Analyzer uses a set of test targets to characterize equipment ranging from fisheye to telephoto lenses, including macro and low-resolution cameras (including camera-phones). The characteristics of the available test targets are listed in the table below.

Chart type	Chart name	Measure
Dots chart 	DU0001_200 DU0001_200_V2 DU0002_120 DU0003_60 DU0006_120	B: Blur DC: Distortion/Lateral Chromatic Aberration EFL: Effective Focal Length V: Vignetting FL: Flash uniformity
X-Rite ColorChecker® classic 24 patches 	X-Rite ColorChecker® classic X-Rite ColorChecker® classic mini X-Rite ColorChecker® classic XL	CF: Color Fidelity ISO: ISO Sensitivity N: Noise CS: Color Sensitivity
Noise chart 	N0001	DS: Dark Signal TC: Tone Curve N: Noise ISO: ISO Sensitivity
HDR Noise chart 	HDR0001	DS: Dark Signal TC: Tone Curve N: Noise ISO: ISO Sensitivity

MTF chart 	SU0001_200 SU0002_140 SU1020_140_HR	MTF: Modulation Transfer Function FSHMTF: MTF on fisheye lenses
CPIQ SFR chart 	SRU0001_200 SRU0002_140	RADMTF: MTF on a radial MTF chart
Texture chart 	TU0003_78	TEX: Texture Preservation STB: Stabilization systems AF: Autofocus
Color fringing chart 	CF0001_32	FR: Color Fringing
LED Universal Timer 	TMR0001	TMR: Timing TMR: Time lags AF: Autofocus

Composite chart 	CT001	HDR: High Dynamic Range
DXOMARK Chart 	DMC001	AZ Mate
Visual noise chart 	VNU0002_140_P VNU0001_200_P	VVN: Visual Video Noise

The X-Rite ColorChecker® classic, mini and XL are the only test targets that DXOMARK IMAGE LABS does not manufacture. They are produced by X-Rite, and are checkerboard arrays of 24 scientifically-prepared squares containing a wide range of colors. DXOMARK IMAGE LABS provides with these targets, cardboard frames with detection markers.



Left: cardboard frame with detection markers. Right: same with X-Rite ColorChecker® classic chart

Detection of the position of the target is fully automatic for raw and RGB images with this frame.

All other test targets are manufactured by DXOMARK IMAGE LABS. In this document they are referred to as the DXOMARK IMAGE LABS test targets. They have been designed by DXOMARK IMAGE LABS to facilitate the characterization of a wide range of digital cameras. The Dots charts and the MTF charts are composed of a rigid panel and a grid of black dots or squares printed on white paper. The paper is carefully affixed to the panel to create a test target which is rigid and flat. The HDR noise chart is a transmission target that must be set in front of a retro-lighting device.

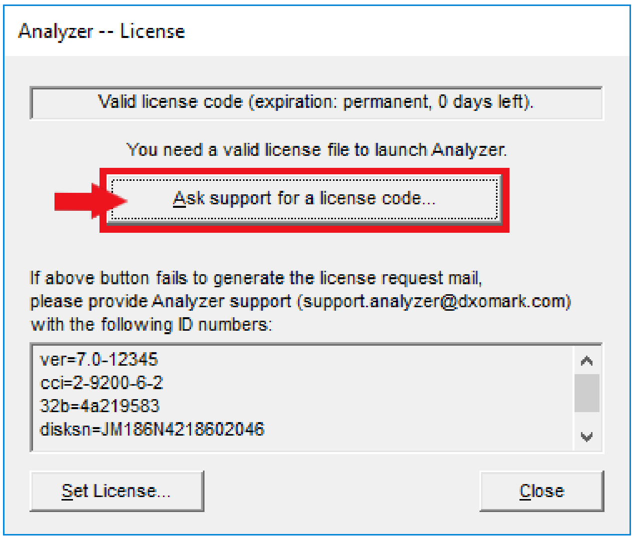
Section 4.12 gives details of the specific uses of each test target.

The manufacturing tolerances for the Dots test targets give an accuracy of within 0.1 mm (1/254") on the diameter and the position of the spots. Flatness tolerance is better than 0.1% for all test targets with glass panels. Every test target that is delivered by DXOMARK IMAGE LABS is fully checked before shipping.

2.3 License request

The support team will send you the license codes associated with the serial number of your hard drive, or with the ID of an USB dongle provided by DXOMARK IMAGE LABS.

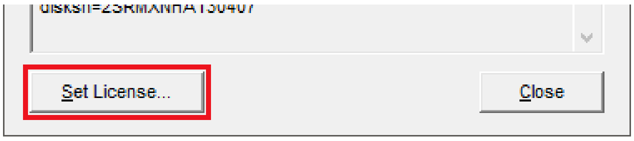
When you first open the application or use the "? / License..." menu option to change an existing license, Analyzer will bring up the license dialog:



The simplest way to communicate the ID numbers to the support team is to click on the *[Ask Support for a license code...]* button, which generates an email with these numbers ready to be sent to the support team.

Otherwise, you can select the ID numbers field contents and copy-paste them into an email that you will send to support.analyzer@dxomark.com.

Once the code received from support, click on the *[Set license...]* button.



Then copy-paste the whole received code into the registration field and press [OK].

Note: If the USB dongle is removed while in use:

- You will no longer be able to start new measurements.
- Exports will be deactivated.
- Results cannot be displayed in new windows.

3 – Laboratory set-up

This section explains how to lay out your laboratory and set up the test targets to obtain the most accurate measurements possible.

3.1 Laboratory room

3.1.1 Dimensions

Depending on the tests you will carry out, your laboratory must have certain dimensions to correctly illuminate the targets.

The largest dot target is at least 200 × 150 cm. ISO standards recommend that targets be illuminated at an angle of about 45 degrees. The room dimensions should be at least $W600 \times L800 \times H250$ cm. We recommend that the room dimensions be at least $W450 \times L500 \times H250$ cm to be able to test broad range of devices.

Warning: if you plan on testing systems with larger focal lengths, you may want to have a longer room than recommended.

3.1.2 Air conditioning

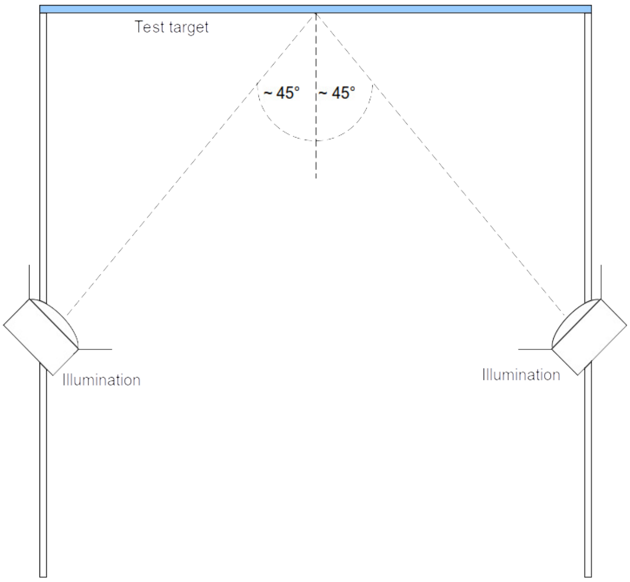
The laboratory should have an air conditioning system capable of keeping the ambient temperature at 23 °C±2 °C and relative humidity at 50%±20% when conducting measurements, as stated in ISO 554.

3.1.3 Painting

The walls, the ceiling, and the floor of the laboratory room should be matte-finished either in black or in neutral[1] dark grey to avoid any unwanted reflections during measurements (see photo below). If possible, we recommend measuring the spectral response of the paint on a sample to check that its reflection spectrum is as neutral as possible (i.e., having the same reflectance at all wavelengths).

[1] A body has a spectrally-neutral reflection if the reflected light has the same spectral distribution as the incident light.

All shiny or reflective surfaces must be covered with black cloth, which must also be as spectrally neutral as possible so as to avoid the reflection of infrared (IR) light, which can disturb or bias the measurements.



For easier handling and positioning of the test targets and the illuminants, we recommend a lightweight mounting system.

3.1.4 Illumination

We recommend use of at least two pairs of illuminants, Tungsten (A) and Daylight (D65), to illuminate the target as uniformly as possible. We do not recommend using spotlights, as their light beams are concentrated and may yield biased measurements. More specifically, we recommend:

- Tungsten: At least 750 W for each lamp.
- Daylight: Tungsten lamps with appropriate filters to achieve proper daylight. HMI bulbs are *not* recommended due to heavy peaks within their spectra.

According to ISO 61966, test targets should be illuminated at an incident angle of about 45 degrees. Check the uniformity of the light distribution on the target with a luxmeter to ensure a proper measurement. The differences between the given measurement points should not exceed 7% (0.1 EV) for the Vignetting measurement.

3.2 Positioning the test target

Caution: Many DXOMARK IMAGE LABS test targets are bulky, heavy and fragile (see the list and characteristics in Section 2.2). They must be handled with great care, particularly during transportation and setup. Be careful when handling test targets, as glass can cut. Do not use any test chart that is broken, or that appears to have broken glass inside the packaging when it was unpacked. We recommend that you wear gloves at all times when handling charts to avoid leaving any kind of finger marks that would be impossible to remove and can produce measurement errors.

Glass-mounted targets: We recommend that glass-mounted DXOMARK IMAGE LABS test targets be permanently attached to one of the studio walls. This is particularly important for the most fragile targets. This avoids frequent handling (and risk of damage), and establishes fixed conditions for testing, to ensure that test shots are completely repeatable. More details about fixed installation are given later in this section.

If the studio cannot be reserved exclusively for Analyzer measurements, you may need to install the test targets so that they can be removed. In this case, you must keep the targets perfectly vertical by using clamps and Manfrotto®-type stands. Alternatively, you may attach the targets onto a studio easel (such as used by artists). If the targets are removable, you must check carefully the test target alignment with the camera axis before each measurement. A method to obtain a good alignment is described in Section 5.2.

At least three people are needed to set up the studio. Do not handle the test targets on your own.

> **Composite-mounted targets:** We recommend that the DXOMARK IMAGE LABS test targets be attached to a wall or onto a fixed-mount system. This has the advantage of establishing set conditions for testing, to ensure that test shots are repeatable. More details about fixed installation are given later in this section.

You must carefully check the test target alignment to the camera axis before each measurement.

At least two people are needed to install the largest targets. Do not handle the test targets on your own.

> **Caution:** Do not allow any liquid to come into contact with the printed surface of a test target. Any intentional alteration of the test target without the prior approval of DXOMARK IMAGE LABS shall result in the termination of support for the test chart. Avoid prolonged exposure of the test target to high temperatures. When not used for measurements, test charts should be stored away from heat, light, and moisture.

3.2.1 Checking for perfect flatness of the DXOMARK IMAGE LABS test target

Place a single light first to the right and then to the left of the test target, in order to light the test target at a glancing angle, and check for total absence of bubbles or defective adhesion.

> **Note:** This visual check is not sufficient on its own. You must also carry out a complementary flatness check using the software. This procedure is explained in the end note in Section 13.13.

3.2.2 Positioning and adjusting the lighting of the test target

The test target must be evenly lit in order to obtain suitable images for carrying out measurements under optimal conditions.

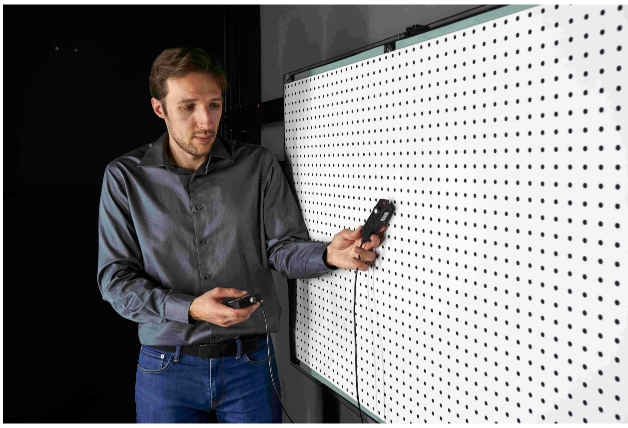
Do not use natural lighting. Take all test shots a room without windows, or whose windows have been carefully blacked out to avoid any light filtration.

Use ALS (Automated Lighting System) to light the test target.

Do not allow any object (such as an electric cable or a support arm) to cast a shadow on the test target.

Carry out the following procedure for each test target you need to set up:

1. Ensure that the two ALS devices are placed symmetrically in relation to the optical axis of the camera, at approximately 1 m from the camera and 1 m from the test target.
2. Ensure that the lighting axes are at an angle of 30–45° in relation to the plane of the test target. The ALS device on the left should aim at the left-hand third of the test target, and the ALS device on the right should aim at the right-hand third of the test target.
3. Black out the windows if necessary. Turn the ALS on. Ensure that there are no objects (such as electric cables) casting a shadow on the test target.
4. Wait at least 10 minutes before shooting test images to be sure that temperature of the illuminant is stable. For tungsten bulbs, the waiting time can be shorter.
5. Use an luxmeter to check the illumination uniformity of the test target. Adjust the position and/or horizontal orientation of the ALS so that the tolerance is suitable for the test you wish to perform. If the variation is too high, move the ALS slightly and adjust their orientation until you obtain an acceptable value. For example, when measuring vignetting, the variation between the darkest and lightest areas must be less than 0.1 EV or 7%.



4 – Analyzer general information

4.1 Optics, sensors and raw images

This section describes the basic elements of the digital image acquisition system. This is not an exhaustive description, but is meant to give enough information to understand the measurements provided by Analyzer.

The first element of a camera is the optics. In this document, it is often referred to as the lens. Strictly speaking, the term “*lens*” is incorrect, since the optical system of a camera contains a set of lenses and filters. The number of lenses depends on the type of camera. Small camera phones usually have 3 or 4 lenses, while autofocus optics for DSLRs typically contain between 7 and 25 lenses. In both cases, the purpose is identical: the optics focus (concentrate) light rays so that all the photons coming in from a given direction hit a single plane, known as the *plane of focus*, in a spot as small as possible, known as the *blur spot*. However, this describes an ideal situation, and several phenomena that can be deduced from the laws of optics can be observed.

First, the location of the points of optimal focus is not a plane, but a general surface. This surface depends on the direction of incoming rays and on their wavelength. However, light is indeed collected on a plane, the *sensor plane*. Hence, the size of the blur spot also depends on the wavelength and on the position in the field. The image on the sensor plane suffers from *(longitudinal) chromatic aberration*, resulting from different focuses for different wavelengths. The blur spot should ideally be a point, but this is never the case. Any lens loses high-frequency information, and images in the plane of focus are never as sharp as the shot scenes. Moreover, the blur spot has a shape, which depends on the position in the field and the wavelength. A strong *astigmatism* is the result of a strongly anisotropic blur spot.

The image on the plane of focus is not a simple perspective projection of the scene, as it would be with a simple but impractical pinhole camera (see Glossary 40).

Light rays do not cross the lens in a straight path. Moreover, rays whose direction differs much from the *optical axis* (the axis of symmetry of the lens) undergo a larger deviation. This effect is more important for cameras with a large *field of view* (or an equivalently small *focal length*), such as those using fisheye lenses. In short, straight lines in the scene do not remain straight in the image. Moreover, the amount of distortion also depends on the wavelength of incoming rays. In addition to *geometrical distortion*, this effect yields a color plane shift called *lateral chromatic aberration*.

A uniformly-lit scene does not produce a uniformly-lit image on the plane of focus. The brightness is lower on the periphery of the image than at the center for several reasons: the length of off-axis optical paths is larger, and off-axis beams are viewed across the pupil and the sensor through a smaller solid angle that beams on the optical axis. All in all, fairly simple optical considerations predict that light rays incoming with an off-axis angle of θ are attenuated by a $\cos^4 \theta$ factor. However, this *light fall-off*, also called *vignetting*, is only a first approximation and some optical systems can overcome this attenuation factor. On the other hand, light rays from off-axis directions may also be blocked by objects such as the lens barrel, which also decreases the number of photons reaching the sensor.

For more complex reasons, vignetting also depends on the wavelength, and a spectrally-neutral object may have changing colors in the image field. One of the causes of the *color vignetting* is that digital camera sensors are sensitive to infrared radiations. To filter out these photons, infrared filters are used. However, the bandwidth of an infrared filter is shifted by an amount that is function of the angle of incidence. For high-incidence angles, the IR filter progressively attenuates frequencies in the visible domain, starting from red, then green, and then blue.

After passing through the lens, light hits the sensor. On digital cameras, the sensor is an array of photosites. Each photosite has a microlens that refocuses the light to the center of the photosite. More importantly, each photosite also contains a color filter. There are usually three types of filters, characterized by their spectral response: the first type has a peak value in a wavelength corresponding to red tones, the second one to green tones, and the third one to blue tones. This choice was primarily made to more or less follow the response of the cones and rods of the human eye. However, the spectral responses of those filters usually do not coincide with those of the eye. Therefore, sensors may be thought of as color blind compared to the human eye.

The different filters are set on a regular array. One of the most common architectures is the *Color Filter Array* (CFA), following the idea of B.E. Bayer (U.S. Patent 1976, Eastman Kodak). With CFA, there are three types of filters. A single color – the green – is duplicated, thus the elementary cell of the array contains four photosites (1 red, 2 green, 1 blue). The different channels are denoted by R, G, and B, and if the sensor is a CFA and the two green channels are differentiated, they different channels are denoted by R, Gr, Gb, and B.

Color filters have a specific response to each wavelength. This behavior is defined by its quantum efficiency. The quantum efficiency gives a number of electrons that depends on the input light spectrum. Usually this quantum efficiency is measured by the spectral sensitivity. Finally, each photosite is hit by a certain number of photons that are converted into electrons. So the number of electrons will depend on the color filter's spectral sensitivity. For more information, see Color sensitivity Section 30.

These electrons generate a current. The voltage is measured and converted into a numerical value, usually encoded on 10, 12 or 14 bits. This value is theoretically proportional to the number of photons hitting the photosite. However, because of thermal effects and the power supplied to the system, the sensor always produces a small electrical signal, even in absence of light. This *dark current* is subtracted to make the sensor response as linear as possible for usual luminances.

On the other hand, the sensor has a saturation luminance beyond which it will still output the same numerical value.

Output numerical values are always noisy; the noise is more important when photosites are small. The noise may come, for instance, from the photonic effect (the number of photons coming to the sensor is random and fluctuates slightly) and analog/digital conversion.

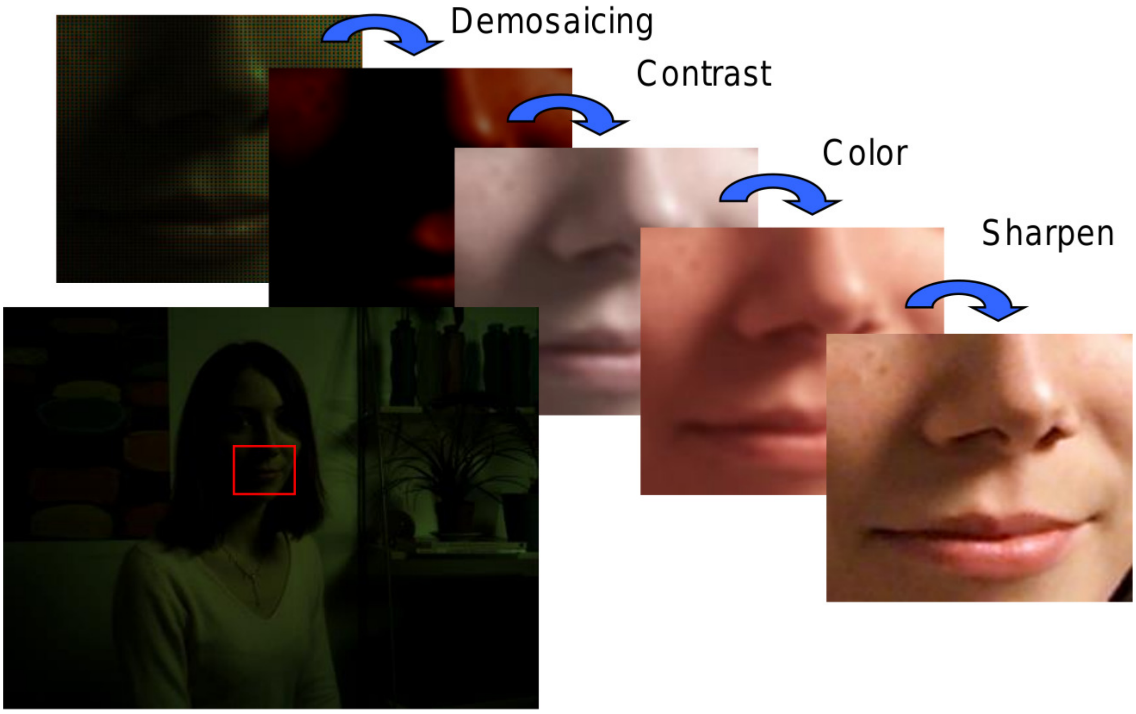
Moreover, some photosites may be *defective* and simply not have the expected response. And in fact, there may be disparities between the response of whole lines and columns, creating *fixed pattern noise*. In contrast to defective photosites, which are simply unreliable, fixed pattern noise can be calibrated and corrected.

The array of numerical values output from the CFA is called the raw image (or raw format image).

4.2 Raw conversion

Raw conversion is a sequence of numerical algorithms that transform the signal from the sensor array into an image with the same number of pixels, each pixel containing R, G, and B channel values. Note that raw images provided by manufacturers may not be exactly the array of values immediately after analog/digital conversion, since corrections may have already been applied. Typically, fixed pattern noise or defective photosites may have already been numerically corrected.

Manufacturers usually design their own raw conversion sequence. Thus the different steps described in the following paragraph are indicative, since they may or may not be included in a raw conversion sequence, or may occur in different sequences.



Example steps in a raw conversion process

- White balance: Each color filter has a specific spectral sensitivity. So the color filter in front of the photosites and the photosites themselves do not respond equally for all light wavelengths. In addition, different lighting has different spectral distributions. Therefore, an object which is spectrally neutral usually does not yield equal values in the R, G and B channels, though they should. *White balance* correction consists in applying different gains to the R, G, and B channels to restore neutrality. This channel-dependent scaling changes the spectral distribution.
- Demosaicing: This consists of mixing the values of neighboring photosites to reconstruct R, G, and B values in each pixel. This is actually a very challenging task, and simple methods usually introduce either some blur or some annoying artifacts (such as color aliasing).
- Color rendering: Since the spectral distribution of color filters and sensors are not exactly the same as those of the human eye, colors of demosaiced images are usually not satisfactory. A transformation of the color space aims to retrieve more exact or more visually-pleasing colors (which might not be the same). It also changes the spectral distribution of noise.
- Denoising: The signal in raw images is intrinsically noisy. Moreover, noise can also be amplified or spectrally changed by the different steps described above. Denoising methods smooth the image so that homogeneous areas look more regular. The performance of denoising methods is hard to evaluate since they should remove unwanted oscillations but still preserve edges, sharpness, and fine textures.

- Sharpening: The response of an optical system strongly depends on the spatial frequency of the input. The maximum response is usually attained for the null frequency, and the response drops for higher frequencies. Edges may appear blurry, and fast oscillating textures may appear dull or may even be lost. In the latter case, there is nothing that can be done, but in the former case, the image can be numerically enhanced and sharp transitions may be retrieved. However, sharpening usually increases noise and may introduce numerical artifacts such as *ringing*.
- Contrast: In raw images, the numerical value of a photosite is proportional to the number of photons hitting the photosite (up to electronic noise and analog/digital conversion noise). However, the response of the human eye is not linear: a reduction in the number of photons does not visually yield a proportionally darker image. CRT monitors also do not have a linear response. This nonlinearity is taken into account in the sRGB color space. For compatibility with these devices and for better-looking images, manufacturers apply a nonlinear change of brightness (a *tone curve*, also known as *gamma correction*), which may differ from the one prescribed in the sRGB color space. This usually increases noise in low-light areas, as the slope of the tone curve is quite steep there.
- Compression: Standard graphical devices can display images encoded on 8 bits on each color channel. Thus, the cost of a pixel is 3 bytes. Currently, images with a resolution of 40 Mpixels are very common in DSLR cameras and in camera phones. Storing these images at these sizes is usually unacceptable because of memory or transmission constraints. Thus, images are usually compressed. The best compression rates (a 1:10 ratio is very common) are obtained with lossy compression methods, although artifacts may appear for high compression rate. This introduces some noise, usually near edges and in textures. JPEG is certainly the most widespread lossy compression standard.

These steps are the basis of most raw conversion sequences. Some additional steps may also correct for artifacts caused by the optical system and the sensor, such as distortion, vignetting, noise, or blur.

4.3 Nature of the measurements performed by Analyzer

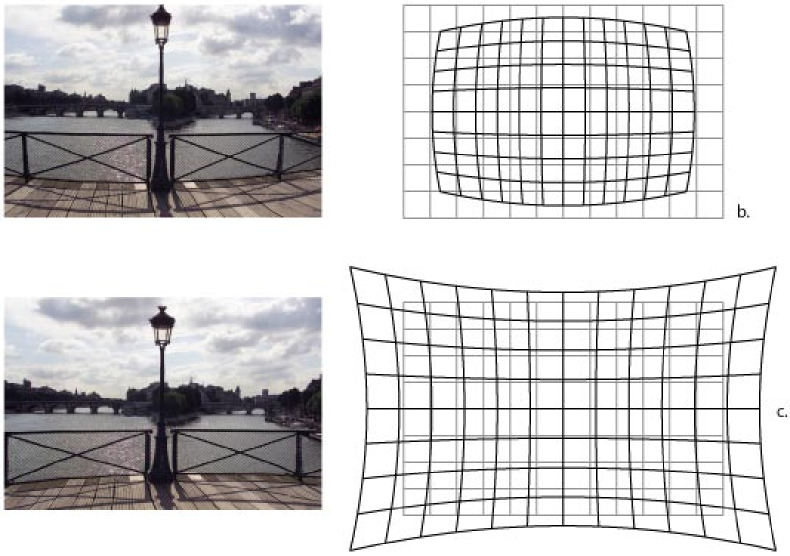
The system analyzes the overall performance of a camera using the image files that are produced with the test targets. In other words, Analyzer characterizes the coherent combination formed by a lens (or a zoom lens set to a given focal length), a sensor and its demosaicing software, and the settings for aperture, sensitivity, sharpness, color space, and so on. Several parameters have an influence on the results of a measurement, and this is why the repeatability criteria set out in Section 4 must be strictly adhered to.

Analyzer measurements characterize the following parameters:

- B measures perceived blur, in BxU units; a particularly innovative method characterizes the true sharpness of images.

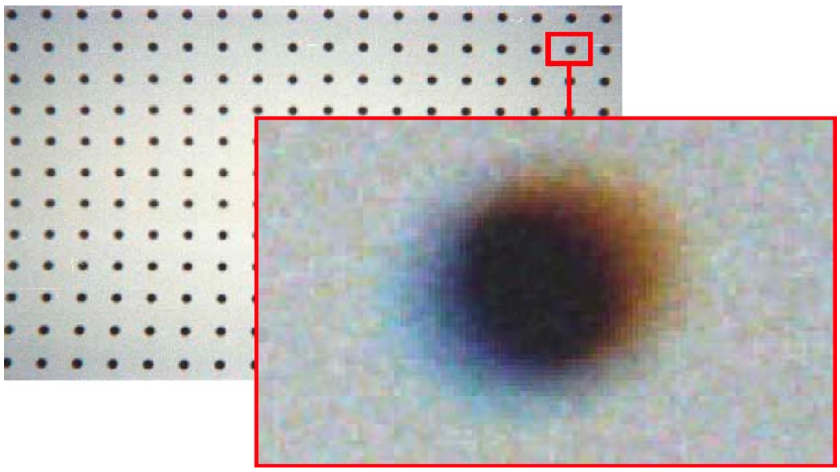
Left image is blurred, right image is sharp

- MTF measures the spatial frequency response of the camera. This varies in the image field and with the light wavelength.
- DC measures geometric distortion and lateral chromatic aberration. Geometric distortion basically takes two forms:
  - Barrel distortion: peripheral lines in the resulting image take the shape of a barrel (bending inward).
  - Pincushion distortion: peripheral lines in the resulting image take the shape of a pincushion (bending outward).



Top: barrel distortion – Bottom: pincushion distortion

– Lateral chromatic aberration is shown by the presence of a colored fringe around a black point in the image.

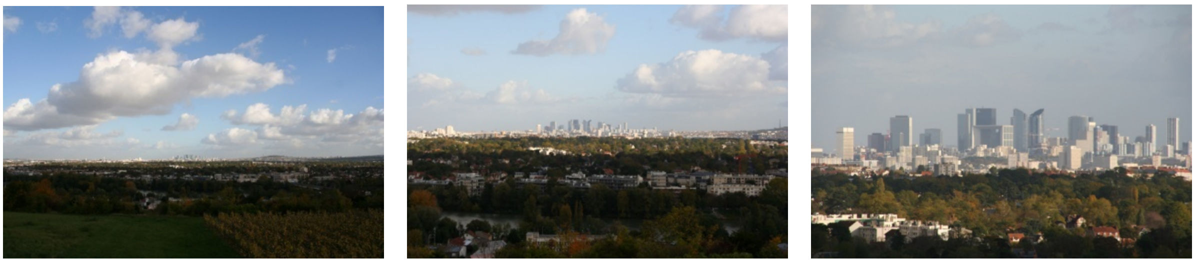


Example of lateral chromatic aberration

- V measures vignetting, present in images whose edges are darker than the center.

Example of vignetting, noticeable in upper corners of the image

- EFL measures the effective focal length and the field of view of a camera. Results depend on the lens, and also on the sensor size, which can vary from one camera model to another.

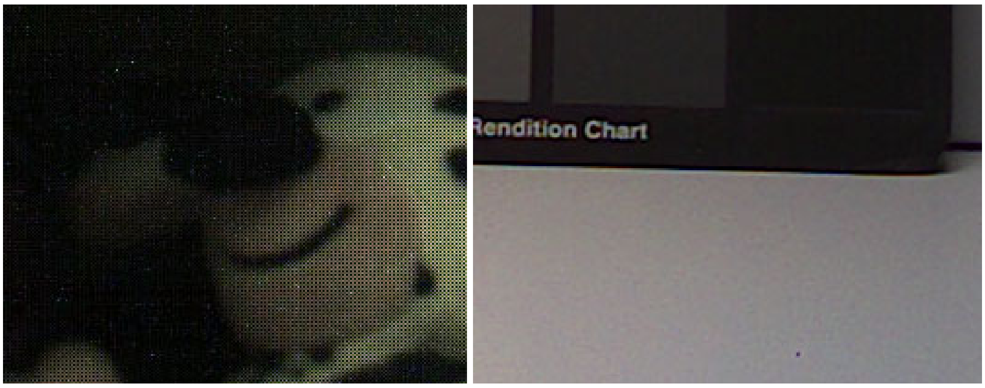


A scene taken with the same camera at three different focal lengths

- N measures noise, which is the presence of pixels with different values within an area, when these values are expected to be more similar.
- RCN measures the patterns of noise along the rows and columns of the sensor.

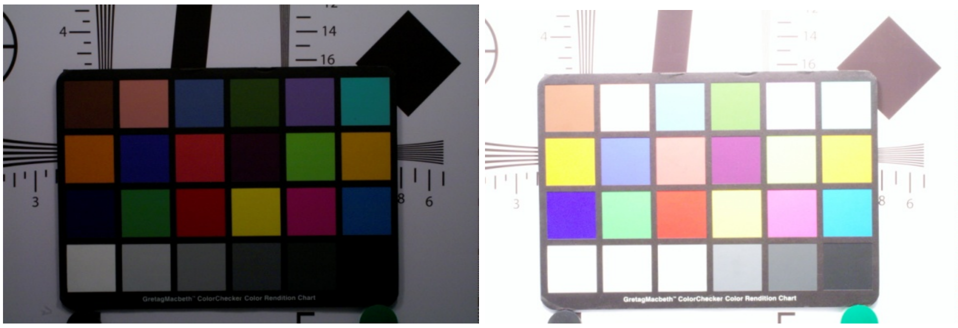
Example of noise, especially visible in homogeneous areas

- DP (raw images only) measures the numbers of defective (bright or dark) photosites of a sensor.



Bright defective photosites are visible in dark areas (left), dark defective photosites are visible in bright areas (right)

- DS (raw images only) measures the dark signal of a sensor, which is the response of the sensor in the absence of light. More generally, the Dark Signal measurement also returns the response of the sensor to different light exposures.
- CS measures the color sensitivity of a sensor, defined as the effective number of colors the sensor can discriminate when noise is considered.
- TC measures the tone curve of a camera, which is the conversion of the number of received photons into grey levels.
- ISO measures the ISO sensitivity; it determines the gain of the camera depending on different lighting conditions.



The same image shot with two different ISO sensitivities (ISO speeds)

- CF measures the color fidelity: different cameras have different color renderings depending on the spectral response of the sensor, the sensor noise, and/or the aesthetic choices of the manufacturer.

Two cameras rendering colors differently for the same scene

- FL measures the flash uniformity, centering, and chromatic deviation of a camera/flash pairing.
- TEX measures the preservation of fine details (texture) in images.
- FR measures the size and intensity of color fringes in over-exposed areas of the image.
- 3D measures the calibration of the two cameras of a stereovision system.
- STB measures the contribution of stabilization systems to image quality.
- TMR measures the different timings of a camera.

4.4 Image files formats

Analyzer can read 8-bits encoded image files in TIFF or JPEG format, or 16-bits encoded TIFF files (except for Texture measurement that supports only 8-bits images). Image files in PNG format are also read.

Analyzer can also read image files in raw format. The available formats are DNG, CR2, CRW, RAF, MRW, NEF, RAW-TIFF, DXR and CFA (raw format, described in Section 4.7). The complete list of all supported raw formats is available in the release notes of each version.

Analyzer reads files directly from the camera memory card, if it can be treated as a hard disk by a PC.

If the camera memory card cannot be read directly, copy the files from the card onto the PC hard disk using the connection software supplied with the camera.

Analyzer does not copy image data onto the PC hard disk, but only reads image data at the location indicated by the operator. Analyzer computes the desired measures and stores the results into the *Results* folder. We suggest that you should organize this folder for easy data retrieval. If, for any reason, you need the image files to be stored on the PC, it is better to have Analyzer work directly on these PC image files than on the camera memory card.

Note that the JPEG compression ratio can affect some measurements that are performed by Analyzer. This point is noted and explained in the relevant sections.

> **Note:** Camera-phones image files may be saved onto a PC hard disk using USB or Bluetooth.

4.5 Sidecar files

For some measurements, you must provide more data to Analyzer to perform measurements. For example, you must provide the distance to the target to perform a focal measurement.

To provide the additional data to Analyzer, you will need to generate a supplementary data file, known as a sidecar file. The sidecar file is simply a text file with the same name as the image file followed by extension ".ini."

For example, for an image named "image1.jpg", Analyzer tries to read a sidecar file named "image1.jpg.ini" in the same folder as “image1.jpg.”

Sidecar files have the same syntax as “.ini” files, and must be ANSI encoded (ISO 8859-1).

Grey level values for raw images must be given in 15b format, the format that Analyzer uses internally. This means that for a 10 b raw image, for example, the value in 10b format must be multiplied by 32 (2^5) in the sidecar file.

Here are all the values you can provide to Analyzer using sidecar files. In most sidecar files, only one or two of these sections will be necessary:

```
[Common]  // common section
//Manual  X-Rite ColorChecker\textregistered classic chart position
X1=...  // x coordinate of the top-left corner
Y1=...  // y coordinate of the top-left corner
X2=...  // x coordinate of the top-right corner
Y2=...  // y coordinate of the top-right corner
X3=...  // x coordinate of the bottom-left corner
Y3=...  // y coordinate of the bottom-left corner
X4=...  // x coordinate of the bottom-right corner
Y4=...  // y coordinate of the bottom-right corner

[Crop]               // analysis area section
Left= ...            // left position
Right= ...           // right position
Top= ...             // top position
Bottom= ...          // bottom position

[Black]              // Black value section
BlackValue= ...      // value to subtract to have 0 black (must be in 15b for raw images)

[EFL]    // Effective Focal Length section
ReciprocalFile=...   // Second image file name (optional)
DotSpacingMM=...     // Distance between 2 dots on the chart in mm
NodalDistanceMM=...  // Distance between the chart and the nodal point (in mm)
SensorWidthMM=...    // Sensor width in mm
SensorHeightMM=...   // Sensor height in mm

[Fringing]    // Fringing section
ColorRedRed= ...     // coeff. a
ColorRedGreen= ...   // coeff. b
ColorRedBlue= ...    // coeff. c
ColorGreenRed= ...   // coeff. d
ColorGreenGreen= ... // coeff. e
ColorGreenBlue= ...  // coeff. f
ColorBlueRed= ...    // coeff. g
ColorBlueGreen= ...  // coeff. h
ColorBlueBlue= ...   // coeff. j

[Iso]                // ISO sensitivity section
Aperture=...         // Aperture to compute ISO sensitivity
ShutterSpeedMs=...   // Shutter speed in ms to compute ISO sensitivity
[DensityChart]       // luminance of the HDR Noise chart patches section (cd/m2)
Patch1=1662
Patch2=1300
Patch3=1038
Patch4=773
Patch5=614
Patch6=466
Patch7=400
```

```
Patch8=296
Patch9=247
Patch10=188.4
Patch11=140.3
Patch12=52.8
Patch13=14.2
Patch14=1.1
Patch15=0.1

[Include]  // links to exported files section
MTFXLSFile=...  // MTF : file of the tranfert function to correct
NoiseXLSFile=...  // Color sensitivity : simple export file of a Noise  measurement

[MTF]  // MTF section
X1=...  // x coordinate of a point to compute MTF (optional)
Y1=...  // y coordinate of a point to compute MTF (optional)
X2=...  // x coordinate of a point to compute MTF (optional)
Y2=...  // y coordinate of a point to compute MTF (optional)
X3=...  // x coordinate of a point to compute MTF (optional)
Y3=...  // y coordinate of a point to compute MTF (optional)
X4=...  // x coordinate of a point to compute MTF (optional)
Y4=...  // y coordinate of a point to compute MTF (optional)
TCInvert=...  // set to 1 to apply a transfert function correction
TCGamma22=... // set to 1 to apply a transfert function correction with a gamma 2.2 curve

[MTF_ROI_X_H] // Definition of a MTF ROI. X must be 1 to 4. There
Left=...        //  must always be a pair of ROI, for horizontal (H)
Right=...       //  and vertical (V) transition.
Top=...         //  Each ROI must contain a centered SFR transition.
Bottom=...

[MTF_ROI_X_V]
Left=...
Right=...
Top=...
Bottom=...

[Color]    // Color section
Illuminant=... // A, B, C, D50, D55, D65 or D75
x_whitepoint=
y_whitepoint=
L1=
a1=
b1=
...
L24=
a24=
b24=

[ROI]
Left = ...   // coordinate of the left side of the ROI
Right = ...  // coordinate of the right side of the ROI
Top = ...    // coordinate of the top the ROI
Bottom = ... // coordinate of the bottom the ROI

[TimeBoxCalibration]  // Timing section, timer calibration
LineCalibration1=...  // top line
LineCalibration2=...
LineCalibration3=...
LineCalibration4=...
LineCalibration5=...  // bottom line

[TimeBoxCapture]  // Timing section, capture data
LineCapture1=...  // top line
LineCapture2=...
```

```
LineCapture3=...
LineCapture4=...
LineCapture5=...  // bottom line

[Delay]
TimeDelay=...    // delay used for the series in ms

[VideoTemporalCrop]  // section for temporal crop of videos. These
                     // parameters are mutually exclusive, select the
                     // ones you need to define the temporal crop (in
                     // sec or frames, and with end or duration)
StartTimeSec= ...    // start time of the measurement, in sec
EndTimeSec  = ...    // end time of the measurement, in sec
DurationSec = ...    // duration, in sec
StartFrame  = ...    // start time of the measurement, in frames
EndFrame    = ...    // end time of the measurement, in frames
FrameNumber = ...    // duration, in frames
```

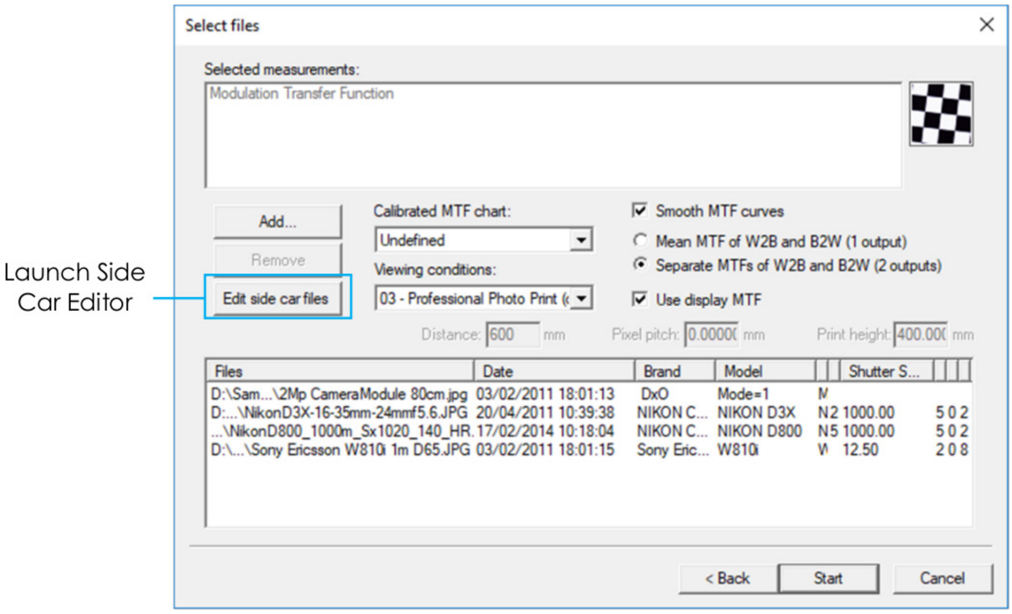
4.6 Sidecar editor

Analyzer provides a user interface to define, import, and export certain sidecar information:

- Crop area
- Regions Of Interest (ROI) for MTF measurements

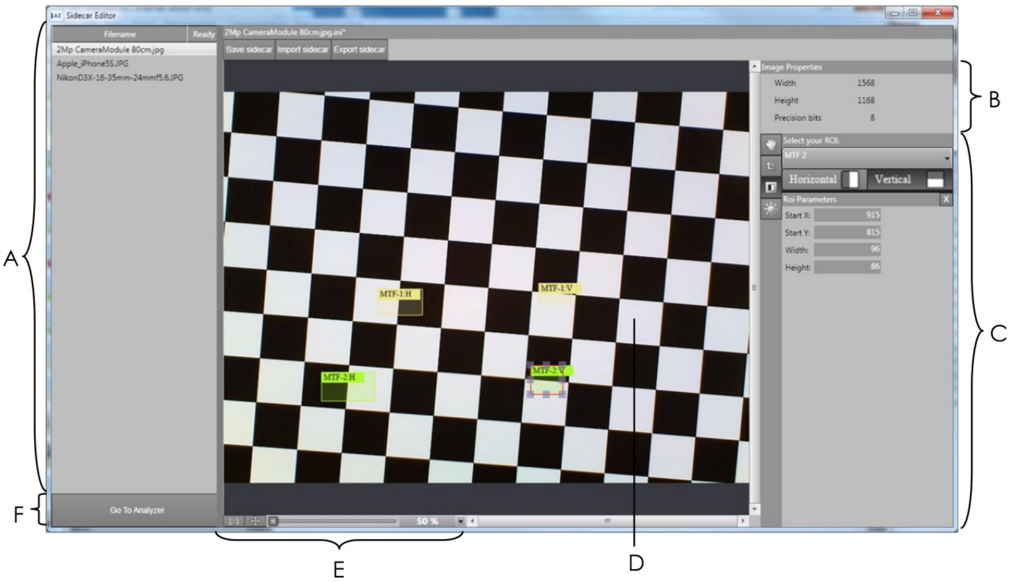
4.6.1 Select files in Analyzer

- Select a chart button and a measurement to perform.
- In the “Select Files” dialog box, click on the “Add…” button to select the files to analyze in the standard file dialog box, or alternatively, drag and drop files in the “Select Files” dialog box.
- Click on “Edit sidecar files”



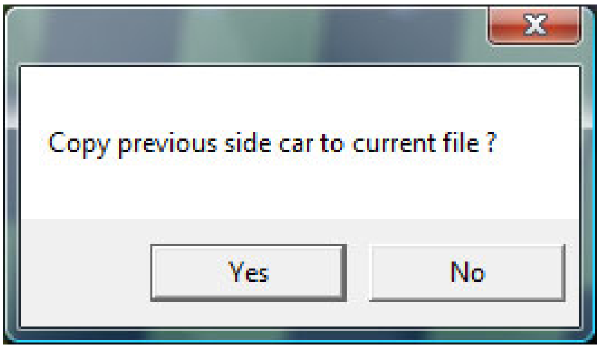
4.6.2 Edit sidecar files in Sidecar Editor

Sidecar Editor work area



A	File List
B	Image properties
C	Toolbox
D	Image display area
E	Zoom parameter
F	Exit button

- The Sidecar Editor starts on the first image of the file list.
- To edit a sidecar file, double-click on the image file name. The image is displayed and you can modify the sidecar parameters.
- Use the Crop or ROI MTF to modify the corresponding parameters (see 6.6.3 for more details).
- Click on the “Save sidecar” button.
- Select another image by double-clicking on the file name in the file list (area A).
- A dialog box offers to copy the previous sidecar parameters (Crop and ROI MTF parameters only) to the current file. Click “Yes” if you want to copy.

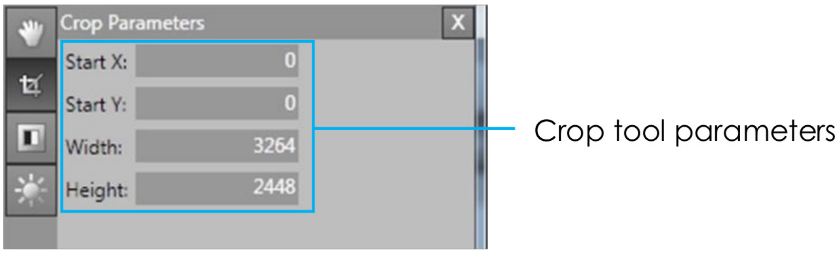


- Once all parameters have been provided for all your pictures, you can click on the “Go to Analyzer” button to quit Sidecar Editor.

4.6.3 Toolbox

- Crop Tool 

Use the crop tool to define an area within the image as the input of the measurement.

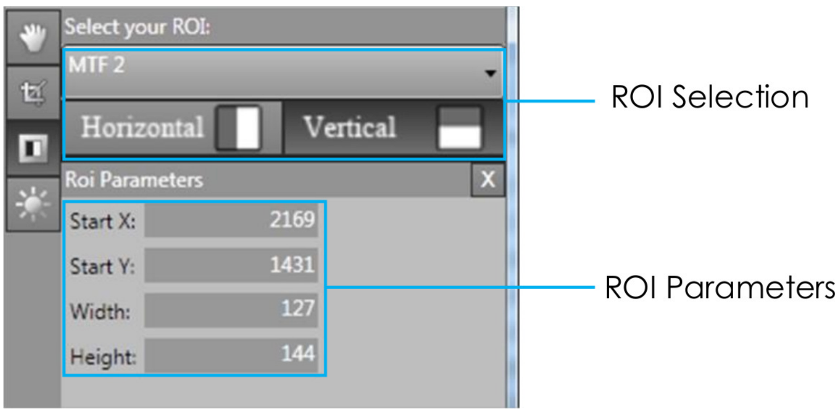


– Select the Crop tool
– Click in the image and create the rectangle.
– Adjust the rectangle if necessary, either from one of the 8 handles around the rectangle, or using the four text boxes to edit the values.

- To delete a crop, simply click on the X button.
- ROI MTF Tool

Use the ROI MTF tool to define Regions Of Interest for the MTF measurement.

– You can define up to four MTF measurement points.
– Each MTF measurement point must define one horizontal and one vertical ROI.
– MTF measurement points must be defined in the natural order from 1 to 4, which means you cannot define measurement point #3 if you have not defined #1 and #2 first. If you do so, Analyzer will return an error if you try to perform the measurement with an invalid sidecar file.



1. Select the desired MTF measurement point from the combo box.
2. Select horizontal or vertical.

3. Define the ROI with a click in the image to create a rectangle.
4. Adjust the rectangle if necessary, either from one of the 8 handles around the rectangle, or using the four textboxes to edit the values.

- To delete the current ROI, simply click on the X button.

To export the current sidecar file:

- Click on the "Export sidecar" button. A standard dialog box allows you to select a folder and file name for saving the sidecar file.

To import a sidecar file

- Click on the "Import Sidecar" button. A standard dialog box allows you to select a file to load into the sidecar file.

4.7 Measurements in raw format

Analyzer allows you to make measurements directly in raw format. Some measurements are only available in this format since they do not make sense otherwise (such as for defective photosites or Dark Signal measurements). On the other hand, the tone curve and the Color Fidelity measurements make sense for RGB images only.

Measurements in raw are complementary to measurements in RGB and are a powerful tool for diagnosing the joint performance of the optical system and the image signal processing.

We emphasize that the measurements on raw format images are not supposed to give the same results as in RGB format (JPEG or TIFF). This section aims to illustrate the usefulness of joint raw and RGB measurements on a few examples.

While doing raw measurements, be aware that some cameras shoot raw images with some rows or columns that are not lit when the shutter is open. In that case, you should use the crop parameters in a sidecar file so that Analyzer will ignore these pixels.

RGB measurements characterize the performance of the imaging system (optics + sensor + raw converter)

For a photographer, it is important to evaluate an imaging system globally in order to predict its quality and compare it with other systems. Whether defects come from the optics, the electronics, or the ISP is irrelevant.

Raw measurements characterize the performance of the optical system (lens + sensor)

For example, the MTF measurement in raw describes the frequency response of the lens. The results can then be compared with predictions given by optic design tools.

Noise measurements in raw evaluate the quality of the sensor and its actual tonal range (the effective number of values it can discriminate when noise is considered). Cross-talk between photosites can be diagnosed from the noise autocorrelation.

Raw measurements evaluate the fit between the optics and the sensor

For example, digital signal sampling theory predicts that a signal can be reconstructed with no artifacts if its frequency content is zero beyond a value determined by the sampling frequency. This latter value depends only on the sensor, while the frequency response depends mainly on the optics. The MTF measurement enables the prediction of visual artifacts such as aliasing for a given lens/sensor combination.

Raw measurements can predict the performance of the system even when ISP (Image and Signal Processing pipeline) is not available, or can help designing the ISP

For example, the vignetting (light fall-off) measurement evaluates the non-uniformity of the response of the optical system under uniform lighting. The necessary amount of correction to be applied can be predicted from the measurements. The MTF measurements on different color channels allow the prediction of (longitudinal) chromatic aberrations.

Raw measurements can track down hardware and software defects

Engineers who design an imaging system need to assess its quality. If this assessment fails, they must find out where the defects come from.

Analyzer provides measurements on images generated by the imaging system, whether it is on raw data directly out of the analog-to-digital converter or on any intermediate image generated by the ISP.

Analyzer helps engineers track down defects, check the hardware independently of the ISP, compare measurement results at different levels of the image generation chain, and find out which (hardware or software) components need to be improved.

Raw measurements can be used for better hardware design

The ISP may be pre-determined so that performance cannot be improved by the software. By characterizing all the steps of the ISP, Analyzer can backtrack possible sources of improvement of the system through new optical or sensor designs.

Raw measurements make hardware sourcing easier

At an early stage of an imaging system design, engineers need to carefully choose the components to use depending on the quality they want to achieve and the price of the final product.

Analyzer provides measurements on raw data for evaluating the quality of hardware components and for comparing them with other components on the market, independently and without the need for an ISP.

4.8 CFA file format

In order to have a homogenous raw file format, we have specified a very simple file format named CFA (for "Color Filter Array").

The CFA file format supports all Bayer-type files with up to 15 bits dynamic.

A CFA file has two main parts: a header and a pixel array. This means that a CFA file is self-sufficient.

CFA files observe the following conventions:

- All data types are integer, signed or unsigned, 8, 16 or 32 bits.
- A signed integer is referred as intX where X is 8, 16 or 32.
- An unsigned integer is referred as uintX, where X is 8, 16 or 32.
- All data in the file are in little-endian order (that is, integers are encoded starting with the lower-weight byte, ending with the higher-weight byte).

4.8.1 Header

The header is a 128-byte data structure with a C-like structure as follows:

```
{
```

```
    uint32 cfaID;
    uint32 version;
    uint32 uCFABlockWidth;
    uint32 uCFABlockHeight;
    uint8  phase;
    uint8  precision;
    uint8  padding[110];
}
```

`cfaID` must be equal to "CFA " (0x43464120)

`version` is currently 1

`uCFABlockWidth` is the number of CFA blocks (2×2 pixels) horizontally

`uCFABlockHeight` is the number of CFA blocks (2×2 pixels) vertically

`phase` is the position of the colored filters in a Bayer block:

-0 is $\begin{matrix} G & B \\ R & G \end{matrix}$

-1 is $\begin{matrix} B & G \\ G & R \end{matrix}$

-2 is $\begin{matrix} R & G \\ G & B \end{matrix}$

-3 is $\begin{matrix} G & R \\ B & G \end{matrix}$

`precision` is the number of sampling bits (up to 15)

`padding` is reserved for future use

4.8.2 Pixel array

The pixel array is a uint16 array of `uCFABlockWidth` × `uCFABlockHeight` × 4 elements representing the raw pixels one line after the other.

4.9 CFA Converter

Many camera prototypes output raw pixel data in a file without the necessary header information needed to interpret the file as a raw image. In this case, you must provide the missing information to interpret the file. It is good practice to convert and store each raw image as a new self-sufficient file (such as a CFA format file) that includes the header information.

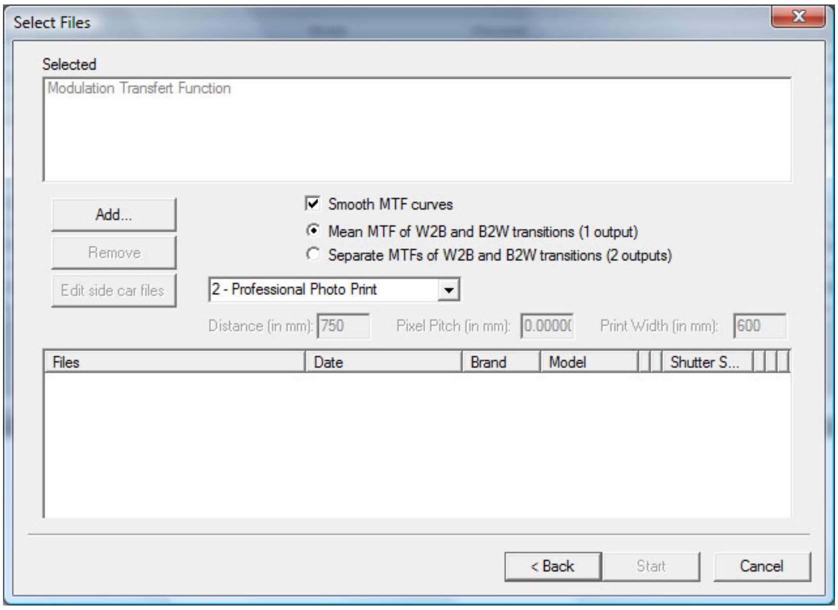
Analyzer provides a simple user interface to interpret that kind of files and convert them to CFA files that can be archived, including a viewer to check that the interpreted file looks right.

Raw pixel data files must have a ".RAW" (or ".raw") extension; if this is not the case, you must rename your files so that they have the ".RAW" extension.

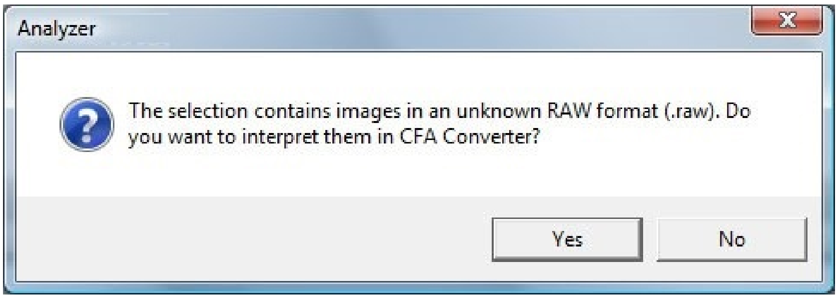
4.9.1 Select ".RAW" files from Analyzer

The process is exactly the same with a ".RAW" file as with any other type of raw file, except that you must take the additional step of using the CFA Converter to provide the missing header information to interpret the file. Remember that some measurements are not available for raw (such as Color Fidelity).

- Select a chart and a measurement to perform (available for raw).
- In the "Select Files" dialog box, click on the "Add..." button to select the files to analyze listed in the standard file dialog box, or alternatively, you can drag and drop files into the "Select Files" dialog box.



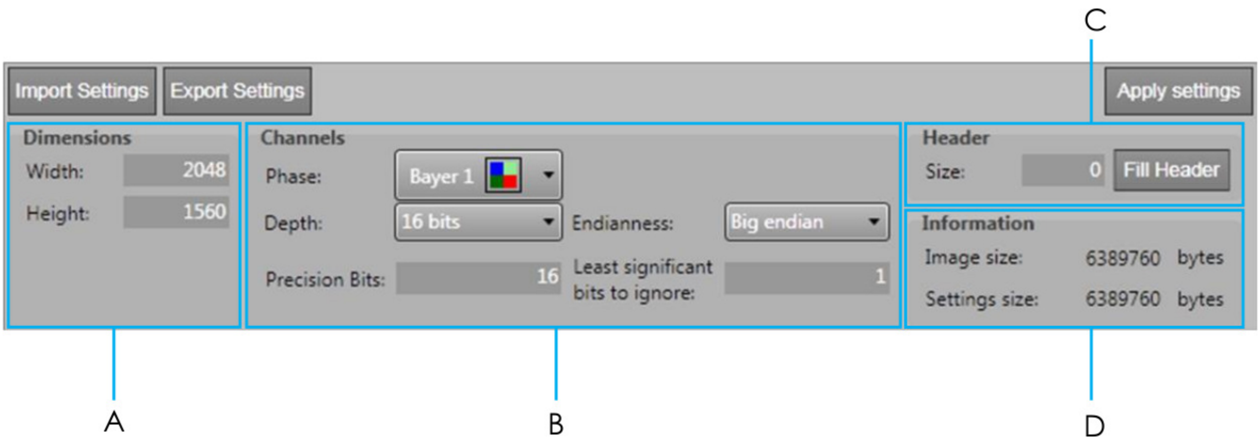
- If Analyzer detects ".RAW" files in the selection, it offers to interpret them with the CFA Converter using the following dialog box



- Click on “Yes” to launch CFA Converter.

4.9.2 “.RAW” files parameters

CFA Converter requires different parameters to interpret “.RAW” files. Below is the parameters area:



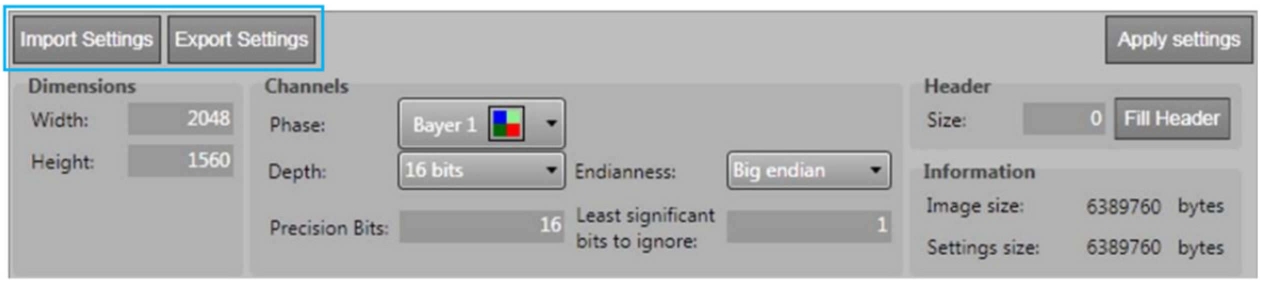
A	Dimensions
B	Channels
C	Header
D	Information

- Dimensions:
  - Width and height of the raw image.
    Both width and height numbers must be even, since the raw image is composed of Bayer blocks, and must be smaller than 8192. As a reminder, Analyzer supports only raw formats using a Bayer filter array.
- Channels:
  - Phase: phase of the Bayer pattern.

  - Depth: The data size of a pixel (container); currently, only 16 bits is supported.
  - Endianness: Byte ordering of the pixel data. Little-endian means least significant byte first, Big-endian means most significant byte first.
  - Precision bits: The number of bits that encode a pixel value, between 8 and 15.
  - Least significant bits to ignore: Number between 0 and 15 of least significant bits that must be ignored and "right shifted."
- Header: This is the number of bytes that must be ignored to reach the beginning of the image in the file. Once you have provided the dimension parameters, you can automatically fill this value by clicking on the "Fill Header" button, provided the end of the image is at the end of the file.
- Information (no parameter to provide):
  - Image size is the actual file size in bytes.
  - Settings size is the file size corresponding to the provided raw parameters.

Every time you modify one or several settings, you must click the "Apply settings" button on the top right for the CFA Converter to interpret the raw file with the new parameters.

Once you have provided all the raw parameters, you can export and reimport your parameters using the CFA Converter.



To export the parameters:

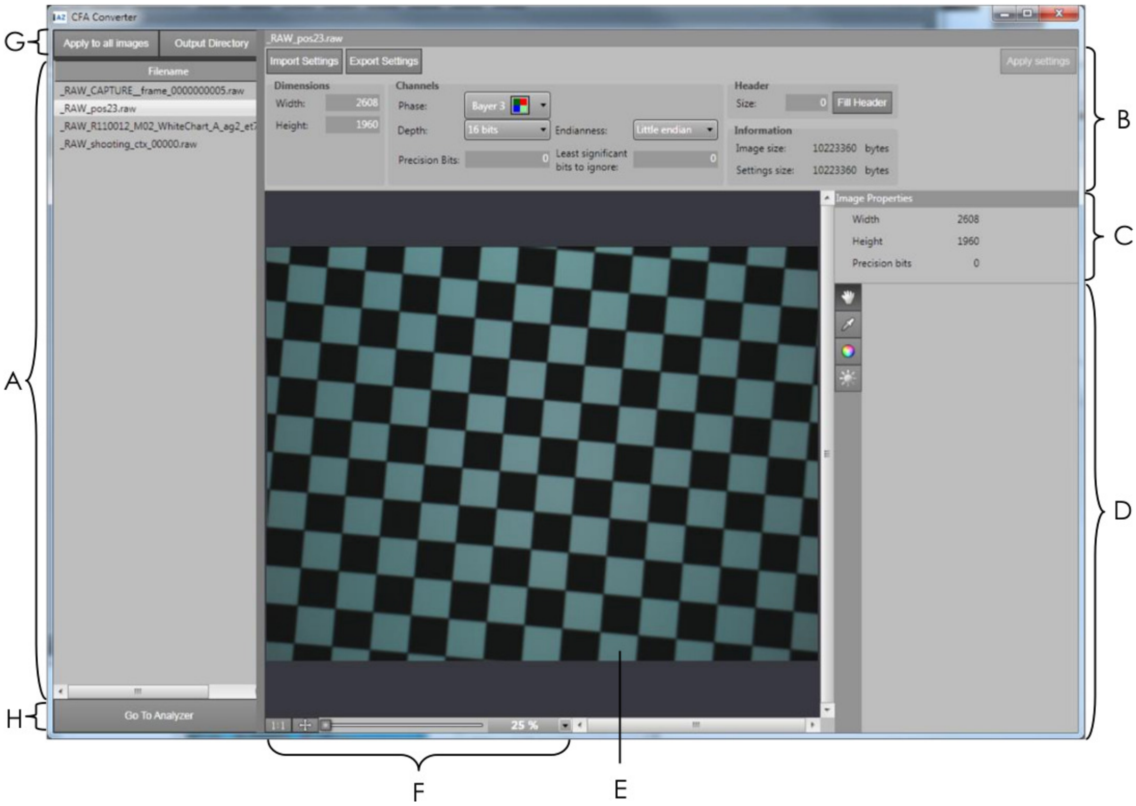
- Click on the “Export Settings” button.
- A standard dialog box allows selecting a folder and file name to save the settings.

To import the parameters:

- Click on the “Import Settings” button.
- A standard dialog box allows you to select a file for loading the settings.
- The current “.RAW” image file is updated with the new raw parameters.

4.9.3 Interpreting a “.RAW” file in CFA Converter

CFA Converter work area:



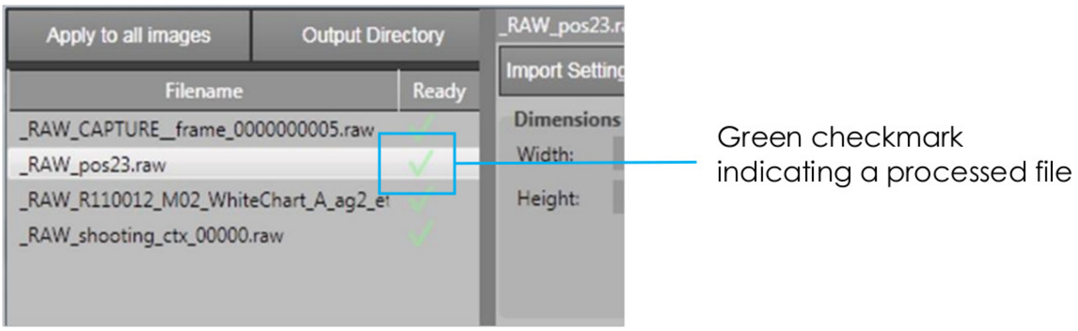
A	File List
B	Raw Parameters
C	Image properties
D	Tools
E	Image display area
F	Zoom parameter
G	Batch tools
H	Exit button

- File List in area A is the list of ".RAW" files to be interpreted; by default the first item is selected. Since no raw parameters have been provided yet, no image is displayed. If you want to work on another file, just double-click on the file name in the list (area A).

- Output directory: all “.RAW” files will be interpreted and converted to CFA file format to be measured in Analyzer. By default, they are stored in a temporary directory and deleted after measurements. If you wish to store the files for further use or to archive them, click on the “Output Directory” button in area G and select the folder where CFA files are stored. The initial “.RAW” files are never modified by the CFA Converter.
- The raw parameters required to correctly interpret the raw image must be provided in Area B.

To interpret a file:

- Provide all parameters: width, height, phase, depth, endianness, precision, least significant bits to ignore, and header size (see 4.9.2 for more information).
- Click on “Apply settings” (in the upper right corner of area B) to interpret the file and view the content of the file using the provided raw parameters.
- If the displayed image does not look right, you can change the raw parameters as much as required and click again on “Apply settings”.
- If several files are to be interpreted with the same set of raw parameters, you can batch-process a set of files with the current parameters: click on the “Apply to all images” button in area G. A dialog box offers the following choices:
  - “Apply to all images”: applies the current parameters to all “.RAW” files.
  - “Apply to unprocessed files”: applies the current parameters to all unprocessed files.
  - “Cancel”: cancels batch processing.
- Batch processing time depends on the number and size of the files to process. A dialog box appears when batch processing is finished; simply click on “OK.”
- Processed files have a green checkmark in area A.



- If some files have different raw parameters, double-click on the filename and repeat the process.
- Once all files have been processed, click on the "Go to Analyzer" button to quit from the CFA Converter.
- A dialog box offers to process all the files; you can click "Cancel" if they have already been processed.

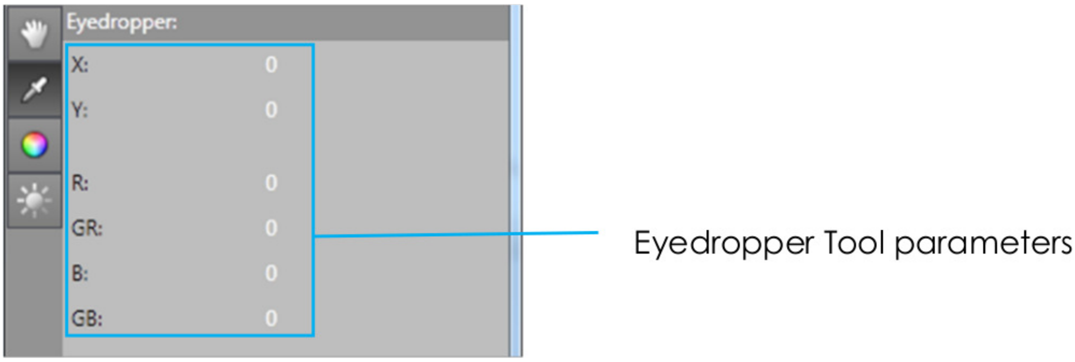
4.9.4 Toolbox

The tools provided by the toolbox only affect the display of the image, it will neither impact the generated CFA file nor the Analyzer measurements.

- Hand Tool 

  Select this tool and left click in the picture to pan. You can use the mouse wheel to change the zoom factor.

- Eyedropper Tool 



  Select this tool to get the following information on a specific pixel

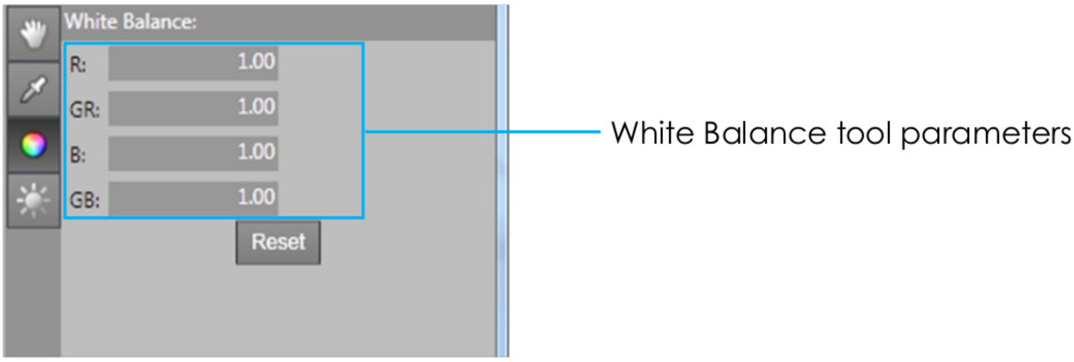
  - Position: X and Y are the pixel position in the image.
  - Color information on a Bayer block:
    - R: Red channel
    - GR: Green channel on the same line as the Red channel
    - B: Blue channel
    - GB: Green channel on the same line as the Blue channel

  Notes:

  - If the zoom factor is smaller than 75%, the values of a whole Bayer block are displayed, otherwise only the value of the pixel under the eyedropper is displayed, corresponding to a single color channel.

– Values displayed by the eyedropper tools are the pixel values of the image and do not take into account visualization tools such as white balance, exposure, and gamma.

- White Balance tool 



Use the White Balance tool to adjust white balance as a specific scale for each color channel.

White balance has four scaling coefficients:

– R: Red channel coefficient

– GR: Green channel (on the same line as the Red channel) coefficient

– B: Blue channel coefficient

– GB: Green channel (on the same line as the Blue channel) coefficient

Click on the "Reset" button to reset the coefficients to the default value of 1.

You can set white balance either by:

– Manually entering the values you wish for each coefficient in the textbox, between 0 and 3.

– Selecting a white or grey area in the image. A left-click in the image will compute white balance scales to neutralize an 11×11 Bayer block area around the selected pixel.

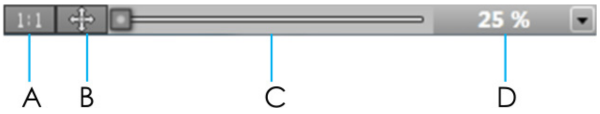
- Brightness Tools 

Use the Brightness tools to adjust the brightness of your display. These tools will neither impact the generated CFA file nor Analyzer measurements.

– The Exposure tools can increase the exposure of a dark image by applying a global scaling coefficient between 0 and 4.

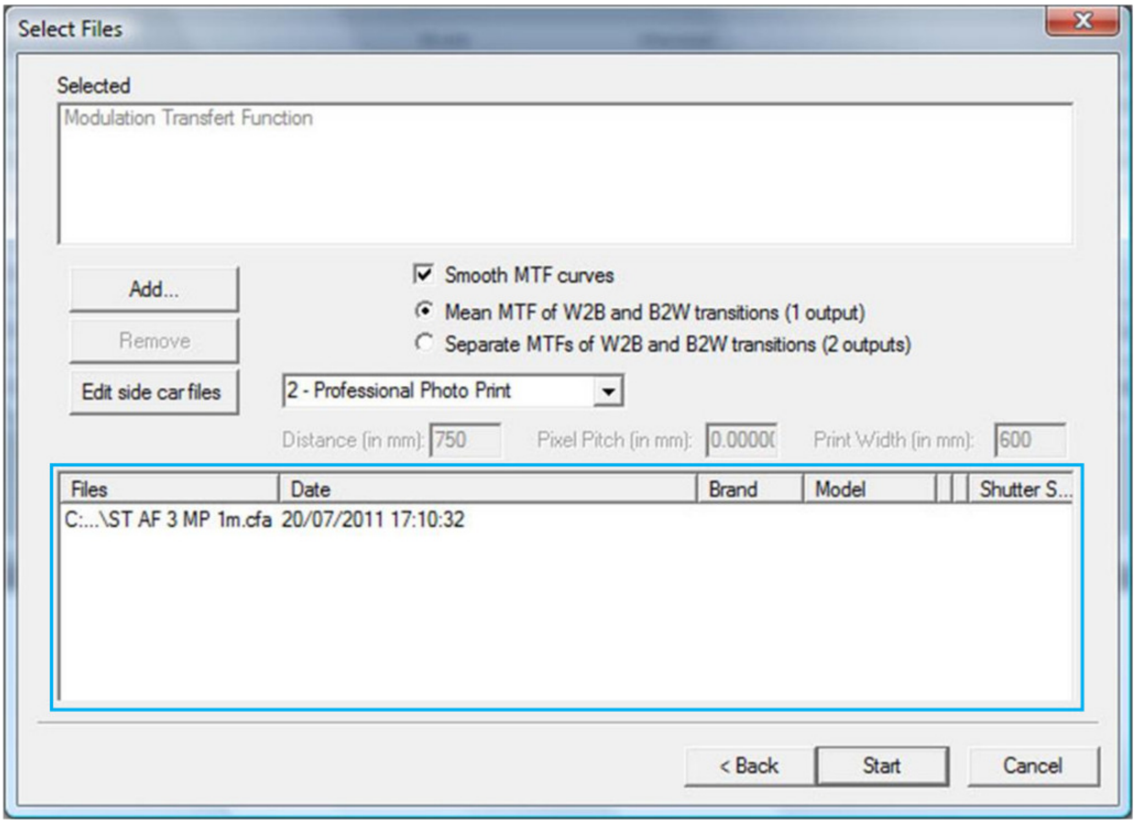
– The Gamma tool applies a gamma correction to the image. It is useful because a linear image always appears to have dark midtones. Usual color spaces use values of gamma between 1.8 and 2.4.

- Zoom tool



A	Zoom 100%	Click on this button to set zoom to 100% which means one picture pixel corresponds to one displayed pixel.
B	Zoom to fit	Click on this button to adjust zoom so as to display the whole picture in the available area.
C	Zoom slider	Select a zoom factor between 10% and 2000%.
D	Combo box	Select a zoom factor from a predefined set of values.

4.9.5 Launch the measurements in Analyzer



- Returning to Analyzer, the CFA files generated by the CFA Converter have been added to the file list. If no output directory has been set in the CFA Converter, the CFA files are stored in a temporary folder and will be deleted when you quit Analyzer.
- Click on the “Add...” button or drag and drop files to add new images.
- Click on the “Start” button to launch the measurements.

4.10 DNG file format

The DNG (*Digital Negative*) format is developed as an open standard for storing raw images.

Based on the TIFF format, DNG files can store raw sensor data from many different sensor configurations, as well as metadata (stored as TIFF tags) describing how to read and process sensor data.

The following tags are used by Analyzer when running measurements on DNG files:

- **BlackLevel** (and **BlackLevelRepeatDim**): These tags are used by the camera manufacturer to specify per-image or per-channel calibrated black level values. The black level is the pixel value threshold under which there is zero signal, and therefore the measured pixel value consists entirely of noise. Raw processing software usually subtract this black level value from the measured pixel value, as do Analyzer measurements by default.

  The RCN: Row and Column Noise or DS: Dark Signal measurements can be used to measure this value.

  If needed, the **BlackValue** sidecar parameter can be set to override the black level value, or set it to zero.

- **ActiveArea**: This tag is used to specify the usable area of the image other than the full size. Raw sensor data often include extra rows or columns that can correspond to debug information, such as sensor registers or black level calibration areas:

  If needed, the **Crop** sidecar section can be set to override this value.

The DNG format is supported by Analyzer starting from version 7.0, with the following restrictions:

- Sensor configurations other than RGBG Bayer matrices are not supported
- Sensor bit depths equal to or above 16 bits/pixel are not supported
- Non-integer black level values are truncated to an integer value

- In case multiple black level values are present, the minimum value will be used
- Per-row and per-column black level values (BlackLevelDeltaH and BlackLevelDeltaV tags) are not supported

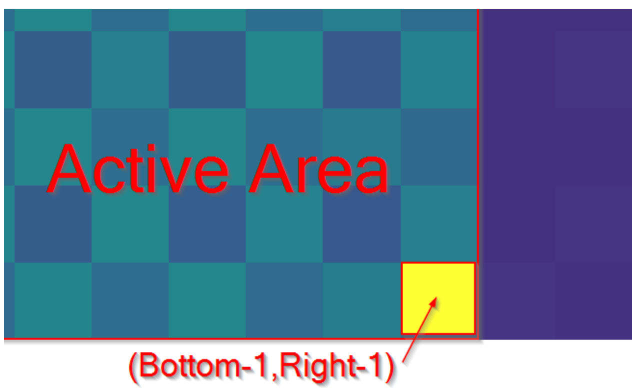
Metadata read from DNG files are displayed in the Analyzer report in the **Overview** section, including Black Level and Active Area tags:

Image format	RAW
Image depth	14 bits/channel
Width	5796 pixels
Height	3870 pixels
Date	02/08/2018 - 10:03:42
Color space	Sensor

Brand	Canon
Model	Canon EOS 5D Mark III
Aperture	5.6
Focal length	32.00 mm
Shutter speed	16.67 ms
ISO speed	100
Ev bias	0.00
White balance	Auto white balance
Black Level	2047
Active Area	L:122 R:5918 T:80 B:3950

The **Black Level** section contains the original black level value, expressed in the same depth as the sensor pixels. For all measurements except RCN, it must be scaled to a 15-bits value in the sidecar **BlackValue** parameter (e.g. for a 13-bits image depth, the original black level tag must be multiplied by $2^{15-13} = 2^2 = 4$ in order to produce the same measurements).

The **Active Area** section contains crop coordinates of the original active area, in the form "L:Left R:Right T:Top B:Bottom", which corresponds to the sidecar parameters with the same names. The top-left coordinates are included in the area, but the bottom-right coordinates are not included:



4.11 Measurements on video files

Analyzer lets you make measurements on videos. Videos can be video files, or a series of images (frames) extracted from the video stream.

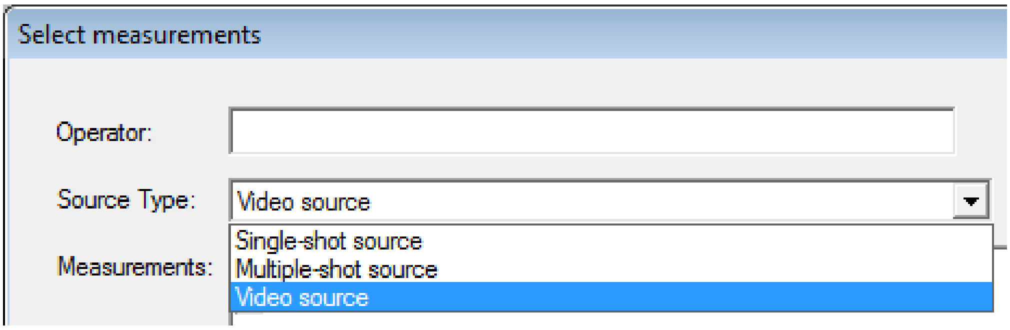
In a camera, the image processing chain is usually different for still images than it is for videos: the resolution for videos is often lower than for still images, and the applied algorithms may differ. This is because the expected rendering is different for video than for images. On still images, for example, sharpness is very important, while on video, people generally prefer good motion rendering with a little blur.

This means it is important to test the image quality for video and for still images independently.

The following Video measurements are possible:

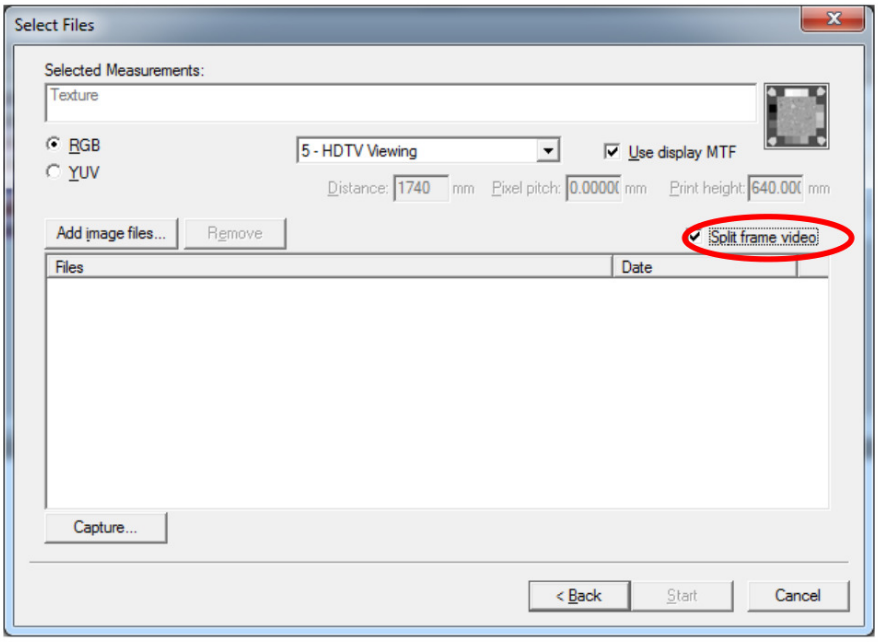
- STB: Video Stabilization
- TMR: Timing
- VIDEO-N: Video Noise
- VIDEO-TEX: Video Texture Preservation

To do a Video measurement, you must select the input chart, and then choose “Video source” as the source type in the “Select Measurements” dialog box. “Single-shot source” is for measurements on single images, and “Multiple-shot source” is used only for the Photo Stabilization measurement.



Selecting the source type for a Video measurement

The input video can be a video file, or a series of images extracted from a video. To use extracted frames as input, you must check “split-frame video” in the dialog box for file selections. Images are processed in alphabetical order.



Choice of video input: video files or extracted frames

In the video sidecar files, you can select a temporal crop — i.e., the start time of the measurement and its end time within the video stream. It is possible to define these times in seconds or in number of frames. The duration of the measured video can be defined by filling the start and end times, or the start and duration times, but not both simultaneously.

```
[VideoTemporalCrop]  ; section for temporal crop of videos
StartTimeSec= ...    ; start time of the measurement, in sec
EndTimeSec  = ...    ; end time of the measurement, in sec
DurationSec = ...    ; duration, in sec
StartFrame  = ...    ; start time of the measurement, in frames
EndFrame    = ...    ; end time of the measurement, in frames
FrameNumber = ...    ; duration, in frames
```

For videos as a series of frames, the sidecar file must be named after the first frame of the video.

4.12 Choice of test target

If the testing conditions meet the criteria for a given characterization to be performed, Analyzer can make the required measurement. It performs regular checks during the measurement that warn about bad conditions or confirm that conditions are good. In particular, the distance between the camera and the test target must be chosen such that the camera captures the entire area of the test target.

Each test target has a specific use:

- The Dots charts are used for measuring Blur, Distortion and Lateral Chromatic Aberrations, Vignetting, and Effective Focal Length.
- The MTF charts are used only for MTF measurements (MTF , CPIQ radial MTF and fisheye MTF).
- The HDR Noise chart is used for measuring Noise, Dark Signal, Tone Curve, and ISO.
- The X-Rite ColorChecker® classic is used for measuring Color Fidelity and Color Sensitivity. It can also be used for Noise and ISO Sensitivity, but for those, we recommend using the HDR Noise chart.
- The Texture Preservation chart is used for measuring the quality of texture, especially in terms of image-processing software with noise reduction capabilities. It is also used for measuring Visual noise.
- The Video visual noise chart is used for measuring Visual noise on Videos.
- The HDR composite chart is used for measuring texture preservation, color fidelity, noise and enthropy on a high dynamic scene

DXOMARK IMAGE LABS targets are exclusively designed to allow Analyzer algorithms to compute characterizations. They cannot be used for a direct visual analysis of these characterizations.

4.12.1 Dots charts

The Dots chart is used in the following measurements:

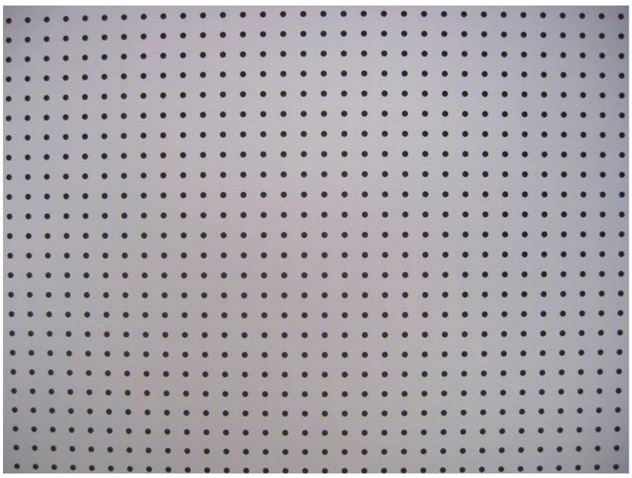
- B: Blur
- DC: Distortion and lateral chromatic aberration
- EFL: Effective focal length
- V: Vignetting
- FL: Flash uniformity

It is available in the following formats:

Code	Dimensions (W×H cm)	Material	Weight (kg)	Dot size (mm)	Dot spacing (mm)
DU0001_200	200×135	Wood	30	12	42
DU0001_200_V2	200×136	Aluminum	25	12	42
DU0002_120	120×90	Glass	27	8	26
DU0002_120_D	120×90	Dibond	4.7	8	26
DU0006_120	120×90	Glass	27	20	42
DU0003_60	60×47	Glass	6	4	13

The right target to choose depends on:

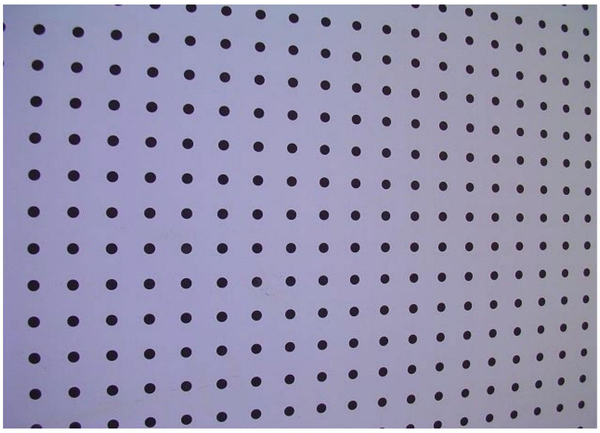
- Camera resolution
- Effective focal length
- Focusing distance
- Level of accuracy needed for the distortion measurement



A correct shot of the dot chart

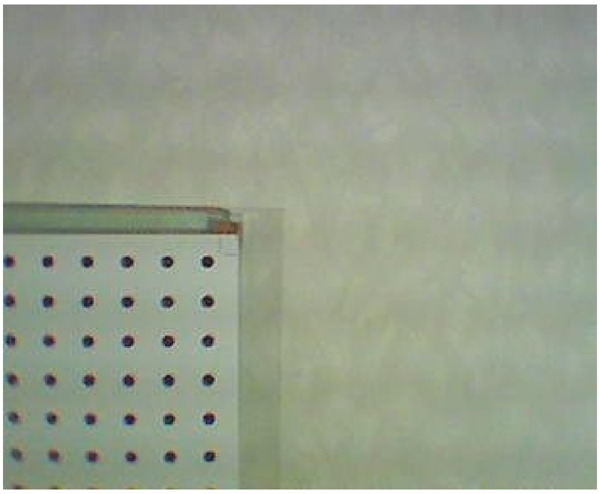
Independent of the measurements and the camera, take care to ensure the following testing conditions:

- Exposure: the target must be sufficiently contrasted that dots can be automatically detected.
- Orthofrontality: the chart should be approximately parallel to the sensor plane. The Effective Focal Length measurement integrates a procedure to make the target as orthofrontal as possible. However, except for the focal length, orthofrontality can be approximate:



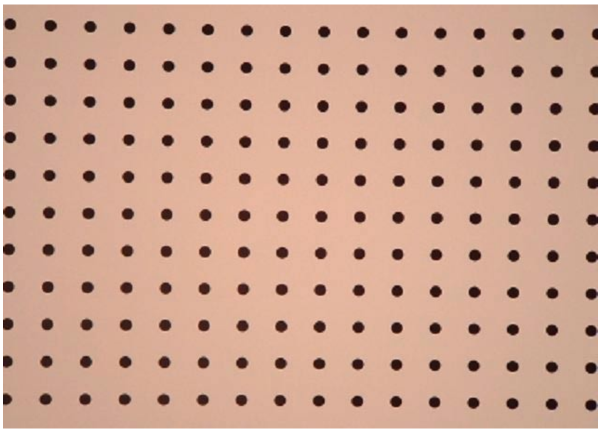
Incorrect shot of the Dots chart: the target is not orthofrontal enough

- Sharpness: the image can be slightly blurry, except for the Blur measurement, for which sharpness must be optimal since it is the object of the measurement.
- The target must *always* fill the field of view:



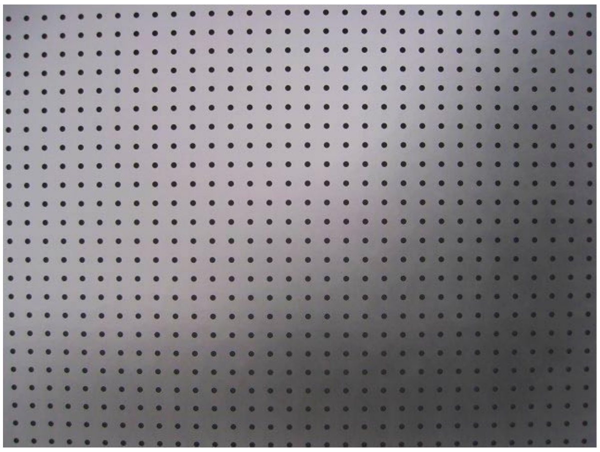
Incorrect shot of the Dots chart: the target must fill the whole image

- The white balance should be as correct as possible. This is a must for the lateral chromatic aberration and the Color Vignetting measurement.



Incorrect shot of the Dots chart: white balance is incorrect

- Lighting must be as uniform as possible. This facilitates the automatic detection of the target. This is crucial for the Vignetting measurement.

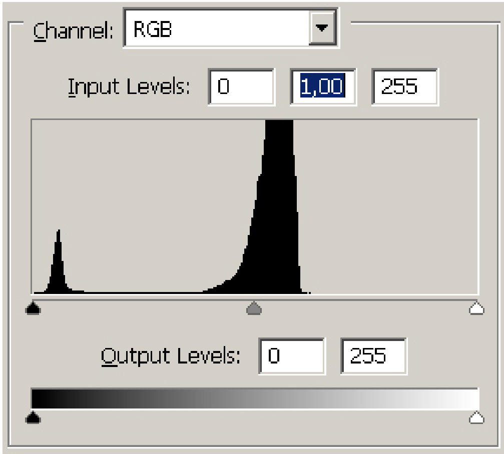


Incorrect shot of the Dots chart: lighting is not uniform

- The dots should be approximately aligned with the vertical or horizontal axis. A variation of less than 10° from the horizontal or vertical is recommended.

The dots should have a minimal size in the image. Some measurements are slightly less demanding, as listed below. Take care with measurements on raw images, as the resolution of each channel is half as much as the resolution of the channels in an RGB image.

You can validate a shot of the Dots chart by computing the histogram of the grey levels. The distribution should be clearly bimodal, as in the following illustration:



Histogram of a good view of a Dots chart showing two modes and no clipped values

For camera phones especially, the effective focal length may be unknown. Specifications of a good shot are given below for a typical image format. The main parameters are the number and the size of dots in the image, which varies from one camera to another. However, the typical use cases are as follows:

- For cameras with resolution below 1024x768 and 63° diagonal field of view, you should usually use the D0006_120 target, as its dots are larger so as to get enough pixels on each dot.
- For other cameras, many different combinations are possible, depending on the resolution of the camera, the shooting distance, and the field of view. The latter depends on the focal length of the lens and on the size of the sensor. The real constraints are expressed in terms of the number and size of dots. However, the typical use cases are determined by the following table that gives the maximum distances at which a Dots target fills the field of view for a lens without distortion. Note that for lenses with high barrel distortion like fisheye lenses, the shooting distances will be lower and the chart will not always fill the frame.

Diagonal field of view	DU0001_200	DU0002/6_120	DU0003_60
170°	0.10 m	0.06 m	0.03 m
150°	0.31 m	0.19 m	0.10 m
130°	0.53 m	0.33 m	0.17 m
122°	0.64 m	0.40 m	0.20 m
107°	0.85 m	0.53 m	0.26 m
94°	1.07 m	0.66 m	0.33 m
84°	1.28 m	0.79 m	0.40 m
75°	1.49 m	0.92 m	0.46 m
63°	1.87 m	1.16 m	0.58 m
47°	2.67 m	1.65 m	0.83 m
29°	4.53 m	2.81 m	1.40 m
24°	5.33 m	3.30 m	1.65 m
12°	10.67 m	6.60 m	3.30 m

Green : usable.
blue : usable but risk of casted shadows. Vignetting and distortion measurements may fail on affected areas.
black : usable but requires a large laboratory (Shooting distance exceeds DXOMARK Foba studio stand rail length).
Red : Not usable.

4.12.1.1 Blur

Resolution	<800×600	>800×600
Minimum dot diameter (in pixels)	10	10
Minimum number of dots	6×6	10×7

The image should be as sharp as possible, without the use of any sharpening method. If not, the Blur measurement may be strongly biased.

4.12.1.2 Distortion/ Lateral chromatic aberration

Resolution	<800×600	>800×600
Minimum dot diameter (in pixels)	7	10
Minimum number of dots	200	300
Sharpness (transition size in pixels)	2	4

4.12.1.3 Effective focal length

Resolution	<800×600	>800×600
Minimum dot diameter (in pixels)	7	10
Minimum number of dots	200	300
Sharpness (transition size in pixels)	2	4

4.12.1.4 Vignetting

When testing vignetting, the number of dots and their size is not critical. However, it is critical that there is uniform lighting across the whole target chart.

4.12.1.5 Flash uniformity

When testing flash uniformity, the number of dots and their size is not critical.

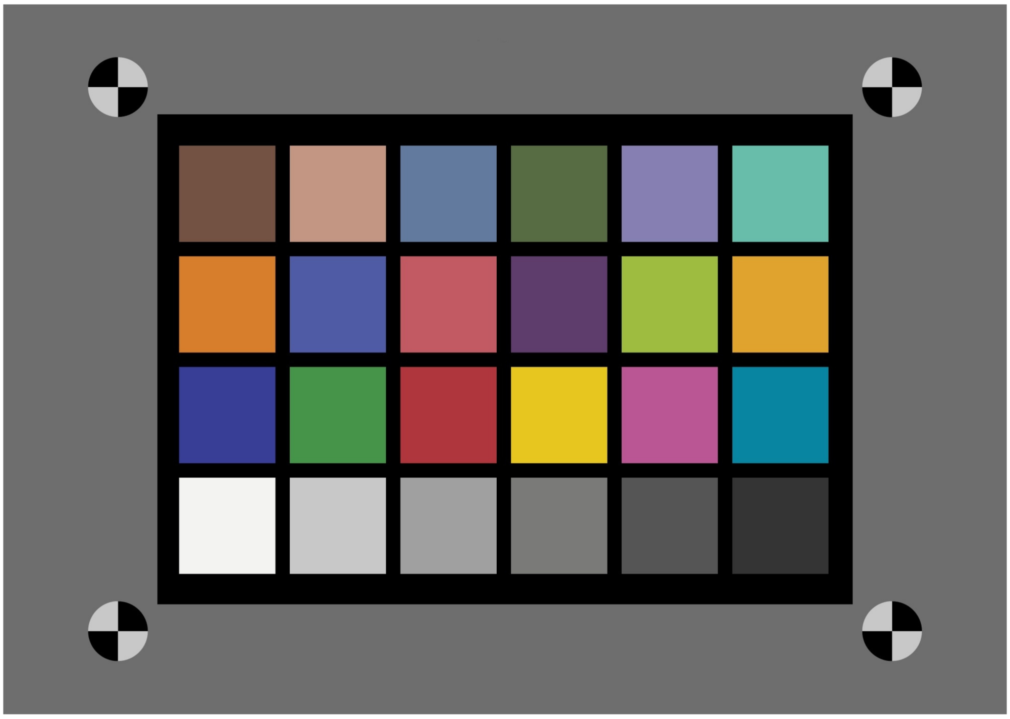
4.12.2 X-Rite ColorChecker® Classic 24 patches

Use the X-Rite ColorChecker® classic for the following measurements:

- N: Noise
- ISO: ISO sensitivity
- CS: Color sensitivity
- CF: Color fidelity

It is available in the following formats:

Code	ColorChecker Dimensions (W×H cm)	Frame Dimensions (W×H cm)
X-Rite ColorChecker® Classic XL	53×37	78.5×60.3
X-Rite ColorChecker® Classic	28.9×20.57	42×29.7
X-Rite ColorChecker® classic mini	10.8×6.35	15×10



View of a X-Rite ColorChecker® Classic in a frame with markers

The following shooting conditions apply to all the measurements requiring use of a X-Rite ColorChecker® classic.

- You can install the target in a specific frame with markers that allows automatic target detection in raw and JPEG even within a natural scene.

Otherwise:

- The target should fill between half and three-quarters of the image to avoid possible vignetting.
- There must be a uniform background. Detection may work when objects are in the background. However, we recommend that you always shoot images that contain only the target chart (and any neutral supporting device).
- The orientation of the chart must be correct, with the line of grey patches aligned horizontally at the bottom of the target. The angle of the chart should not deviate from the horizontal by more than 10°.

Incorrect orientation of the X-Rite ColorChecker® Classic

- Orthofrontality: always try to keep the target perpendicular to the optical axis, although this does not need to be extremely accurate.
- The white balance setting should be fair, unless you are testing for white balance.
- The exposure should be good enough. Automatic target detection is robust, but may fail in extreme shooting conditions.

Underexposed image of a X-Rite ColorChecker® Classic

- The minimum size of the color patches is 45×45 pixels, independent of the resolution. You will be warned if the size is under 64×64 pixels, which is the minimum size required by ISO 15739.

4.12.2.1 Typical shooting distances

This table gives shooting distances for a chart filling one third of the camera horizontal field of view.

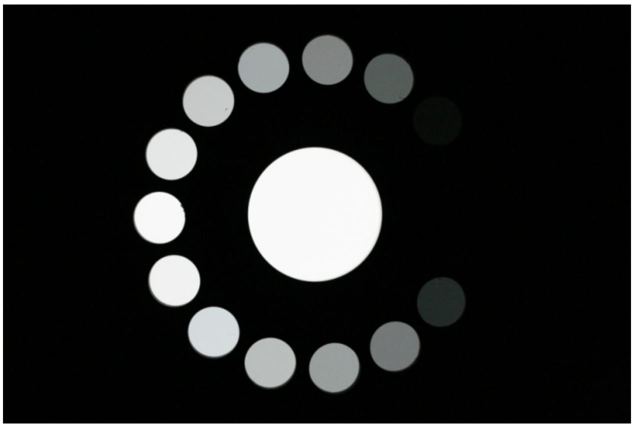
Diagonal field of view	ColorChecker® Classic XL	ColorChecker® Classic
170°	0.08 m*	0.04 m
150°	0.24 m*	0.13 m
130°	0.41 m*	0.23 m
122°	0.49 m*	0.27 m
107°	0.65 m*	0.36 m
94°	0.81 m	0.46 m
84°	0.98 m	0.55 m
75°	1.14 m	0.64 m
63°	1.42 m	0.80 m
47°	2.03 m	1.14 m
29°	3.46 m	1.93 m
24°	4.07 m	2.28 m
12°	8.13 m	4.55 m

Green : usable.
blue : risk of casted shadows. Color measurement may fail on affected areas.
black : usable but requires a large laboratory (Shooting distance exceeds DXOMARK Foba studio stand rail length).
red : not usable.
* : size of the target in the image field might need to be reduced.

4.12.2.2 Default *sRGB* values of the patches for *Illuminant D65*

4.12.3 Noise chart

This chart is deprecated. You can use the HDR Noise chart described below to make the same measurements.



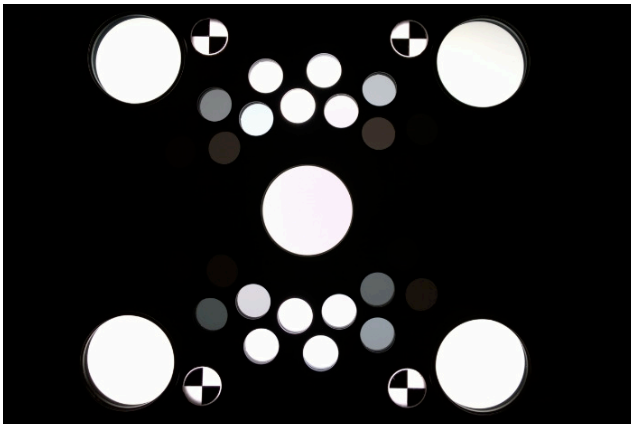
The Noise chart

4.12.4 HDR noise chart

Code	Dimensions (W×H cm)	Material (optical filters)
HDR0001	Adapted to retro-lighting. Usually 58.3×29.2 cm	Dark plastic mount, 27 optical glass filters, and 5 polarizers.

The HDR0001 chart can be used for the following measurements:

- N: Noise
- DS: Dark signal
- TC: Tone curve
- ISO: ISO sensitivity



The HDR Noise chart

Using the chart requires a retro-lighting device. You can calculate the luminance of the patches theoretically if the luminance of the lighting device is known. However, because the lighting may not be uniform, we recommend measuring the luminance of each of the chart patches directly with a luminance meter. The setup for measuring luminance is illustrated in the figure further below.

- Take care to place the head of the luminance meter right in the center of the measured patch.
- No light should be visible on the side of the luminance meter head.
- Let the retro-lighting device heat up long enough so that the luminance is stabilized.
- Take the luminance measurement the same way you would take any Analyzer measurement — with all lights off, except for the retro-lighting device.

The luminance values of the patches should be recorded in a sidecar file (see Section 4.5). These values are required for the ISO Sensitivity and Tone Curve measurements, and optional for the Noise and Dark Signal measurements. For these latter two measurements, only the relative exposure matters, so the theoretical densities of the patches can be used.

This chart is a transmission chart. It contains 28 spectrally-neutral glass filters with densities ranging from 0 to 6 (equivalent to 120dB).

0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
1.0	1.2	1.4	1.6	1.8	2.0	2.2	2.4	2.6	2.8
3.0	3.2	3.4	3.6	3.8	4.0	5.0	6.0		

This chart uses polarizers to help cameras with auto-exposure algorithms to achieve a correct exposure. In most cases, the polarizers should be closed to limit flare and glow on the image.

Observe the following conditions when testing with the HDR0001 chart:

- The target must be the only source of light.
- Lighting should be as uniform as possible.
- The target must fill the image field as much as possible with all four markers visible.
- The target must be clean, with no fingerprints or dust on the filters.
- The retro-lighting panel must be clean.
- Ensure acceptable white balance for RGB images (Tone Curve measurement).
- The minimum diameter of the patches is 90 pixels. ISO 15739 specifies the minimum patch size for a Noise measurement as 64×64, which corresponds to a 90-pixel diagonal (only the inscribed square is used for measurement). This value is reachable with a 2 megapixels sensor in RGB mode. For raw measurement, this specified number is usually unreachable with camera phone sensor, but the Analyzer measurement remains precise down to a diameter of 42 pixels.

For a correct exposure, there should be at least two over-exposed filters and not more than five saturated filters in the image.

Here are the steps for obtaining a good exposure. When using a camera with auto-exposure, you should test each step in the following order until the exposure is correct, and then stop. As opening the polarizers usually decreases the image quality, do this only if other methods do not work.

You should first test the exposure with an image of the chart with all polarizers closed, and an EV bias of 0. If the exposure is not correct:

- Change EV bias if possible.
- Use touch exposure on bright filters if possible.
- Open the central polarizer to 20 % of the luminance of the brightest filter. Use touch exposure on the central polarizer. Take a picture.
- Open the central polarizer to 30 % of the luminance of the brightest filter. Use touch exposure on the central polarizer. Take a picture.
- Open all polarizers to 20 % of the luminance of the brightest filter. Take a picture.
- Open all polarizers to 30 % of the luminance of the brightest filter. Take a picture.

4.12.5 MTF chart

Code	Dimensions (W×H cm)	Material	Weight (kg)	Square size (mm)
SU0001_200_V2	200×135	Dibond	12	120
SU0007_200_V3	200×135	Dibond	12	40
SU0002_140	140×97	Dibond	6	70
SU1020_140_HR	140×97	Dibond	6	40
SU0008_32_HRP	32×20	Carbon	0.2	16
SU0009_17_HRP	17×12	Carbon	0.1	8

The MTF chart is used for the MTF measurement. It consists of a slanted checkerboard.

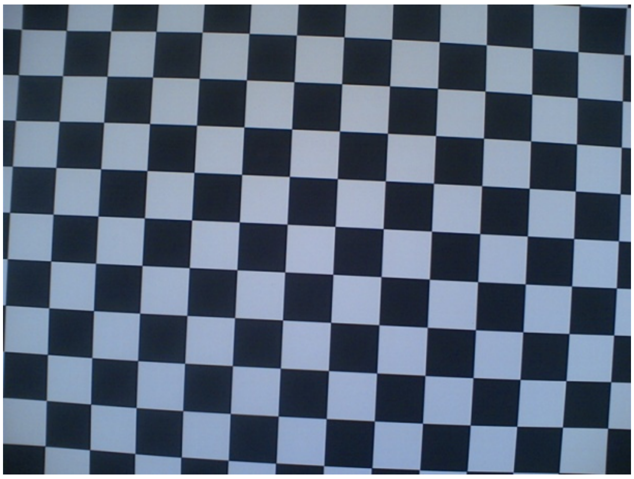


Image of a MTF chart

Observe the following conditions when testing with the MTF chart:

- The chart must always fill the image.
- The chart must be horizontal such that the angle between the edges and the horizontal or vertical is between 5° and 7° to vertical. Outbound angles usually do not prevent measurement, but results may

be biased.

- The illumination must be uniform over the chart. Vignetting strongly biases the measurement at the corners.
- The target should be as orthofrontal as possible. Use the mirror method to position the camera suitably (see Section 5.2).
- Distortion can make the MTF measurement impossible in corners if the angle of the slanted edges is not between 5° and 7°. In this case, MTF measurement is possible only in the center of the image.

4.12.5.1 Typical shooting distances

Diagonal field of view	SU0001_200_V2 SU0007_200_V3	SU0002_140 SU1020_140_HR	SU0008_32_HRP	SU0009_17_HRP
170°	0.10 m*	0.07 m	0.02 m	0.01 m
150°	0.31 m*	0.21 m*	0.05 m	0.02 m
130°	0.53 m	0.37 m	0.08 m	0.04 m
122°	0.64 m	0.44 m	0.10 m	0.05 m
107°	0.85 m	0.58 m	0.13 m	0.07 m
94°	1.07 m	0.73 m	0.17 m	0.08 m
84°	1.28 m	0.88 m	0.20 m	0.10 m
75°	1.49 m	1.02 m	0.23 m	0.12 m
63°	1.87 m	1.28 m	0.29 m	0.15 m
47°	2.67 m	1.83 m	0.42 m	0.21 m
29°	4.53 m	3.10 m	0.71 m	0.35 m
24°	5.33 m	3.65 m	0.83 m	0.42 m
12°	10.67 m	7.31 m	1.67 m	0.83 m

Green : usable.
blue : usable but risk of casted shadows. MTF measurement may fail on affected areas.
blacke : usable but requires a large laboratory (Shooting distance exceeds DXOMARK Foba studio stand

rail length).
red : not usable.
* : fish-eye or collimator setups are recommended for large field of views.

4.12.5.2 Typical use cases

To obtain a correct measurement in the image field, the number and size of transitions must fit the following requirements:

Resolution	<800×600	>800×600
Minimum size of patch (pixels)	40×40	50×50
Minimum number of squares in the field	7×7	7×7

The SFR charts also have their own MTFs. Depending on the resolution of the sensor, and the distance to the chart, these MTFs will reduce the measured camera MTF. To limit this influence, the distance ratio to the target / focal length must fit the following requirements:

Pixel pitch	SU0001_200_V2 SU0002_140 SU0007_200_V2	SU1020_140_HR SU0008_32_HRP SU0009_17_HRP
3 µm	74×	42×
4 µm	56×	32×
5 µm	45×	25×
6 µm	37×	21×
7 µm	32×	18×

Minimum distance ratio to target / focal length depending on the pixel pitch of the sensor

This means that for a camera with a pixel pitch of 6 µm, the distance between the camera and the chart must be at least 21 times the focal length when using the high-resolution chart, and 37 times when using the other charts.

4.12.5.3 Calibrated MTF charts

DXOMARK IMAGE LABS supplies calibrated MTF, RadialMTF and ROF charts. Include the chart reference among the input options for the MTF measurement. Use of calibrated charts ensure a more accurate measurement : the measured MTF of the chart itself is subtracted from the measured MTF of the camera.

4.12.6 CPIQ SFR chart

Code	Dimensions (W×H cm)	Material
SRU001_200	200×135	Dibond
SRU002_140	140×97	Dibond

Use the CPIQ SFR chart for the “RADMTF” (MTF on radial chart) measurement. It follows the specifications of the CPIQ standard for the CPIQ sharpness measurement.

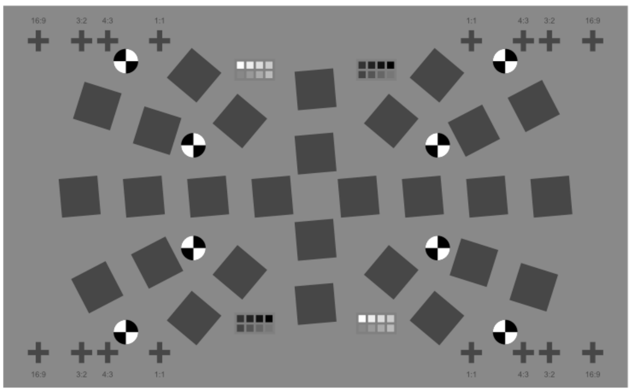
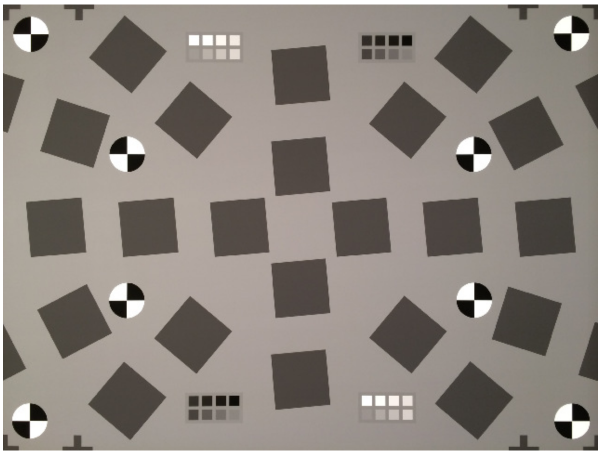


Image of the CPIQ SFR chart

Observe the following conditions when testing with the MTF chart:

- The test target must fill the image. Use the cross-shaped markers on the chart to select the correct framing, which depends on the W/H ratio of the sensor.


Correct framing of the CPIQ chart, on a 4:3 sensor

- The illumination must be uniform over the entire chart. Vignetting strongly biases the measure at corners.
- The target should be as orthofrontal as possible. Use the mirror method to position the camera suitably (see Section 5.2).

4.12.6.1 Typical shooting distances

Diagonal field of view	SRU0001_200	SRU0002_140_P
170°	0.07 m*	0.05 m*
150°	0.23 m	0.16 m
130°	0.39 m	0.27 m
122°	0.47 m	0.33 m
107°	0.62 m	0.44 m
94°	0.78 m	0.55 m
84°	0.94 m	0.66 m
75°	1.09 m	0.77 m
63°	1.36 m	0.96 m
47°	1.97 m	1.37 m
29°	3.31 m	2.33 m
24°	3.90 m	2.74 m
12°	7.79 m	8.21 m

Green : usable.
blue : usable but risk of casted shadows. MTF measurement may fail on affected areas.
black : usable but requires a large laboratory (Shooting distance exceeds DXOMARK Foba studio stand rail length).
red : not usable.
* : fish-eye or collimator setups are recommended for large Field of views.

4.12.6.2 Typical use cases

The CPIQ standard defines the maximum sensor resolution depending on the target spatial frequency content. The MTF of the chart is corrected by the measurement.

CPIQ SFR chart	Maximum sensor resolution (as defined in CPIQ standard)
SRU0001_200	24 Mpix
SRU0002_140_P	12 Mpix

This specification is very exacting. It is possible to use these charts with sensors with higher resolutions (up to 24 Mpix for the SR002, 48 Mpix for the SR001) when a measurement accuracy of 8% is acceptable.

4.12.7 Texture Preservation chart

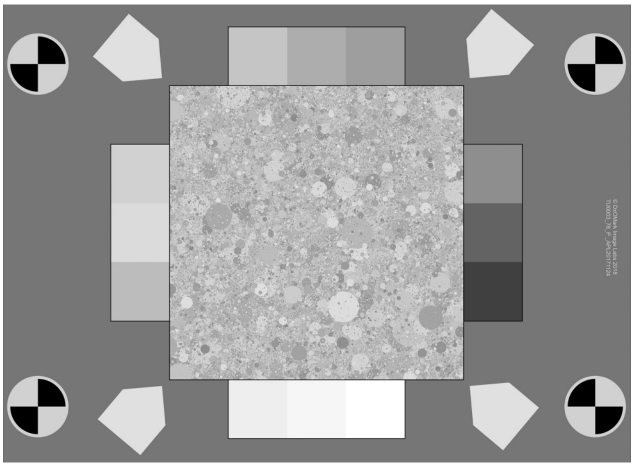
Code	Dimensions (W×H cm)	Material
TU0003_78_P	78.5×60.3 cm	Dibond
TU0008_30_P	30×22 cm	Dibond

The Texture Preservation chart contains a textured patch with the so-called Dead Leaves image, several grey level patches for OECF inversion and visual noise measurement, four SFR edges and four detection markers. The TU0003_78_P chart is used for the following measurements:

- “TEX” Texture Preservation and Visual Noise measurements.
- “VIDEO-TEX” Video Texture Preservation measurement.
- “STAB” Photo and Video Stabilization measurement.
- “AF-HDR” AF-HDR measurement.

The TU0008_30_P chart is used for the following measurement:

- AF-HDR measurement.



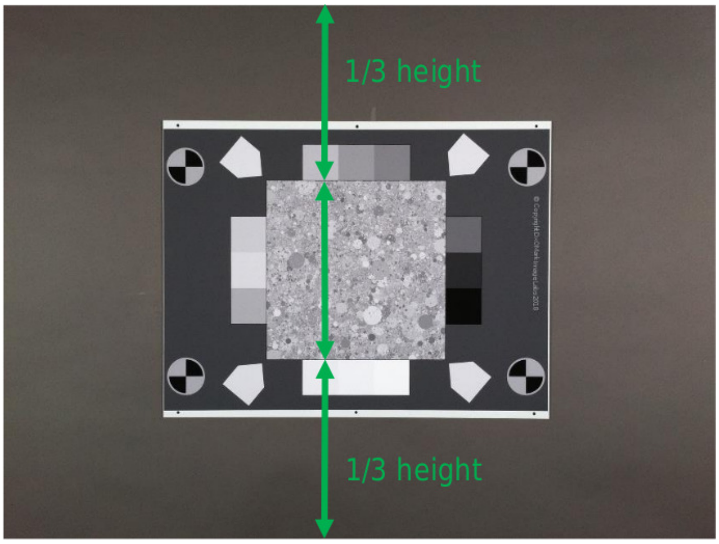
The Texture Preservation chart

Analyzer uses the four position markers to automatically detect the target. The markers must be clearly visible in the image.

If automatic detection fails, you can enter the target position into the measurement algorithm using a sidecar file. See the Texture Preservation measurement chapter (Section 10.15) for a description of the sidecar file content.

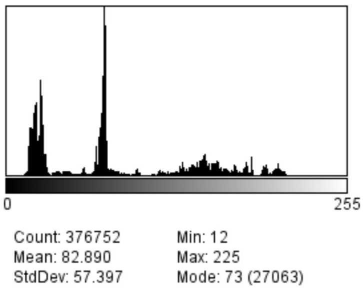
Observe the following conditions when measuring with the Texture Preservation chart:

- The target must be attached to a wall or to a mobile studio easel such as the DXOMARK Easel_003.
- The visible background behind the target must be uniformly grey (we recommend an 18% grey). Be aware that changing the background color can change the camera exposure.
- Few cameras may overexpose the chart. In this case we recommend a white background.
- Light must be uniform on the target (7% maximum difference).
- The target must be positioned at the image center.
- The borders of the target must be parallel to the image borders.
- Orthofrontality must be set up accurately.
- The texture patch must fill at most one-third of the image height to avoid vignetting issues (see image below).



Framing of the Texture Preservation chart

- The image must be well-exposed. Ideally, bright areas of the target should be at two-thirds of the sensor dynamic so that no pixel values on the JPEG image is saturated. The luminance histogram of the JPEG image should look like this:



4.12.7.1 Typical shooting distances

Diagonal field of view	TU0003_78_P	TU0008_30_P
170°	0.09 m	0.03 m
150°	0.26 m	0.10 m
130°	0.46 m	0.17 m
122°	0.55 m	0.21 m
107°	0.73 m	0.28 m
94°	0.91 m	0.35 m
84°	1.10 m	0.42 m
75°	1.28 m	0.48 m
63°	1.60 m	0.61 m
47°	2.28 m	0.87 m
29°	3.88 m	1.47 m
24°	4.56 m	1.73 m
12°	9.13 m	3.46 m

Green : usable.
blue : usable but risk of casted shadows. MTF measurement may fail on affected areas.
black : usable but requires a large laboratory (Shooting distance exceeds DXOMARK Foba studio stand rail length).
red : not usable.

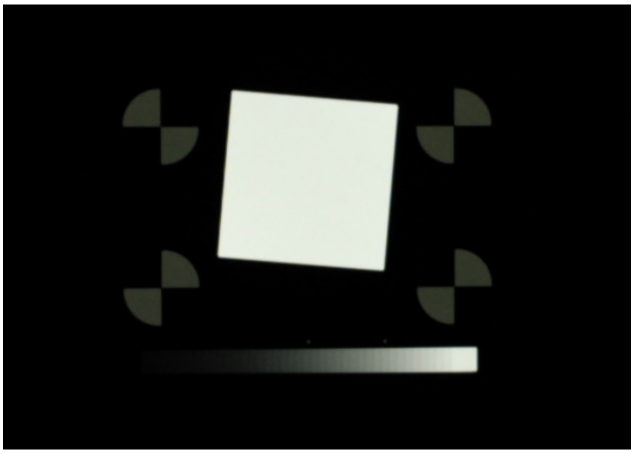
4.12.8 Color fringing chart

Code	Dimensions (W×H cm)	Material
CF0001	32×29 cm	Aluminum metal sheet and Stouffer T4105

CF0001 chart on a Kyoritsu LV-9500

The color fringing chart is a transmission chart used for the Color Fringing measurement. It consists of four detection markers, a slanted square, and a step wedge to measure saturation. The chart has been designed to be correctly detected for an exposure around ten times the sensor saturation.

The CF0001 target is compatible with Kyoritsu LV-9500 and LV-9502 light boxes.



Shot of the color fringing chart

Analyzer uses the four position markers to automatically detect the target. The markers must be clearly visible in the image.

If automatic detection fails, it is possible to use a sidecar file to enter the target position into the measurement algorithm.

Observe the following conditions when measuring with the color fringing chart:

- The target must be the only source of light.
- Lighting should be as uniform as possible.
- The chart must be horizontal so that the angle between the square edges and the horizontal or vertical is between 5° to 7°.
- The target should be as orthofrontal as possible. Use the mirror method to position the camera suitably (see Section 5.2).
- Markers should be at least 30 pixels in height, 60 pixels for a raw image.
- Ensure an acceptable white balance for RGB images.

The size of the saturated part on the step wedge indicates the saturation level:

Step wedge saturation	Sensor saturation
No saturation	<1×
One quarter	3×
One half	10×
Three quarters	30×

4.12.9 White chart

The X-Rite ColorChecker®White Balance chart is an uniform white chart that has a neutral spectrum.

Shot of the color fringing chart

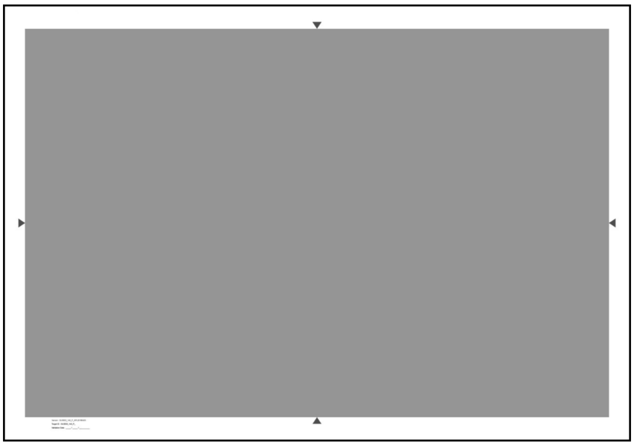
Code	Dimensions (W×H cm)	Weight (Kg)
XRITE_WHITE_01	21.59×27.94 cm	0.227

The White chart can be used for the following measurements:

- DP: Defective Photosites
- FL: Flash
- V: Vignetting

4.12.10 Grey chart

The Grey chart is an uniform grey chart with a standard 30 ± 5% reflectance. Around the chart, 4 markers are available to help centering the chart.



The Grey chart

Code	Dimensions (W×H cm)	Material	Weight (Kg)
GU0002_140_P	140×97 cm	White dibond	6

The Grey chart can be used for the following measurements:

- V: Vignetting
- Fl: Flash
- VN: Video Noise

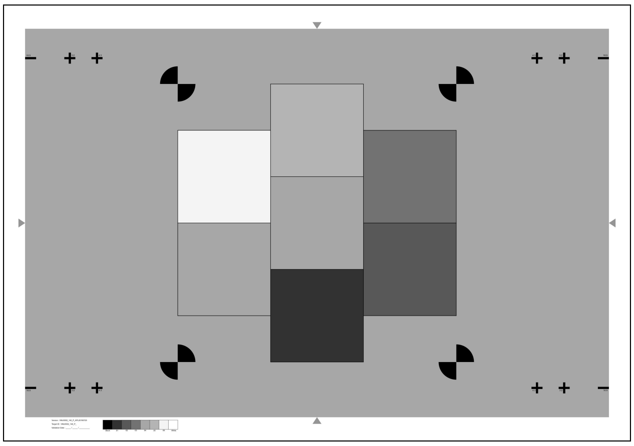
4.12.10.1 Typical shooting distances

Diagonal field of view	GU0002_140_P
170°	0.07 m
150°	0.21 m
130°	0.37 m
122°	0.44 m
107°	0.59 m
94°	0.73 m
84°	0.88 m
75°	1.03 m
63°	1.28 m
47°	2.83 m
29°	3.12 m
24°	3.67 m
12°	7.33 m

Green : usable.
blue : usable but risk of casted shadows. Vignetting measurement may fail on affected areas.
black : usable but requires a large laboratory (Shooting distance exceeds DXOMARK Foba studio stand rail length).

4.12.11 Video visual noise chart

The Video visual noise chart is composed of seven uniform grey patches. Around the chart, 4 markers are available to help detecting the grey patches. Framing is facilitated by 4:3, 3:2 and 16:9 markings.



The Video visual noise chart

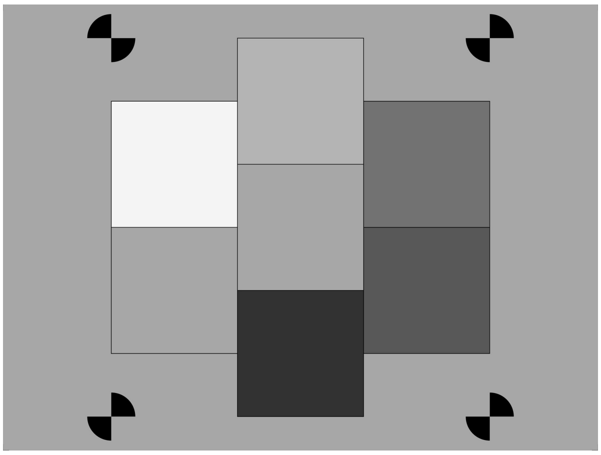
Code	Dimensions (W×H cm)	Material	Weight (Kg)
VNU0001_200_P	200×135 cm	White dibond	12
VNU0002_140_P	140×97 cm	White dibond	6

The Video visual noise chart can be used for the following measurements:

- VVN: Video visual noise

Observe the following conditions when testing with the Video visual noise chart:

- The test target must fill the image. Use the cross-shaped markers on the chart to select the correct framing, which depends on the W/H ratio of the sensor.



Correct framing of the Video visual noise chart, on a 4:3 sensor

- Illumination must be uniform over the grey patches.
- The target should be orthofrontal. Use the mirror method to position the camera suitably (see Section 5.2).

4.12.11.1 Typical shooting distances

Diagonal field of view	VNU0001_200_P	VNU0002_140_P
170°	0.08 m	0.07 m
150°	0.26 m	0.20 m
130°	0.46 m	0.37 m
122°	0.55 m	0.44 m
107°	0.74 m	0.59 m
94°	0.92 m	0.73 m
84°	1.11 m	0.88 m
75°	1.29 m	1.03 m
63°	1.62 m	1.28 m
47°	2.31 m	1.83 m
29°	3.92 m	3.11 m
24°	4.62 m	3.66 m
12°	9.23 m	7.33 m

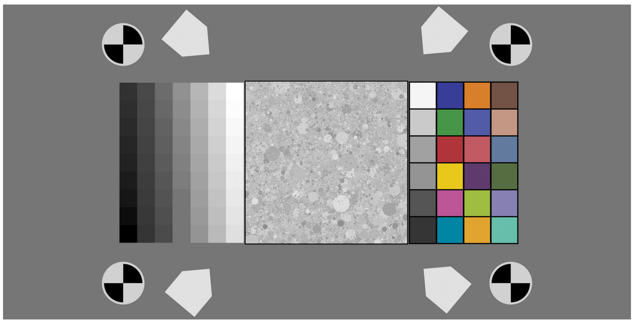
Green : usable.
blue : usable but risk of casted shadows. Visual noise measurement may fail on affected areas.
black : usable but requires a large laboratory (Shooting distance exceeds DXOMARK Foba studio stand rail length).

4.12.12 HDR Composite chart

The HDR Composite chart chart is composed of the following elements:

- 1 grey scale with 63 patches.
- 1 dead leaves patch.

- 24 color patches.
- 4 SFR slanted edges for MTF measurement.
- 4 markers for automatic chart detection.



The HDR Composite chart

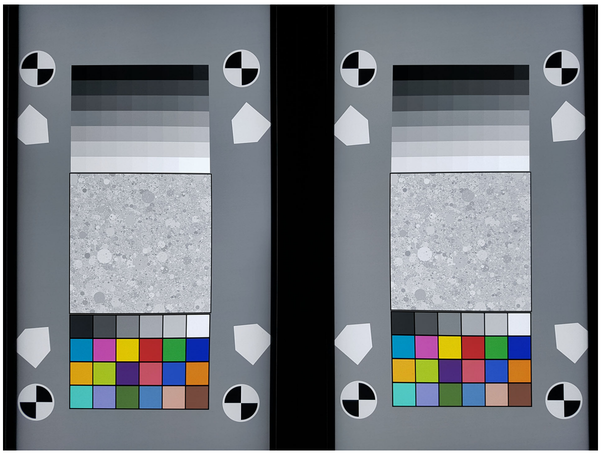
Code	Dimensions (W×H cm)	Material	Weight (Kg)
CT001	58.3×29.2 cm	Transparent plexiglass	0.65

The HDR Composite chart can be used for the following measurements:

- HDR (Hight Dynamic Range)
- AF HDR (Autofocus High Dynamic Range)

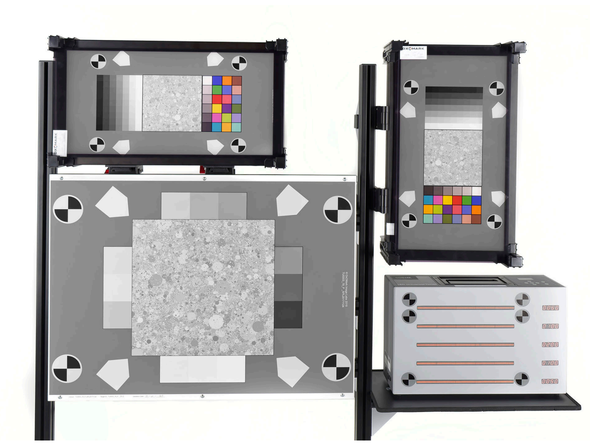
Observe the following conditions when testing with the HDR Composite chart:

- The HDR Composite chart must be uniformly backlit with a Kino Flo CELEB 250 LED Panel.
- For HDR measurements, 2 side by side HDR Composite charts must fill the frame as illustrated below.



Correct framing of the HDR Composite charts, for the HDR measurement

- For AF HDR measurements a HDR Composite charts must be positioned on the right of a TU0003_78 dead leaves chart and the second one on the top of the dead leaves chart, as illustrated below.



Correct positioning of the HDR Composite charts, for the AF HDR measurement

- The target should be orthofrontal. Use the mirror method to position the camera suitably (see Section 5.2).

4.12.13 LED Universal Timer

The use of this chart, and of all accessories related to timing measurements, is described in the timing measurements section.

4.13 Viewing conditions

Acutance (explained in 10.2.1) is a metric available in MTF, CPIQ SFR, Texture and HDR measurements. It is always related to the size of the image (be it print or on-screen) and the viewing distance. For example, you can say that for a 40×60 cm print seen at 60 cm, the acutance of the camera used is 0.8.

This distance and print size define the viewing conditions. The measurement algorithm uses these viewing conditions to determine the coefficient for converting the spatial frequency of the CSF of the visual field, expressed in cycle/degree, into cycle/pixel as measured on the image. The effect of the viewing conditions is to stretch the CSF along the *x*-axis (frequency axis). If you look at an image from afar, the CSF will narrow on low spatial frequencies, giving more weight to these frequencies and less weight to the high ones.

You choose the viewing conditions when you select the input files. A preselected list of several viewing conditions is proposed for standard prints and for display on a computer screen. Each choice defines a viewing distance, and a print height (for prints) or a pixel pitch (for computer display).

Two custom viewing conditions, one for prints and the other for computer display, are also given. You can choose the custom viewing distance and print height / pixel pitch in these cases.

The "use display MTF" check box allows selecting a MTF for the printer or the screen.

If you do not check "use display MTF" for the print viewing conditions, Analyzer makes the assumption that the printer has an arbitrary high resolution and that the resolution of the image is limited by the camera and not the printer. For display viewing, the results do not account for the screen MTF.

If you check "use display MTF," the MTF of the printer or the screen are defined as follows:

For a screen:

$$M(v) = \left| \frac{\sin \pi \cdot K_{\text{disp}} \cdot v}{\pi \cdot K_{\text{disp}} \cdot v} \right|,$$

with v in cycles/degree and $K_{\text{disp}} = \dfrac{\text{pixel\_pitch}}{\text{distance}} \cdot \dfrac{180}{\pi}$.

For a printer:

$$M(v) = \exp\left(-\frac{v}{K_{print}}\right)$$

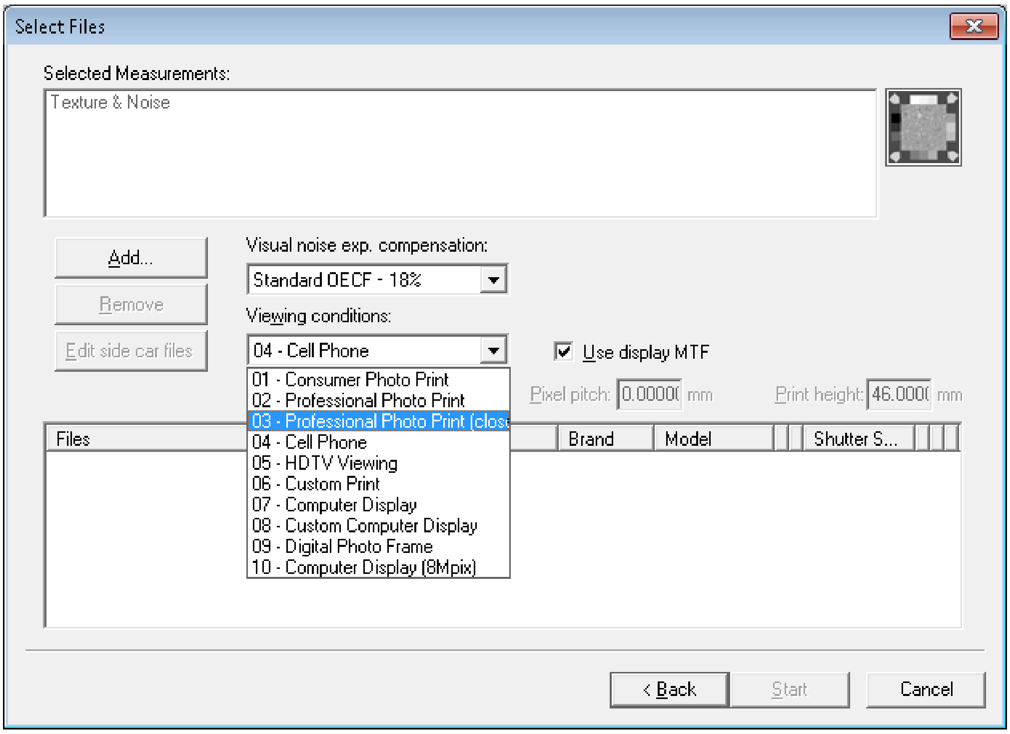
with v in cycles/degree and $K_{print} = \frac{5 \cdot \text{distance} \cdot \pi}{180}$.

Then the previous equation for A 10.2.1 is modified:

$$A = \int_0^{v_c} MTF(v) \cdot M(v) \cdot CSF(v)\,dv$$

The cutoff spatial frequency v_c is defined as:

$$v_c = \frac{0.5}{K_{disp}}, \text{for a screen}$$
$$v_c = K_{print} \cdot \frac{600}{254}, \text{for a printer (600 dpi)}$$



Selection of viewing conditions

Here is the list of viewing conditions, with their associated values for distance, pixel pitch, and length. The corresponding pixels/degree coefficient is given for a 14 Mpix image:

Name	Description	Distance (mm)	Pixel pitch (mm)	Print height (mm)	Pixels / degree for a 14 Mpix camera
Consumer Photo Print	100×150 mm (4×6 inch print)	250	✗	100	133.3
Professional Photo Print	400×600 mm	750	✗	400	100.0
Professional Photo Print (closer)	400×600 mm	600	✗	400	80.0
Cell Phone	3 inch 640×480 display	250	✗	46	289.8
HDTV Viewing	1920×1080 42" HDTV	1740	✗	640	145.0
Custom Print		**user**	✗	**user**	
Computer Display	100% magnification	600	0.254	✗	41.2
Digital Photo Frame	7" frame	1000	✗	110	514.1
Comp. Display (8 Mpix)	8 Mpix image	600	0.254	✗	54.5
Custom Computer Display	**100% magnification**	**user**	**user**	✗	

For a print, this coefficient depends on the height of the image (expressed in pixels), the height of the print (in mm) and the viewing distance (in mm)

$$\frac{\text{Pixels}}{\text{degree}} = \text{height}_{\text{image}} \frac{\text{distance}}{\text{heigh}_{\text{print}}} \cdot \frac{\pi}{180}$$

For a “Computer Display”, it depends on the viewing distance (in mm) and the pixel pitch (in mm):

$$\frac{\text{Pixels}}{\text{degree}} = \frac{\text{distance}}{\text{pixel\_pitch}} \cdot \frac{\pi}{180}$$

For” Computer Display (8 Mpix)”, it depends on the viewing distance (in mm), the height of the image (expressed in pixel), the height of a 4/3 8 Mpix image (expressed in pixel) and the pixel pitch for a 4/3 8 Mpix image displayed at 100% (in mm):

$$\frac{\text{Pixels}}{\text{degree}} = \frac{\text{ditance}}{\text{pixel\_pixel\_8 Mpix}} \cdot \frac{\pi}{180} \cdot \frac{\text{height}_{\text{image}}}{\text{height}_{\text{image (8 Mpix)}}}$$

For a more general point of view, looking at a print more closely will enable you to see more fine details (fewer pixels in one degree). Thus, the pixels/degree coefficient will be lower, and the acutance value will be computed with more weight on high spatial frequencies.

4.14 Quality controls performed by Analyzer

Quality controls are automatic and built into Analyzer.

As Analyzer is sensitive to the accuracy of the exposure (particularly when characterizing the parameters N and B), it automatically carries out the necessary corrections for proper performance of the measurement. Similarly, if the color temperature is not perfectly balanced, Analyzer performs the necessary compensation before carrying out the measurements. However these corrections are applied only in cases of slight discrepancies, otherwise the characterization measures would be flawed.

Similarly, minor framing or centering errors can be corrected automatically. However, we strongly recommend that you follow precisely the instructions given in Section 5.

Analyzer also checks if the required number of spots in the test target is present in the file.

5 – Shooting the test target

You must take a number of elementary precautions before and during shooting to avoid undesirable defects in the image, other than those the test is meant to measure.

Requirements for lighting and positioning the test targets, and tolerances for the camera settings are different for each type of measurement. These specific requirements are detailed in the previous sections.

However, to ensure perfect repeatability of shooting, we recommend that you follow the standardized procedure described below.

5.1 Adjusting test target lighting

Installation and adjustment of the test target lighting are explained in detail in Section 3.2.2.

5.2 Positioning the camera

a) You must firmly attach the camera to be characterized to the head of the tripod, either using the tripod screw, if the camera has a socket, or by holding it using a clamp (for shots taken with a mobile phone or a tablet, for example).

b) Position this assembly with respect to the test target so that:

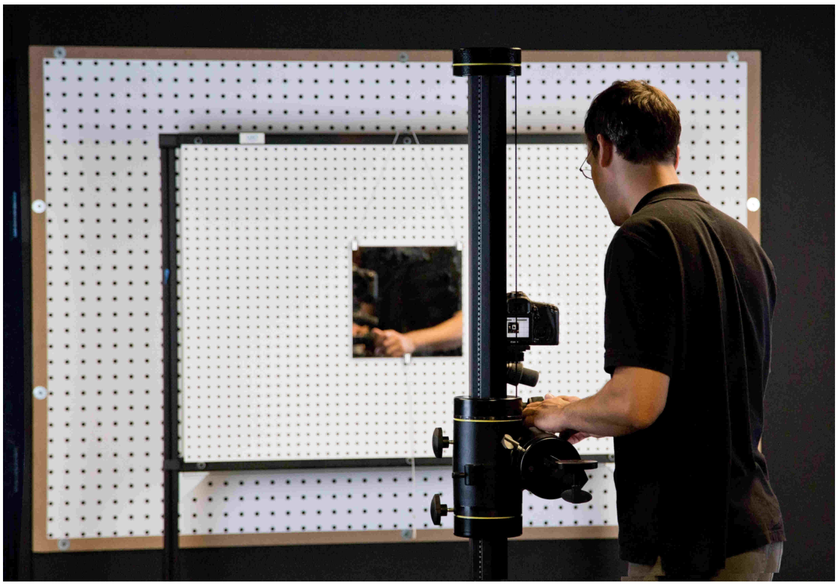
- The lens is approximately centered on the perpendicular center-line marked on the floor and is aimed at the center of the test target (see Section 5.3 for fine adjustments).
- The test target is sharp at the focusing distance being used. For certain measurements, you may need to adjust the aperture so that the test target comes within the depth of field (unless the effects of specific aperture settings are to be tested). For example, for a given combination (focal length, focus distance), a decrease of the aperture implies an increase of the depth of field, and therefore a better sharpness of the test target.
- The framing depends on the considered test target (see Section 4.12). For example, the framing of the Dots chart contains nothing but the test target and allows the imaging of at least the necessary number of whole spots to perform the characterization; this number varies with the type of measurement. The framing of the Texture Preservation chart should contain the entire chart.

c) If the tripod head is not fitted with a spirit level, or if the method of attaching the camera does not allow the use of the head horizontality as a reference, use a separate spirit level (see list of required equipment in Section 2.1) to adjust the horizontality of the lens aiming axis.

d) Set the tripod column at mid-position and adjust the legs so that the aiming axis of the lens is approximately at mid-height of the test target. Place the ruler or tape measure in front of the lens and finely adjust the height using the tripod geared column such that the lens axis is precisely at mid-height of the test target.

e) Using a plumb line if necessary, check that the lens is centered on the adhesive tape on the floor, marking the perpendicular center line to the test target.

f) An alternative method involves an assistant holding a mirror flat up against the test target, pointing towards the lens. For the camera to be perfectly perpendicular, the reflected image of the lens must appear exactly in the center of the viewfinder. To do this:

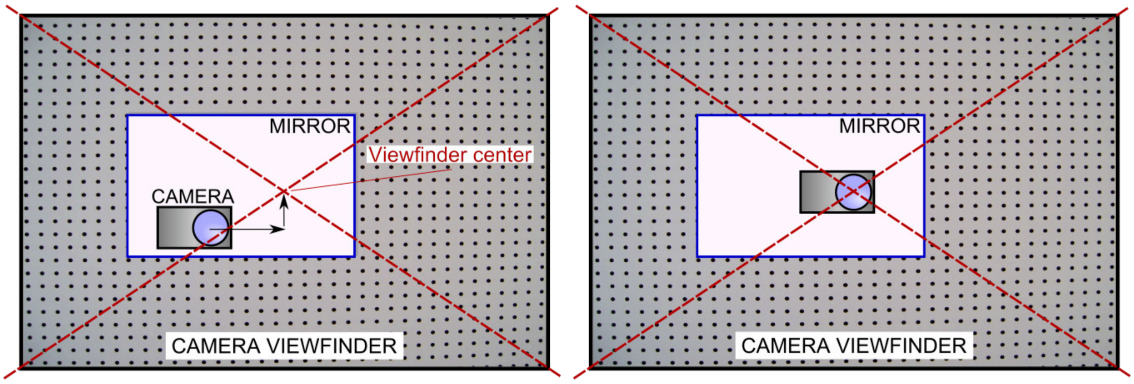


Using a mirror to perfectly position the camera

- The assistant sets the mirror carefully against the target, taking great care not to scratch the target with the mirror.
- Have the assistant move the mirror to where you can see the reflection of the lens. If the camera is already pointing to the target with an approximate right angle, that position should be near the center of the image.
- Rotate the head of the tripod to move the reflection of the lens in the viewfinder until it appears as shown in the second figure below. Translation is of no use for setting up orthofrontality. If your camera has an electronic viewfinder or is connected to a computer with a live preview on

the screen, you may estimate the center of the viewfinder either with a physical device (such as a ruler) or with the mouse pointer on the computer.

- Rotate the camera in the direction of the camera lens reflection: if the camera lens is on the left part of the image, rotate the camera to the left; if it is on the lower part, lower the camera.



On the viewfinder, camera lens must be in the center of the image - left: image on the viewfinder before adjusting orthofrontality, camera must be rotated to left and down; right: orthofrontality is correct, camera lens appears in the center of the image

- If the framing of the chart is not correct following rotation, translate the camera, keeping the same distance to the chart, and trying to keep the same angle to the chart. If you need to translate the camera, restart the whole procedure.
- When performed precisely, this method usually leads to an orthofrontality angle smaller than 1° (see Effective Focal Length measurement, Section 16, for more information about measuring the orthofrontality angle).

5.3 Before shooting

5.3.1 Built-in flash

Unless you want to perform a Flash measurement, you must disable the camera's built-in flash or, if this is not possible, cover it with black *gaffer* tape.

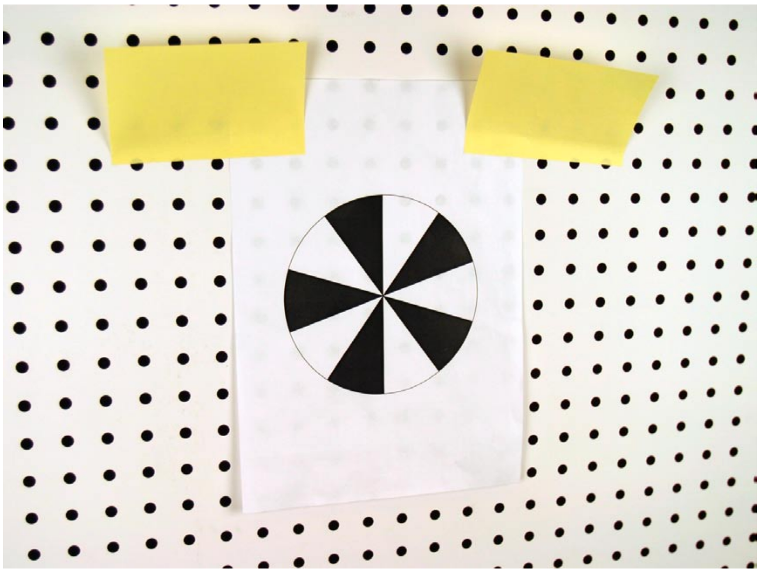
5.3.2 Focusing

Image sharpness (or blur) tolerance varies with measures performed by Analyzer, as described in Section **??**. Below, we indicate how to make sure the test target image is sharp for all types of cameras: without focus mode, with manual focus, and with automatic focus mode.

Some cameras (for example, camera phones) do not have any system for setting the focusing distance. In that case, examine the lens documentation, and place the camera at a distance from the target that is appropriate for and consistent with the lens characteristics. We also recommend taking several successive shots at shorter and longer distances than the one specified.

Whenever possible, set the camera to manual focus mode and set the appropriate lens ring to the exact distance between the wall and the camera, as marked on the floor. We also recommend taking several successive shots with different focusing distances, shorter and longer than the one being measured.

For cameras without a manual focus mode, the test target may confuse automatic focusing systems. If this is the case, prepare a special focusing aid (see illustration below) by using a drawing program. Print it out, and then:



Example of a focusing aid temporarily stuck onto the test target

1. Stick the focusing aid temporarily onto the test target using any means that does not damage the test target.
2. Ensure that the camera holds the focus setting by, for example, using its focus memory.
3. Remove the focusing aid.
4. Shoot.

If the camera does not have a focus memory, an alternative method is to take several successive shots and use the sharpest one.

If the camera offers a choice of several auto-focus zones, always use the central zone.

> **Note:** in some cases, it may be necessary to adjust parameters that do not influence a measurement in order to improve the overall image quality. Nevertheless, you must always respect the influencing parameters.

5.3.3 White balance – color temperature

Set the white balance to produce neutral images.

If the camera system allows the adjustment of imaging characteristics, do the following:

- Turn off any mode that implies a specific image processing (sepia, B&W, saturation, etc.).
- Select the color temperature corresponding to the light sources that illuminate the test target.

Otherwise, the camera auto white balance must produce an image without visible color dominance. Do not try to set the white balance manually as a post-processing step, as this may lead to erroneous results.

5.3.4 Exposure

Exposure must be as accurate as possible. Over- or under-exposure can noticeably affect the calculations.

5.3.4.1 Exposure settings for a Dots test target

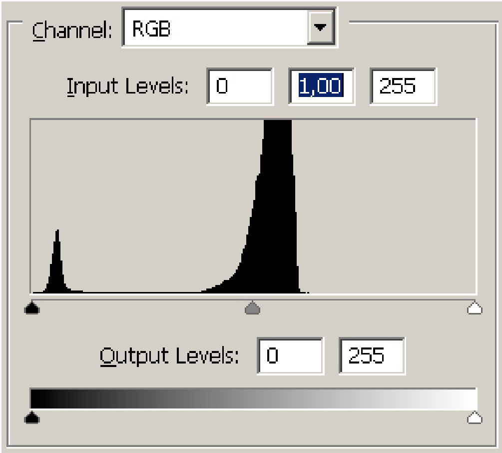
Black and white areas are not equally balanced in the Dots target, with white areas prevalent. This almost always results in under-exposure of shots. There are several ways to address this problem:

- If the camera allows manual aperture and exposure adjustment, place the exposure meter by the test target, so that it points to the camera, then measure the incident light and adjust the camera accordingly.
- If the camera is able to retain the exposure setting adjustment, place a sheet of neutral grey paper

by the test chart (see Section 2.1, under "other items"), store the exposure setting, remove the paper, and shoot.

- If the camera offers none of these possibilities, the resulting image has a grey background.

A correctly-exposed image should have a histogram with a minimum difference of 80 between the peaks corresponding to black and white tones. The histogram should be similar for all three RGB channels.



Histogram with two peaks indicating correct exposure of a DXOMARK IMAGE LABS test target

Note: This note is relevant if the device under test is a very old camera phone with a small resolution. Use the D0006 target to set the exposure for a camera phone (see Section 4.12 for specifications). As the resolution of camera phones is rather small, the black spots in the test target need to be big enough so that each spot is digitized with several pixels, and the percentage of the black area over the white area is large enough. The exposure setting is correct when the image includes significant black and white areas.

5.3.4.2 Exposure settings for the X-Rite ColorChecker® Classic

These tests are based on the following principle: over-exposure or under-exposure occurs when too many pixels lie within very high values or very low values.

Analyzer automatically tests each channel (L, R, G, B). Two thresholds are set: Imax = 250 and Imin = 5.

- An image is said to be over-exposed if more than 10% of pixels lie above the Imax value.

- An image is said to be under-exposed if more than 10% of pixels lie below the Imin value.

These constraints are not too restrictive, so as not to block you when dealing with a special case.

Another test relies on your observations when shooting the test target. As measurements are performed on grey values that lie between the black patch and the white patch, you must check that the white patch is as close as possible to digital value 255, and that the black patch is as close as possible to digital value 0.

5.3.5 Other camera settings

Unless the purpose of the test is to measure the effect produced by a specific configuration, configure the camera settings as follows:

- Maximum resolution.
- Sharpen and digital zoom OFF.
- Compression minimum or OFF.
- Exposure correction to 0.
- Any specific camera mode (saturation, contrast, etc.) set to a neutral position.

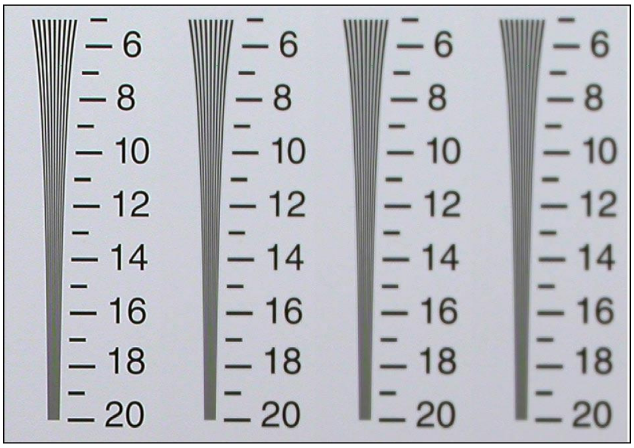
6 – B: Perceptual Blur

6.1 Introduction

The visual perception of the sharpness of an image is directly related to the contrast between the edge of a detail and its surroundings. A thin line reproduced in an image (actually a thin stripe) on a contrasted background will immediately be noticed. This is not the case if the edges are more diffuse. This property of the human eye is described by the common concept of "sharpness." More than the resolution itself, sharpness expresses the perception of a thin detail on a contrasted background. While the resolution power (or limiting resolution) is fairly easy to define (it is the size of the thinnest detail that a system can reproduce), coming up with a single-valued measurement of sharpness (or blur) is more challenging.

Increasing blur level from top left image to bottom right image

The example on the test targets below is striking: the four systems all have the same limiting resolution (about 13 in this case), but different perceptual blur.



Identical separating power (limiting resolution) over the whole image, but increasing perceptual blur level from left to right

6.2 Definitions

The concept of sharpness is related to the ability to reproduce thin details, and naturally related to the Modulation Transfer Function (MTF). The MTF represents the preservation of detail in the image produced by a camera system, for each spatial frequency. It measures the relationship between the output contrast of the camera system and the frequency of the test target. The limiting resolution is the highest spatial frequency that the system can discriminate. (See section 7 for more details.)

It is very common to use the limiting resolution as a measure of sharpness. This, however, is not very satisfactory, as shown in the experiment above.

A method for computing perceptual blur needs to be identified so that:

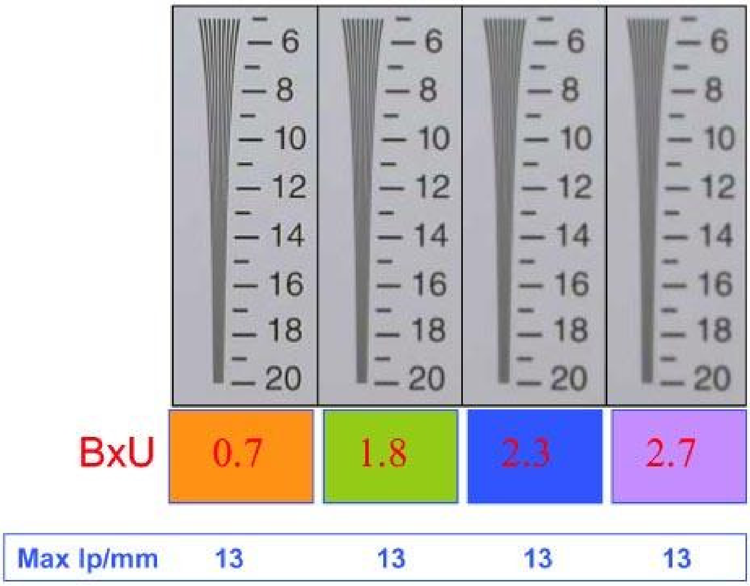
- It is simple to interpret.
- All the components of a camera system (optics, sensor, associated software) can be taken into account.
- Camera systems are easily classified according to their quality level of perceptual blur.
- Blur evaluation is not affected by rotation of the image.
- Blur evaluation is independent of the size of the sensor or photosites.

- Blur evaluation of two stacked systems is the sum of the blur of each system (additivity).

6.2.1 Units of measurement

Researchers at DXOMARK IMAGE LABS designed a method for computing a blur factor that measures the degradation of a digital image by spreading a specific spot. Further information may be found in “Uniqueness of Blur measure,” Jérôme Buzzi and Frédéric Guichard, Proceedings of the IEEE ICIP2004, October 24–27, 2004, Singapore.

As the blur factor is relative to an area, it is independent of the sensor's resolution or size. It synthesizes the MTF curve information in a unique number, which allows comparison and additivity within an optical chain. This number is expressed in “Blur Units,” abbreviated as BxU. While the method of expression of “sharpness” in lp/mm (line pairs per millimeter) is a measurement of high frequencies, BxU measures the MTF curve behavior in the low frequencies. As surprising at it may seem, this corresponds exactly to the perception of details by the human eye. The BxU of the four resolution patterns shown above gives exactly the expected ordering in terms of perceptual blur.



The four test targets have the same resolution: 13 lp/mm, but values of BxU increase from left to right (0.7, 1.8, 2.3 and 2.7). The value expressed in BxU quantifies the different visual perceptions precisely

BxU can also measure the effects of any filtering algorithm that is applied to digital images. Researchers at DXOMARK IMAGE LABS measured the “Blur” attenuation filter in Photoshop CS as a +0.5 value of BxU.

The BxU Blur measurement is homogeneous to an area. In Analyzer, the BxU units are given in pixels 2 or as a number of pixels.

6.3 Influencing factors

Several parameters influence the perceptual blur:

- The lens focal length.
- The aperture.
- For some lenses, the focusing distance may also have an effect, especially at short distances (in macro mode, for example).

6.4 Measurement of perceptual blur

Analyzer measures the BxU on the R, G, and B channels as well as on the luminance Y. The values are computed at different positions of the field. The BxU measurement is obtained on a white and black dots chart.

The image is compared with a binary image blurred by a Gaussian kernel. The variance of the Gaussian kernel is chosen so that the distance between the synthetically blurred image and the shot image is minimal. The returned BxU value is the BxU of the Gaussian kernel.

6.5 Measurement in raw format

Analyzer provides the computation of the BxU in raw format. In this case, the BxU is computed on each of the four color planes. Since the resolution of these planes is half of that of the RGB image, Analyzer multiplies the measured BxU values by 4 to normalize the blur at the resolution of the RGB image. The value of the BxU in raw format is a consequence of the quality of the lens and the MTF of the sensor. As for MTF measurements, the raw conversion usually changes the BxU as follows:

- Demosaicing makes the BxU value in different channels more even.
- Sharpening filters decrease the value of the BxU.

- Noise reduction filters may blur the image and increase the BxU.

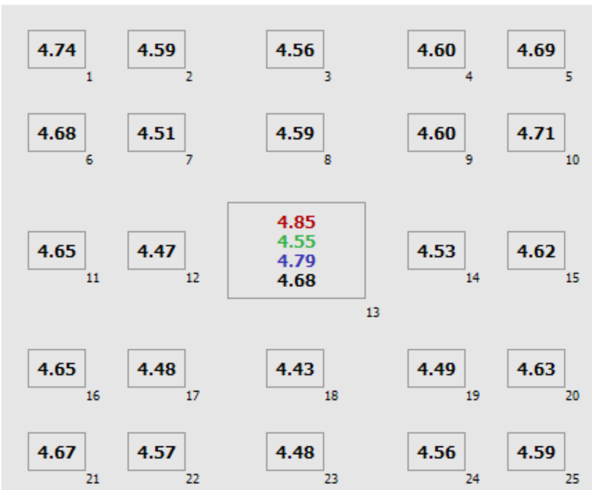
6.6 Analyzer output

Analyzer returns the following data:

- The Summary tab contains the BxU values for the R, G, B color channels and the luminance Y. The table contains the values at the center and the average of the four corner values. The values are expressed in two different units: in pixels squared (which is the actual measurement in the image), and in mm^2 in a 20×30 cm-equivalent image format. (See section 6.11 for the conversion rule.) This latter result makes it possible to compare cameras with different resolutions. Be aware that results in mm^2 are displayed as multiples of 10^{-3} for ease of use.

	Center		Corners mean value	
	in pixels²	in 10^{-3} mm² (20x30cm eq.)	in pixels²	in 10^{-3} mm² (20x30cm eq.)
R Red channel	4.85	35.55	4.86	35.64
G Green channel	4.55	33.38	4.56	33.44
B Blue channel	4.79	35.09	4.95	36.28
Y Luminance	4.68	34.33	4.67	34.25

- The blur map tab contains the values of the BxU for different positions in the image field. Maps of four channels are displayed: channels R, G, B and luminance for RGB images, and channels R, Gr, Gb, and B for raw images.



- The blur maps are also displayed in 10^{-3} mm^2 in 20×30 cm equivalent format.

6.7 Measurement accuracy

Measurement accuracy is ±5%, and above all, depends on the size of the part of the image that is processed. For example, if Perceptual Blur measures 4 BxU, its accuracy is ±0.2 BxU.

6.8 Measurement scale

The following table gives a subjective scale of BxU units (with a 1:1 display on the screen) for RGB images:

BxU (in pixels^2)	Level of sharpness
Between 0 and 0.5	Image is too sharp
Between 0.5 and 1.5	Image is sharp
Between 1.5 and 2.5	Image is slightly blurry
Between 2.5 and 3.5	Blur is visible
Between 3.5 and 4.5	Blur is strong
Above 4.5	Blur is too strong

For raw images, the BxU values can be larger than the RGB values, depending on the possible sharpening of the raw conversion.

The scale above is not very fair to cameras with very good resolutions. Indeed, in order to avoid aliasing effects (see section 7 on MTF), images are usually slightly blurry. Cameras with high resolution can afford this with no problem when images are printed using a usual format, making it is interesting to compute the BxU for such an equivalent format. (See section 6.11 for the calculation rules.)

BxU in 20×30 cm eq. (in 10^{-3} mm^2)	Level of sharpness
Between 0 and 10	Image is too sharp
Between 10 and 20	Image is sharp
Between 20 and 30	Image is slightly blurry
Between 30 and 40	Blur is visible
Between 40 and 50	Blur is strong
Above 50	Blur is too strong

6.9 Set up parameters influencing the measurement

Following set up parameters may change the results of the Perceptual Blur measurement:

- Digital zoom function (this must normally be deactivated, unless it is the subject of the test).
- Resolution (this must be set to the highest available value in order to obtain accurate measurements).
- Sharpening filter (this must be deactivated or set to the minimum).
- Framing the image in 4:3, 16:9, etc. (the photograph must normally be taken with maximum use of the sensor, unless it is the subject of the measurement).
- Special camera settings such as noise reduction filter, saturation filter, contrast enhancer, and so on.
- Exposure quality (the image must be neither over- nor under-exposed, usually by setting the camera to aperture priority).
- Exposure correction must be deactivated (Ev must be set to zero).
- Compression ratio should be as low as possible (TIFF is preferred to JPEG)
- Noise reduction filter
- Special modes of the camera for saturation, contrast, and so on, must be deactivated.

6.10 Measurement validity

An isolated value of perceptual blur is not meaningful. It is always necessary to associate it with the parameters that influence it. For example, stating that the blur of a camera is 3.4 BxU is meaningless. However, stating that the blur of a 6 Mpix camera with a 24 mm focal length at f/2.8, and with no sharpening filter, is 3.4 BxU is meaningful. Any information concerning exposure correction, noise reduction filter, saturation or contrast must be mentioned to validate the measurement.

6.11 Comparing two cameras

Comparing two cameras with different resolutions and/or different sensor sizes and/or different lenses may seem difficult. It all depends on how the images output by the two cameras are observed. We suggest three methods:

- Printing images in a single format, for example 200×300 mm.
- Printing the common part of the field in a single format, for example, 200×300 mm.
- Comparing the images on a screen display using a 1:1 ratio.
- In each case, the “Blur Experience” may be different since it depends on the method of display.

Let us take as an example camera “A” (24×36 mm sensor, 11 Mpixels) and camera “B” (15.1×22.7 mm sensor, 6 Mpixels). The same lens is mounted on both cameras, using the same focal length and same settings for all variable parameters.

6.11.1 Printing images in a single format (for example, 200×300 mm)

The sensors have different sizes, so the content of the images cannot be superimposed. The same would occur were lenses used with different focal lengths. Nevertheless, each image gives its own impression of blur, and we want to compare them.

As an example, take a digital image containing *x* pixels, in 3:2 format, with a Blur measurement of *b* BxU, to be printed in a 20×30 cm format; *b* may be converted by the following formula:

$$\mathrm{BxU}_{200\times300\,\mathrm{mm}} = \frac{b\times200\times300}{x}\ \mathrm{mm}$$

The value of $\mathrm{BxU}_{200\times300\,\mathrm{mm}}$ corresponds to the perception of blur one would have if the image were printed on a 200×300 mm medium, assuming that the printing technique adds no blur to the image.

This value is interpreted as follows: If an image has a BxU of value b, the blur spot (or "spot diagram") is b pixels wide. For a 200×300 mm format print, the x pixels of the image are distributed over a (200×300) mm^2 area. Therefore each pixel occupies an area of $(200\times300/x)$ mm^2. And a b value of BxU corresponds to a $(b \times 200\times300/x)$ mm value of $\mathrm{BxU}_{200\times300\,\mathrm{mm}}$, for a 200×300 mm format print.

For sensors with a format other than 3:2 (for example 4:3), the horizontal/vertical ratio is not preserved if the image is enlarged to a 200×300 mm format. To preserve this ratio, the image must be enlarged so that either its length is 300 mm or its width is 200 mm. The perceived blur will therefore be different in either case.

For an image of $m \times n$ pixels (where m/n is any ratio), the value of x is thus $m \times n = x$ pixels, and the formula for the two cases becomes:

$$\mathrm{BxU}_{L\ 200\times300\,\mathrm{mm}} = \frac{b \times 300 \times 300}{m \times m}\ \mathrm{mm}, \qquad \text{if the length is taken as the reference,}$$

$$\mathrm{BxU}_{l\ 200\times300\,\mathrm{mm}} = \frac{b \times 200 \times 200}{n \times n}\ \mathrm{mm}, \qquad \text{if the width is taken as the reference.}$$

For a 3:2 sensor, the values $\mathrm{BxU}_{L\ 200\times300\,\mathrm{mm}}$ and $\mathrm{BxU}_{l\ 200\times300\,\mathrm{mm}}$ coincide with the value $\mathrm{BxU}_{200\times300\,\mathrm{mm}}$, which in general corresponds to the geometrical mean of the two values.

Consider, for instance, a DSLR with resolution 3504×2336, focal length 35 mm, aperture f:22, and a camera phone with resolution 1600×1200, focal length 4.5 mm, and aperture f:3.2. The DSLR has a BxU equal to 4.70. The camera phone BxU is 1.55.

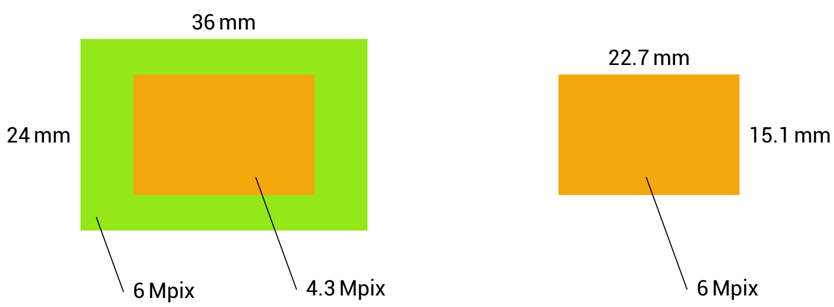
- For the DSLR, $\mathrm{BxU}_{200\times300\,\mathrm{mm}} = \dfrac{4.7 \times 200 \times 300}{8\,185\,344}\ \mathrm{mm}^2 = 0.0344$
- For the camera phone, $\mathrm{BxU}_{200\times300\,\mathrm{mm}} = \dfrac{1.55 \times 200 \times 200}{1200 \times 1200}\ \mathrm{mm}^2 = 0.0431$

Thus when printed at the same resolution, the DSLR appears sharper than the camera phone.

Note: Generally speaking, this comparison process is favorable to higher-resolution images.

6.11.2 Printing the common part of the field in a single format (for example 200×300 mm)

As camera B has a smaller sensor than camera A, its image field is smaller than camera A's when fitted with the same lens. In order to compare the image from camera B with the corresponding part of the image from camera A, we need to extract from camera A the "sub-image" corresponding to the image taken with camera B. First we need to estimate the ratio of the sensor sizes so that the sub-image of camera A that corresponds to the image field of camera B contains 4.3 Mpixels.



Fields of camera "A" (left), and camera "B" (right)

With the help of the formula above:

- For camera A, $\text{BxU}_{C\ 200\times300\,\text{mm}} = \dfrac{b \times 200 \times 300}{4\,300\,000}\ \text{mm}^2$
- For camera B, $\text{BxU}_{C\ 200\times300\,\text{mm}} = \dfrac{b \times 200 \times 300}{6\,000\,000}\ \text{mm}^2$

Again, the BxUs of the two cameras are changed differently. This corresponds to the magnification factor to be applied so that the common part of the field of each image is reproduced in the same print format.

Note: This comparison process generates a normalization of the BxUs that is favorable to the sensor whose pixels are the smallest.

6.11.3 Comparison of images on-screen with a display ratio of 1:1

When one looks at an image on a 1:1 screen (one pixel of the image = one pixel on the screen), BxUs are directly comparable without normalization.

- For camera A, $BxU_{1:1}$ = BxU pixel^2 or number of pixels.
- For camera B, $BxU_{1:1}$ = BxU pixel^2 or number of pixels.

In this comparison, two images with different dimensions occupy different spaces on the screen (and, most of the time, exceed the size of the screen). The image from camera A is approximately twice as large as the image from camera B.

6.11.4 Precautions to take before comparing a given lens on different cameras

A given lens generally gives different values of BxU depending on the sensor (or the camera) used, because:

- The size of the sensors, and therefore the fields, may be different.
- The resolutions may be different.
- Digital sensors naturally generate blur, and they are often associated with an automatic digital processing that depends on the model.
- When the fields are different, BxU measurements made in the corners of the image do not correspond to the same position in the lens (for example, a measure of BxU in the corner for camera B corresponds to a measure in a median position of the field for camera A), therefore it is natural to observe BxU values that are much worse in the corners of full-field cameras (such as A) than those of partial-field cameras (such as B).

When sensors and digital processing have the same level of quality, the values of BxU for a given lens measured at the center, are similar to the second method ($BxU_{C\ 200\times300\,\mathrm{mm}}$).

6.11.5 Examples

In the following table, camera A and camera B are fitted with a 17–35 mm lens, used at a focal length of 17 mm and an aperture of f/2.8; sharpness is deactivated on camera A and set to normal on camera B. The values of BxU are measured at the center of the image.

	BxU	$BxU_{200\times300\,mm}$	$BxU_{C\ 200\times300\,mm}$	$BxU_{1:1}$
“A”	1,26	0,0069	0,0176	1,26
“B”	1,74	0,0174	0,0174	1,74

The table shows that the BxU is better for camera A than for camera B. As the lens is the same, the BxU difference is mainly due to the difference in pixel size between the two sensors.

For a 200×300 mm print, the $BxU_{C\ 200\times300\,mm}$ is much better for camera A than for camera B, because camera A's image requires less magnification than camera B's for the printing process, since it contains more pixels.

$BxU_{C\ 200\times300\,mm}$ of camera A's sub-image (corresponds to the camera B's field) and that of camera B are very close. This is because the lens is the same in both cases and because the blur induced by the camera and the sharpness performed by the digital processing are similar overall for both cameras.

Observed at a ratio of 1:1, the image of camera A appears sharper than the one of camera B.

6.12 Shooting

The Blur measurement uses a Dot chart.

1. **Decide on the important parameters:** focal length, aperture, focusing, resolution, sharpness, digital zoom, framing.
2. **Special shooting conditions** (see also section 5).

The framing must be such that:

- The test target is present in at least the upper right 3/4 of the image.
- No element that is external to the test target should appear in the viewfinder.
- At least 16×16 complete spots are framed in the effective area of measurement.
- The spots must appear sharp and regularly-shaped.
- The complete framed test target must be in the same plane of sharpness.

Take all necessary precautions to avoid shaking the camera when shooting. You may want to use a cable release or trigger the shot from a computer connected to the camera.

> **Note:** it is important to keep a record of all the parameters and settings associated with each shot. Depending on the model, not all cameras record all the EXIF data, and you are going to use the measurement to compare two cameras, the recording conditions for the image files must be strictly identical.

7 – MTF: Modulation Transfer Function

7.1 Introduction

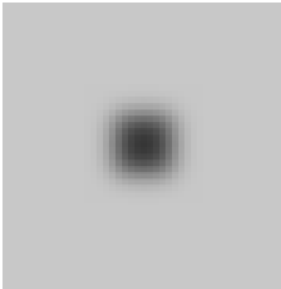
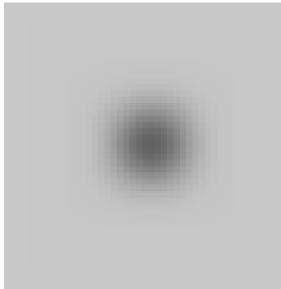
The optical system of a digital camera aims to concentrate (focus) the light onto a sensor. Following elementary geometrical optics, a light source at infinity can be viewed as a planar wave, in other words, all light beams coming from the source are parallel. All the rays crossing the lens intersect at a single point. The intersection is located on a plane perpendicular to the axis of the lens, the *focal plane*, which turns out to be independent of the direction of the light rays. In theory, infinitely thin receptors placed on the focal plane would result in a perfectly sharp image. However, this is not the case, and images are always (at least) slightly blurry, because:

- Objects are not at infinity and wave fronts are not planar, so the rays emitted by a point-wise source do not intersect at a point.
- Real-world lenses do not focus light as ideal thin lenses would.
- Different wavelengths have different optical paths and do not focus at the same position.
- The surface of best focus is not a plane, whereas the sensor is planar for technical reasons.

The pattern created by a small (theoretically point-wise) light source is called the blur spot. A complete description of the blur spot characterizes the response of the optical system to any kind of oscillations. This is not an easy task though, since the blur spot:

- Depends on the position in the field.
- May have a complex shape.
- Depends on the wavelength.

The properties of the blur spot (or Point Spread Function) determine the ability of the system to reproduce oscillatory patterns. Obviously, patterns which are spatially smaller than the blur spot (therefore having high frequencies) are mixed up and seen as uniform by the sensor. The blur spot also prevents edges from being sharp. While the blur spot can be visually estimated (i.e., it is the response to a small light source), it is more useful to analyze its effects in the frequency (Fourier) space.

Blur Spot		
Effect		

Visual impact of two blur spots

7.2 Definitions

The Modulation Transfer Function (MTF) is the modulus of the Fourier transform of the blur spot in a given direction. It measures, for each frequency, the ratio between the contrast amplitude of the input and the observed image. The MTF measurement assesses the preservation of details and contrast in the image.

As with the blur spot, the MTF depends on the position in the field. Moreover, since the blur spot may not be isotropic, the MTF is not necessarily the same in all directions.

The MTF usually assumes a maximum at frequency 0, although it is usually normalized to 1. For most conventional optical systems, it is a decreasing function of the frequency. An ideal lens would have a MTF equal to 1 everywhere. However, the discrete nature of digital images implies that the output signal is band-limited (in other words, it does not contain any information beyond a frequency limit).

7.2.1 Nyquist frequency

Digital images cannot reproduce oscillations beyond a given frequency which corresponds to the alternation of dark and bright lines whose width is one pixel.

This frequency corresponds to one cycle every two pixels, or equivalently to half a cycle every pixel. It is called the Nyquist frequency.

The Nyquist frequency provides a natural unit of frequency in digital images. Another commonly-used unit is the number of line pairs per mm (lp/mm). Nyquist frequency corresponds to a line pair. The conversion between the two units requires that the size of the pixels be expressed in mm, or equivalently, the size of the sensor and the resolution. For instance, a sensor with size 22.5×15 mm with a resolution of 3504×2336 has 78 lp/mm, corresponding to its Nyquist frequency.

A fundamental result of digital signal theory (Shannon's Theorem) states that it is possible to perfectly reconstruct a signal from its (regularly-spaced) samples, provided the spectrum of the signal does not contain any energy beyond the Nyquist frequency. Higher-frequency content must be canceled before sampling, or artifacts such as aliasing and Moiré patterns may appear. On the other hand, frequencies up to the Nyquist frequency should be preserved as much as possible.

It is worth noticing that the sensor makes its own contribution to the MTF of a camera. Indeed, the photosites are not infinitely small. They accumulate photons in a small region, which introduces an additional blur. Moreover, their behavior is not precisely uniform, which makes the sensor MTF particularly hard to evaluate. Analyzer provides a measurement of the MTF of the optics/sensor combination.

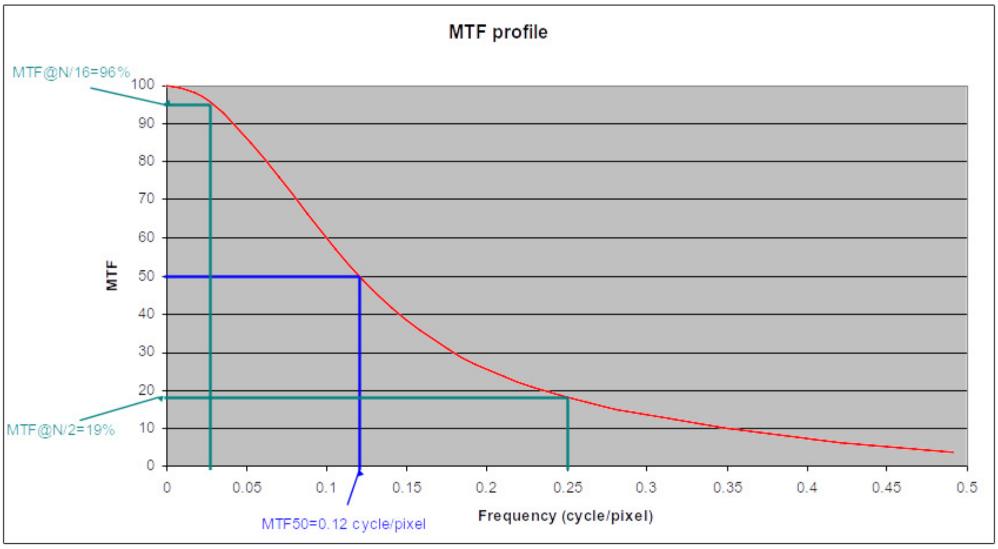
7.2.2 Key values

The three following values are particularly relevant:

- The half Nyquist value: this corresponds to the MTF value at the spatial frequency 0.25 cycle/pixel. It will be denoted by ***MTF*** @Nyquist/2

- ***The Nyquist/16 value***: This corresponds to the MTF value near zero. It is linked to the BxU value (see below). It will be denoted by **MTF@Nyquist/16**
- ***MTF50***: This corresponds to the smallest frequency which is preserved at 50%, in other words to the first frequency f_0 such that MTF(f_0) = 0.5.

As it is not always possible to compare two curves, we can compare the frequency response of two imaging systems by comparing only their MTF50 and MTF @ 0.25 cycle/pixel. The higher these values, the better the imaging system.



MTF of an optical system showing the MTF50, MTF@Nyquist/2 and MTF@Nyquist/16 values

7.2.3 Limiting resolution

The ISO 12233 standard defines the limiting resolution as the frequency at which the corresponding MTF value is 5% of the MTF at a given reference frequency (usually a low frequency close to 0, such as 10 line pairs per image height). However, the reference frequency is not explicitly specified by the standard. The idea is that any frequency content beyond the limiting resolution is considered as lost, since it is much too attenuated.

An average human visual system is capable of distinguish contrasts as low as 10%. That criterion is largely admitted and corresponds to Lord Rayleigh's criterion for diffraction-limited resolution.

7.2.4 Astigmatism

Astigmatism is caused by asymmetric blur spots. In this case, the MTF is different in every direction. The blur spot may have a very complex shape, so astigmatism may be defined with different degrees of approximation, the simplest one being that of comparing the MTF in two fixed directions.

7.2.5 Longitudinal chromatic aberration

Longitudinal chromatic aberration appears when the blur spot (and hence the MTF) exhibits strong differences between different wavelengths.

7.2.6 Ringing

Ringing is an artifact which appears as clear and/or dark lines along edges. Ringing is not an optical phenomenon. It is mainly due to digital sharpening (digital deconvolution), but it is also caused by quantization, compression, and other digital processing.

When the image is a black disk on a constant brighter background, ringing can be seen as an even brighter ring on the boundary of the disk, hence the name.

Discontinuities of the MTF create Gibbs oscillations that are one form of ringing. However, a continuous MTF can also produce ringing, typically when a sharpening filter is applied and the MTF has a local maximum at a non-null frequency.

7.2.7 Relation with the Perceptual Blur measure (BxU)

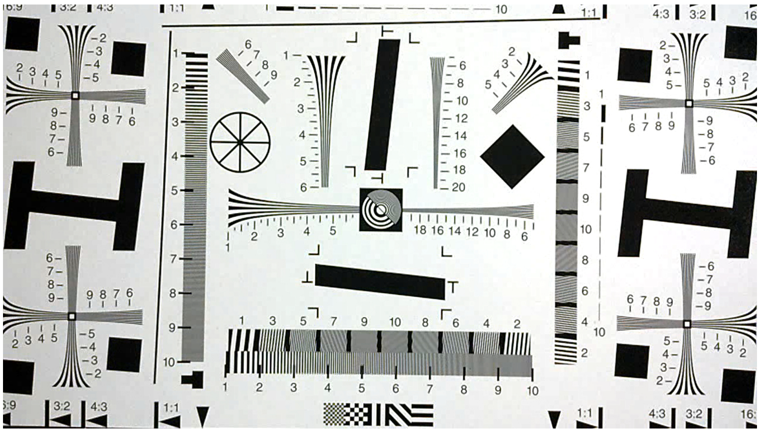
The MTF contains all the information about sharpness and blur including the BxU value which reflects the perceptual blur.

More precisely, if there is no astigmatism,

$$\frac{d^2\mathrm{MTF}}{df^2}(0) = -2\pi^2\mathrm{BxU}$$

— that is, the BxU is proportional to the opposite of the second derivative of the MTF at frequency 0. However, it may not be easy to numerically retrieve the BxU from the MTF measurement. Indeed, the accurate computation of the second derivative of a function needs much numerical care, since it is very noise sensitive. Thus a dedicated protocol, chart, and algorithm are proposed to measure the BxU more accurately.

The ISO 12233 standard recommends the use of the following chart to compute the MTF and the limiting resolution.



ISO 12233 test target

However, the patterns of this chart are not meant to be automatically detected. Moreover, it is not possible to compute the MTF at many different positions of the field in a single shot at different resolutions and different shooting distance. Therefore, Analyzer provides a chart for the MTF measurement, available in different formats (ex. SU0002_140).

7.3 Influencing factors

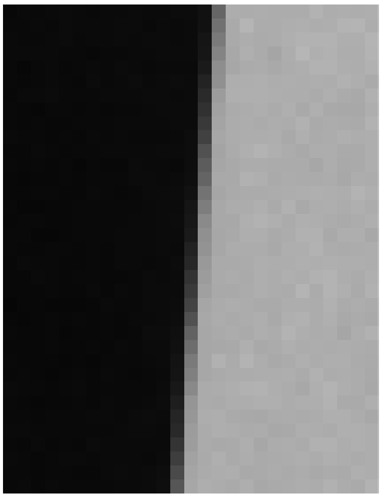
Several parameters influence the measure of the MTF. These are:

- The focal length of the lens.
- The aperture.
- For some lenses, the focusing distance may also impact the measurement, especially at short distances (in macro mode, for example).
- The shooting distance for some fixed focal length lenses.

As mentioned above, ringing is mainly caused by digital processing. Therefore the influencing factors are the setup parameters (see the setup parameters section). The main factor is the use of sharpening filters. For RGB images, the tone curve also modifies the ringing value.

7.4 Measurement of the modulation transfer function

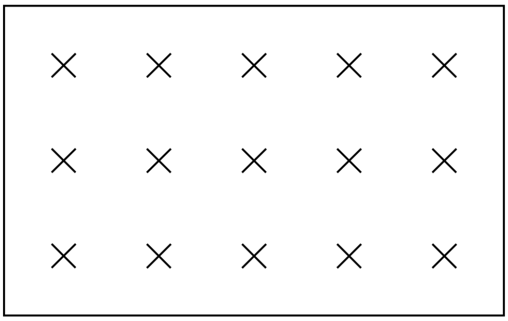
Analyzer implements the ISO 12233 method of estimating the MTF (or SFR spatial frequency response) from a slanted edge image.



Part of a slanted edge used to compute the MTF following the ISO 12233 method. For optimal measurement, the angle between the edge and the vertical or horizontal should be between 5° and 7°

The method consists in extracting the exact profile of the edge transition with sub-pixel accuracy. The derivative of this profile approximates the Line Spread Function (LSF) of the camera. The MTF is the modulus of the Fourier transform of the LSF.

The MTF is computed at 15 different positions in the field.



Positions in the field where MTF is measured

For each position, the MTF values in the horizontal and vertical directions are computed. The MTF is computed for the different color channels (R, G, B for RGB images and R, Gr, Gb, B for raw images).

The values MTF50, MTF@Nyquist/2 and MTF@Nyquist/16 are obtained directly from the graph.

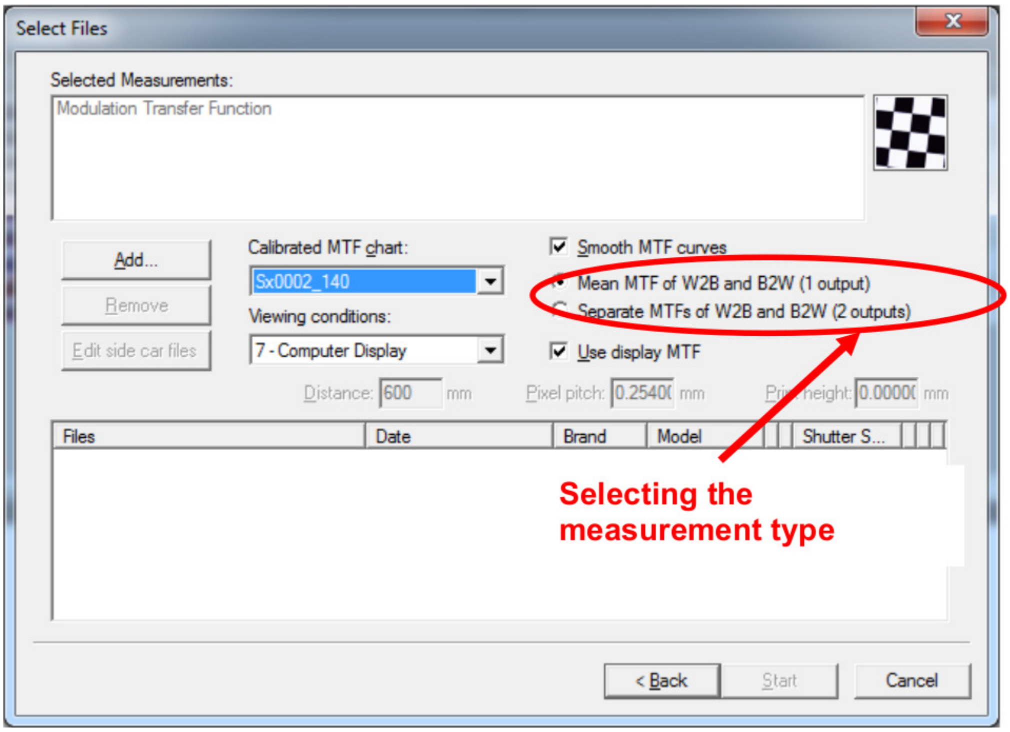
As the conversion of raw images into RGB is not a linear process, differences may appear in RGB measurements between MTF computed from black-to-white transitions and MTF computed from white-to-black.

Nonlinear processing applied on raw images can be, for example, demosaicing, tone curve application, and some color or sharpness processing. These processes can transform differently black-to-white and white-to-black transitions.

So, it is important to compare MTFs computed from the same kind of transition. Analyzer performs two types of MTF measurements:

1. Mean MTF between the nearest black-to-white (B2W) transition and the nearest white-to-black (W2B). For each measurement point, MTF curves are computed twice and the mean is returned. MTF values (MTF50%, MTF10%…) are computed from the mean curves.
2. Separate measurements: MTF for B2W transitions and for W2B are computed separately. For each image of the MTF chart, two measurement results are given, one for B2W transitions and the other for W2B.

Choose between these two measurements when selecting the image chart. A dialog box allows you to switch between mean measurement and separate measurements.



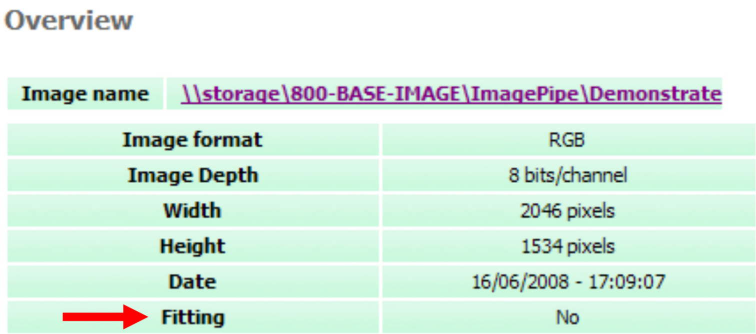
Selecting the studied transitions

Note that if you have given ROI parameters in a sidecar file, this selection will be ignored and measurements will be done on the selected ROI only.

For MTF measurement results, the type of studied transitions is visible in the header. If "W2B" is present in the header, the measurement was done on white-to-black transitions. If it is "B2W," studied transitions are black-to-white. If it is "Mean," the result is the mean between B2W and W2B transitions results. If it is "ROI,"the result is given for the user-defined ROI of MTF.

MTF (B2W)	Measurement on black-to-white transitions
MTF (W2B)	Measurement on white-to-black transitions
MTF (Mean)	Mean measurement
MTF (ROI)	ROI measurement

Another option is available in this window, "Smooth MTF curves." If this option is activated (default behavior), the measurement produces smoothed (fitted) MTF curves. This option is interesting mostly for raw images, to reduce noise on curves and thus increase the repeatability and accuracy of the measurement. In most cases, it has little or no effect on RGB measurements.



Overview

Image name	\\storage\800-BASE-IMAGE\ImagePipe\Demonstrate
Image format	RGB
Image Depth	8 bits/channel
Width	2046 pixels
Height	1534 pixels
Date	16/06/2008 - 17:09:07
Fitting	No

Fitting is visible in the "Shooting conditions" window

The "calibrated MTF chart" selection is used for inverting the MTF chart, if the photographed chart is one that has been calibrated. DXOMARK IMAGE LABS supplies calibrated MTF charts, each of which has its own computed MTF. Supplied with the reference of the input chart, Analyzer computes the distance between the camera and the chart, and corrects the measured MTF by applying the inverse of the calibrated MTF. If "Undefined" is selected, no correction is applied.

The last option pertains to the viewing conditions. The selected viewing condition will change the acutance results.

7.4.1 Acutance

The acutance is a single value metric calculated from a MTF result. A higher value means a sharper image. Acutance depends on the selected viewing conditions. See Texture chapter (Section 10) for more information about acutance and viewing conditions.

7.4.2 Limiting resolution

Analyzer defines the limiting resolution as the smallest frequency f such that MTF(f) = 0.1.

7.4.3 Astigmatism

Analyzer provides a measure of astigmatism as the difference of the MTF in the vertical and horizontal direction.

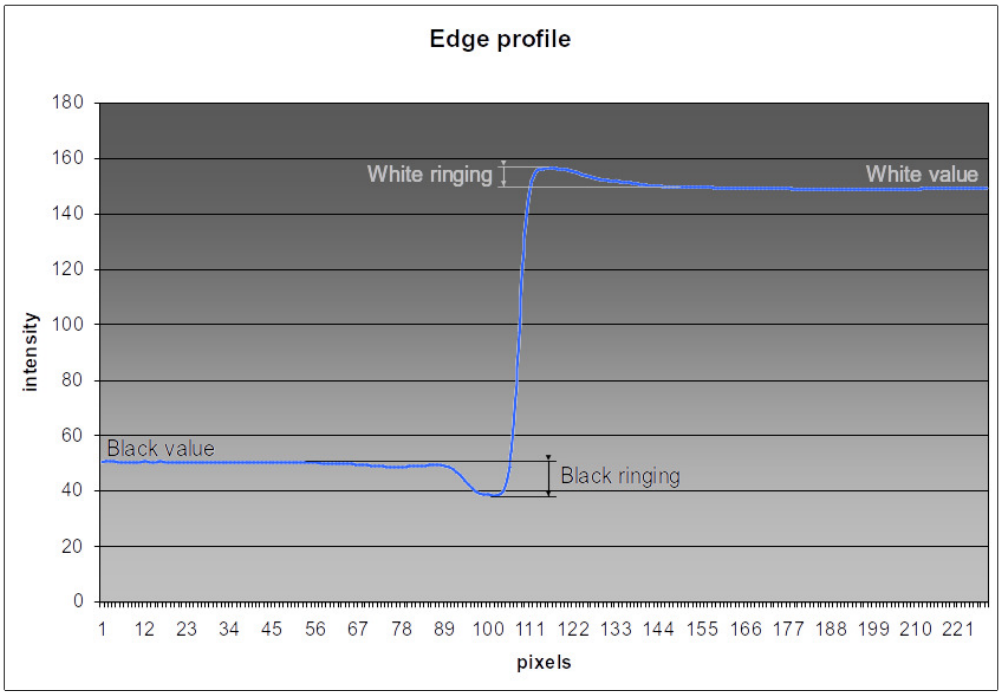
7.4.4 Longitudinal chromatic aberration

Analyzer computes the MTF of the system in the R, G and B channels. A large difference between the MTF in the three channels means that longitudinal chromatic aberration is important.

7.4.5 Ringing

The Ringing measurement is performed at the same time as the MTF measurement, which means that the same chart and shot are used. Measurements are given for each color channel, in the same zones in both directions. Even though some general properties of MTF are known to produce ringing (discontinuities, local maximum), the relationship is not perfectly understood. Hence the method consists in extracting the exact profile of the edge transition with sub-pixel accuracy. In the absence of ringing, the value of the grey level is monotone along the profile. In the presence of ringing, the grey level exhibits some oscillations, and eventually converges with the limit values.

The maximum of ringing oscillations is measured in both black and white zones. Its amplitude is given as a percentage of the step edge amplitude.



Profile of an edge transition with ringing

7.5 Measurement in raw format

You can measure the MTF on both RGB (JPEG or TIFF) and raw images. The results provide completely different information.

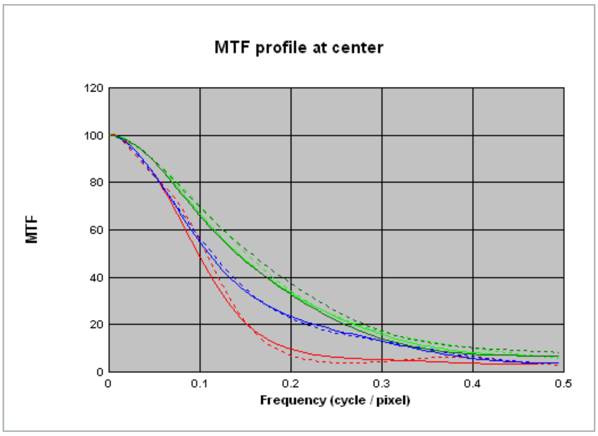
The MTF in raw format quantifies the response of the lens and the sensor. For instance, it is a well-known fact that blue is usually more blurry than red and green for remote objects, yielding longitudinal chromatic aberration. This may cause color fringing in certain shooting conditions, particularly for scenes with saturated backgrounds.

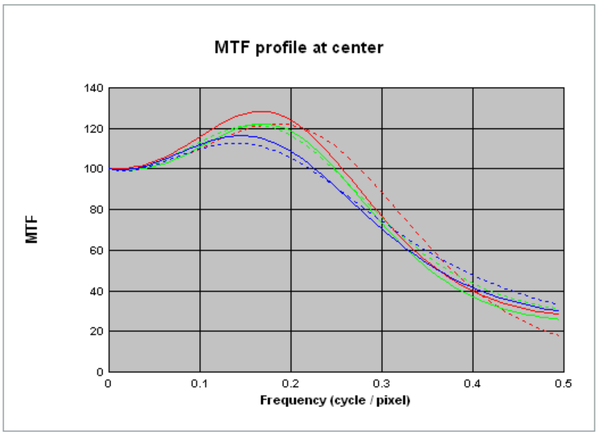
On the other hand, the MTF of images in RGB format takes numerical processing into account. In particular,

- Edges are usually sharpened.
- The frequency contents of the different channels are also mixed by demosaicing.
- Specific channel-dependent filters may be applied to correct longitudinal chromatic aberrations.
- Astigmatism may be corrected.

The difference between the MTF in raw and RGB formats shows the amount of sharpening and other corrections. It is worth noting that the amplification of a given channel at some frequencies also amplifies the noise in that channel.

Strong sharpening filters may also change the MTF so that it can attain its maximum for a non-null frequency. Besides the positive sharpening effect, this may also yield other kinds of artifacts such as aliasing and ringing effects. The following figures show an example of MTF for the same shot before and after raw conversion.





MTF of a camera before raw conversion (left) and after (right)

Low frequencies have been amplified, thus reducing the perceptual blur. High frequencies are more even, reducing longitudinal chromatic aberrations and aliasing.

7.6 Tone Curve inversion

Analyzer offers the possibility of inverting the tone curve (or transfer function) applied to the image. Knowing the tone curve of the camera, Analyzer applies its inverse function. Parameters of the tone curve are given by the sidecar file.

The aim of this feature is to correct the processing done by the camera in order to adapt the image contrast to display screens (see Tone Curve measurement in Section 25).

Monitors' nonlinear response is theoretically compensated by a gamma 2.2 curve, but most camera manufacturers use their own curve, adapted to their desired contrast result.

Analyzer provides two methods to compensate the tone curve. The first method is to assume that the tone curve is a gamma 2.2 function. The second method is to use the result of a prior tone curve measurement.

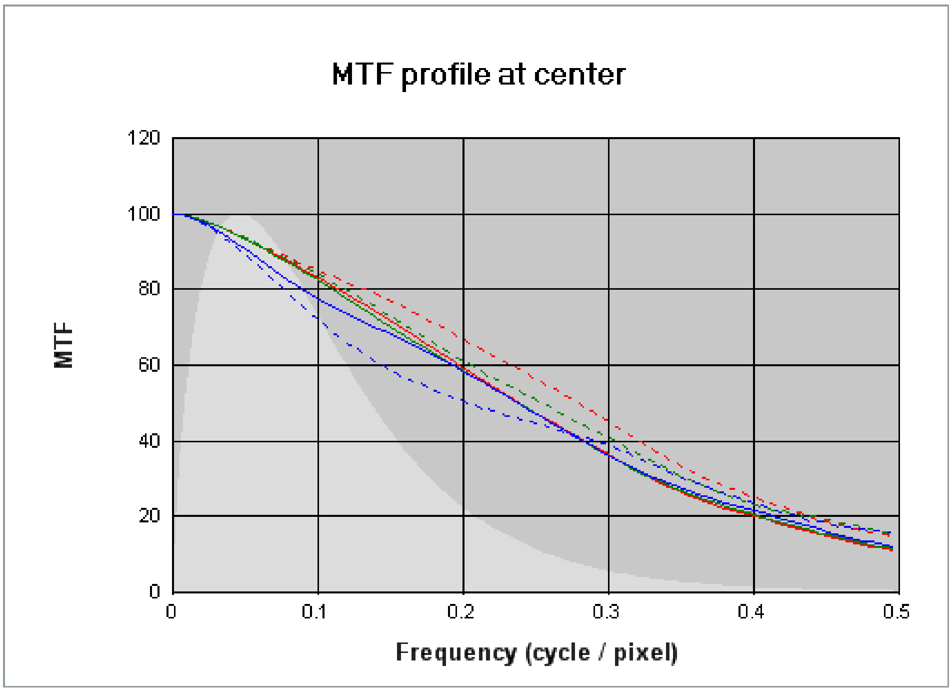
See Section 7.14 to see how to fill the sidecar file.

7.7 Analyzer output

Analyzer returns the following data:

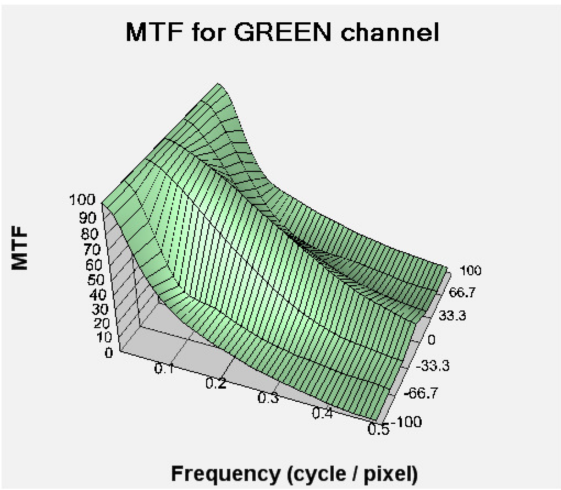
- The summary tab contains two sections:
  - A summary section that displays four key values (acutance, limiting resolution, MTF50 and ringing intensity) for the green channel. The value at the center of the image and the mean of the values at corners are given. Each value is the mean of the corresponding vertical and horizontal values.
  - A details section that displays key values for the three channels. These values are:
    - The conversion factor between cycles/pixel and cycles/degree
    - The acutance
    - The frequencies at MTF 10% and MTF 50%
    - The values of the MTF at Nyquist/2 and Nyquist/16
    - The ringing intensity as a percentage of the step-edge amplitude

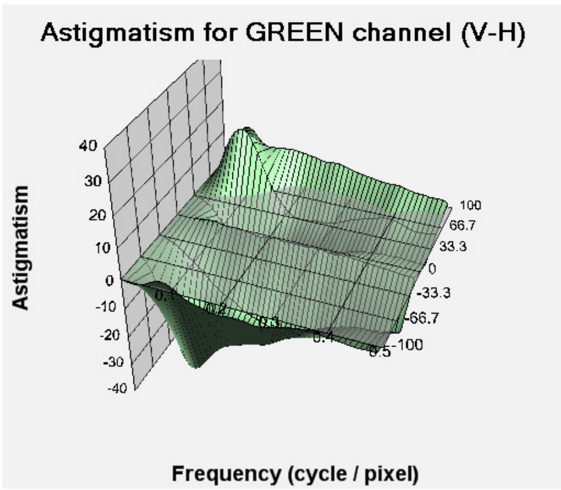
    A mean value is given for the corners. Each value is the mean of the corresponding vertical and horizontal values.
- The MTF graph tab displays the MTF profiles for the different channels (R, G, and B for RGB images, and R, Gr, Gb, B for raw images) at four different positions in the field. The solid line is the MTF in the horizontal direction and the dashed line is the MTF in the vertical direction. The frequencies are expressed in cycle/pixel (Nyquist frequency is 0.5 cycle/pixel). The CSF, used to compute acutance, is displayed in light grey.



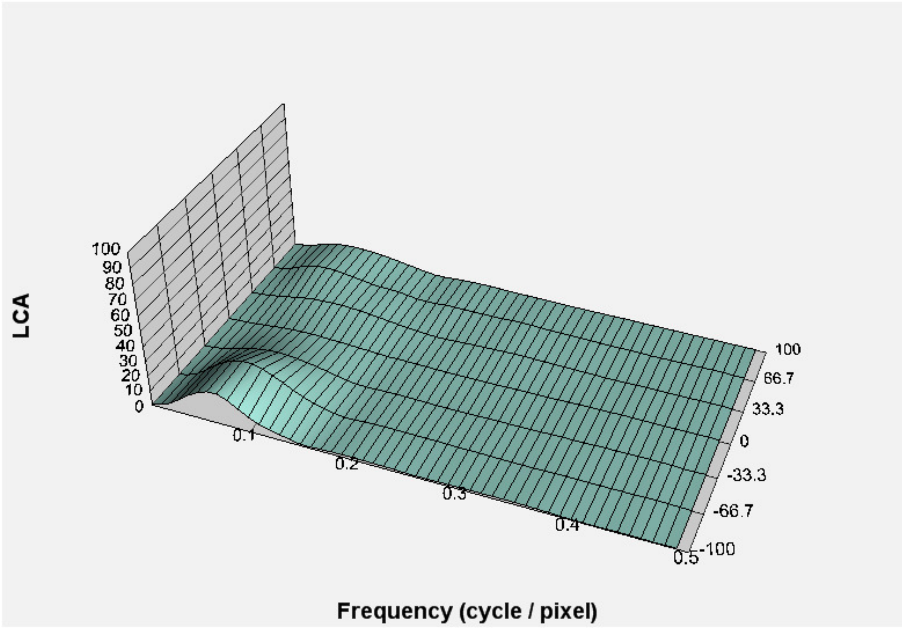
- The 3D graph tab displays:
  - A 3D plot of the MTF as a function of the field position for each color channel. The astigmatism (difference between horizontal and vertical MTF) is displayed in the same way.

    The axis goes from left to right in the image field, with −100% being the mean of the results on the top left and bottom left corners, 0% the image center, and 100% the mean of the top right and bottom right corners.





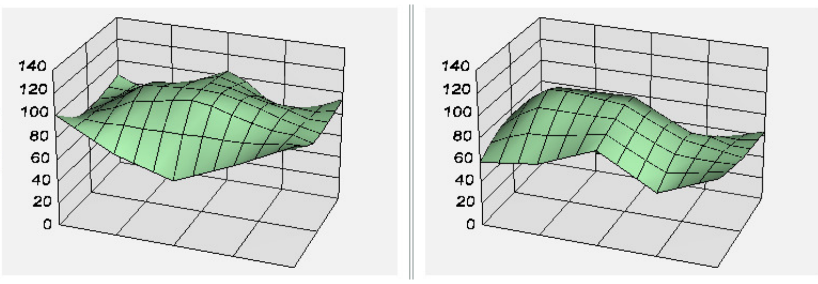
– A 3D plot of the longitudinal chromatic aberration defined at each point as the difference between the maximum and minimum MTF values taken in different channels.



- The six following tabs are for: acutance, limiting resolution (MTF 10%), MTF 50%, MTF@Nyquist/2, MTF@Nyquist/16 and ringing intensity. They contain the key values at 15 positions in the field for each channel. A 3D graph is given for each pair of key values per channel.

  Example: intensities of MTF at frequency Nyquist/2 for the green channel of a Sony-Ericsson W810i camera phone.

86%	71%	104%	77%	93%
78%	109%	113%	103%	89%
101%	74%	59%	81%	107%



64%	18%	16%	43%	64%
74%	103%	99%	76%	68%
58%	65%	86%	57%	79%

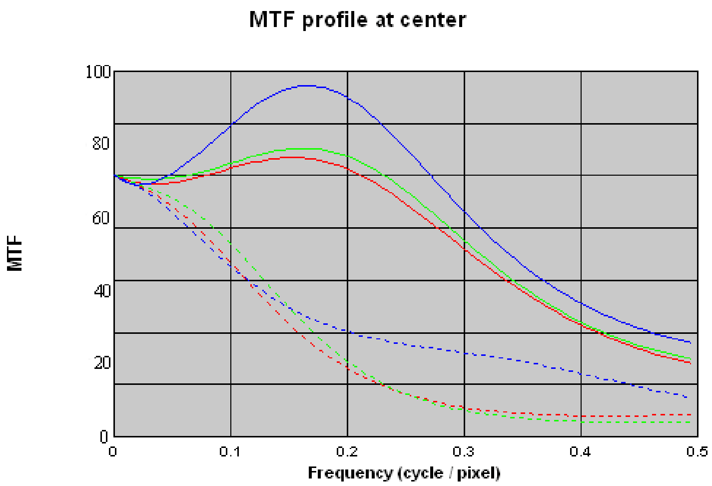
Note that if a sidecar file has been used to define the points of the MTF measurement, the Summary tab and the 3D plot tab will not appear.

7.8 Examples

The figures below show an example of astigmatism. To illustrate this phenomenon, crops along a vertical and horizontal edge are extracted from a chart shot.

Illustration of astigmatism showing ringing along the vertical edge

The image shows some ringing along the vertical edges, while the horizontal one is more blurry. The MTF exhibits this characteristic with figures.



MTF calculated from the two edges above. The solid line is the horizontal MTF (for RGB) and the dashed line is the vertical MTF. Astigmatism is the difference of the MTF

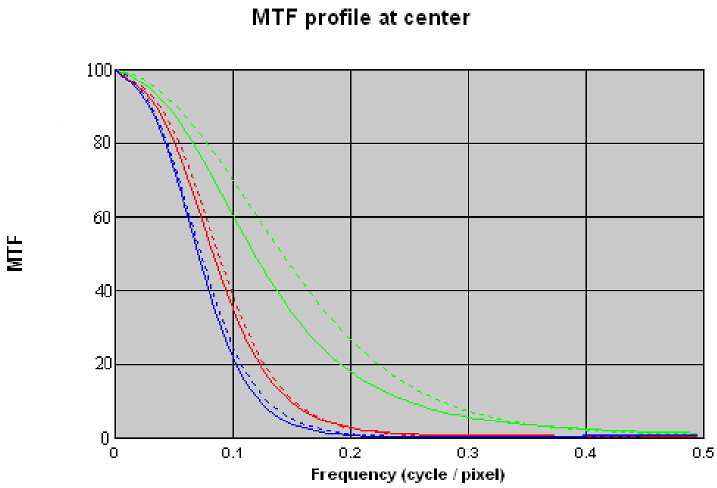
The horizontal MTF (solid line) is clearly above the vertical one (dashed). It also attains values over 1, which is a very good indication of ringing.

The next example is an illustration of longitudinal chromatic aberration. The transition between the black and white parts clearly exhibits color fringes.

An example of longitudinal chromatic aberration which is often characterized by color fringes along edges

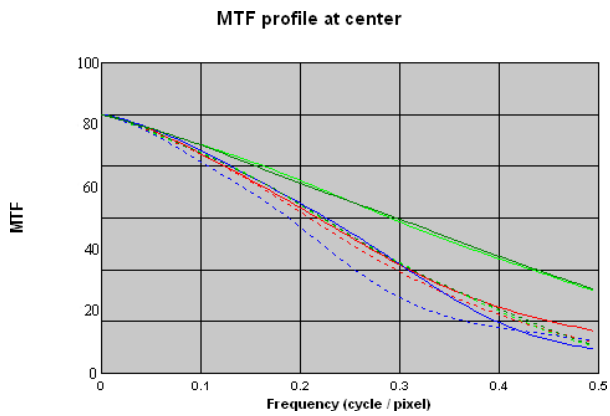
Visually, chromatic aberrations show up as color fringes around edges. There are actually two different kinds of chromatic aberrations:

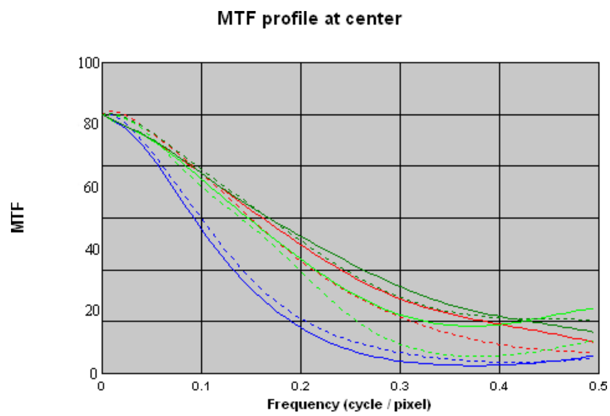
- Lateral Chromatic Aberration occurs because different wavelengths focus at different positions on the sensor and can be locally approximated by a translation between color channels (see Section 12 for the lateral chromatic aberration measurement). This has only second-order impact on MTF and usually a similar impact on all color channels.
- Longitudinal Chromatic Aberration occurs because different wavelengths focus at different distances from the optics. Though, only one wavelength can be in focus and a longitudinal chromatic aberration shows up as a blur difference. Analyzer presents longitudinal chromatic aberration as the maximum difference of MTF between color channels.



MTF of the edge shown above. Differences of the MTF between color channels yields longitudinal chromatic aberration

The following figures show the MTF measurement results for a DSLR (resolution 6 Mpix) and for a camera phone (2 Mpix), both on raw images. The MTF of the camera phone decreases faster than the MTF of DSLR. For the DSLR, the minimum MTF@0.25 is 0.4, whereas it is 0.1 for the camera phone. The blue channel is almost completely lost at this frequency. It can be recovered (to some extent) by the raw conversion. The DSLR shows very little astigmatism and longitudinal chromatic aberration for low frequencies, contrary to the camera phone. These differences are even more important when the resolutions are expressed in an equivalent format for both images (i.e., as 24×36 mm equivalent).





MTF on raw data at the image center for a dSLR (left – Nikon D70, focal length 18 mm, aperture f:8) and a camera module (right – focusing distance 173 cm)

7.9 Measurement repeatability

The measurement repeatability is 4% on average. However, it is more accurate for low frequencies than for high frequencies.

The following table details the measurement repeatability for each frequency interval

Frequency	Accuracy (RGB)	Accuracy (raw)
[0;0.1]	2%	3%
[0.1;0.3]	4%	6%
[0.3;0.5]	7%	10%

For example, if Analyzer measures MTF(0.25) = 61%, the real MTF value is found in the interval [57;65].

The ringing value is expressed as a percentage of the step edge amplitude and is subject to the image noise and the quantization noise. Therefore, the ringing value is rounded to the closest integer.

7.10 Set up parameters influencing the measurement

The following camera settings may change the MTF measurement:

- Digital zoom function (which must normally be deactivated, unless it is the subject of the test).
- Resolution (which must be set to the highest available value in order to obtain accurate measurements).
- Autofocus (which is not perfectly repeatable, and thus will influence the MTF measurement on two separate images taken under the same conditions).
- The sharpening filter must be deactivated or set to the minimum, unless this is the subject of the test (ringing).
- Exposure correction must be deactivated (EV set to zero).
- Compression ratio should be as low as possible (TIFF format is preferred to JPEG if available).

- The noise reduction filter must be turned off, since it smoothes the image. However, if the noise level is too high (i.e., standard deviation higher than 3 at grey level 128), the numerical computation also becomes noisy.
- Special camera modes for saturation, contrast, and so on, must be deactivated.
- Sufficient lighting should be provided to ensure sufficient contrast. The white and black contrast (obtained from the grey level values as $(W - B)/(W + B)$) should be over 20%.

7.11 Measurement validity

The MTF measurement (as with the BxU measurement) is meaningful only if all the information about focal length, aperture, exposure correction, noise reduction filter, saturation or contrast is mentioned.

Giving a MTF curve with no further information is not meaningful. All the values of influencing parameters should be given. The same limitation holds for the limiting resolution or astigmatism. Thus giving the MTF curve of a 6 Mpix camera, with a 24 mm focal length at f/2.8, and with no sharpening filter is meaningful. Any information concerning exposure correction, noise reduction filter, saturation or contrast must be mentioned to validate the measurement.

7.12 Comparing two cameras

It is possible to directly compare the astigmatism and the longitudinal chromatic aberrations of two cameras.

However, comparing the MTF or the limiting resolution of two cameras is possible only if the two cameras have the same resolutions or if the results for the two cameras are expressed in an equivalent resolution, for instance, in-line pairs/mm in 24×36 mm equivalent format.

To convert frequencies as multiples of the Nyquist frequency to frequencies in lp/mm in 24×36 mm equivalent format for a sensor with dimensions WxH, use the following formula:

$$f_{24\times36}(\mathrm{lp/mm}) = f_{Nyq}\sqrt{\frac{WH}{24\times36}}$$

For images whose aspect ratio is different, the conversion takes into account only the direction which actually affects the final resolution. See Section 6.11.

Astigmatism and longitudinal chromatic aberrations can be directly compared.

7.13 Shooting

The MTF measurement uses a MTF chart

a) **Decide on the important parameters:** focal length, aperture, focusing, resolution, sharpness, digital zoom, framing.

b) **Special shooting conditions** (see also Section 6.11).

The framing must be such that:

- The chart is horizontal. The sides of the square must form an angle with the sensor rows of between 5° and 7°.
- The test target must fill the image.
- At least 7 squares are framed in the image height.
- The square sides are at least 40 or 50 pixels long, depending on the resolution. (See Section 6.11).
- Squares must appear sharp and regularly-shaped.
- The whole chart must appear uniformly sharp and must be orthofrontal to the camera.

Take all necessary precautions to avoid shaking the camera when shooting. You may want to use a cable release or to trigger the shot from a computer connected to the camera via a FireWire cable.

7.14 Sidecar parameters

See also Section 4.5.

By default, no tone curve correction is applied. To apply a correction, you must enter the following parameters in the MTF section of a sidecar file:

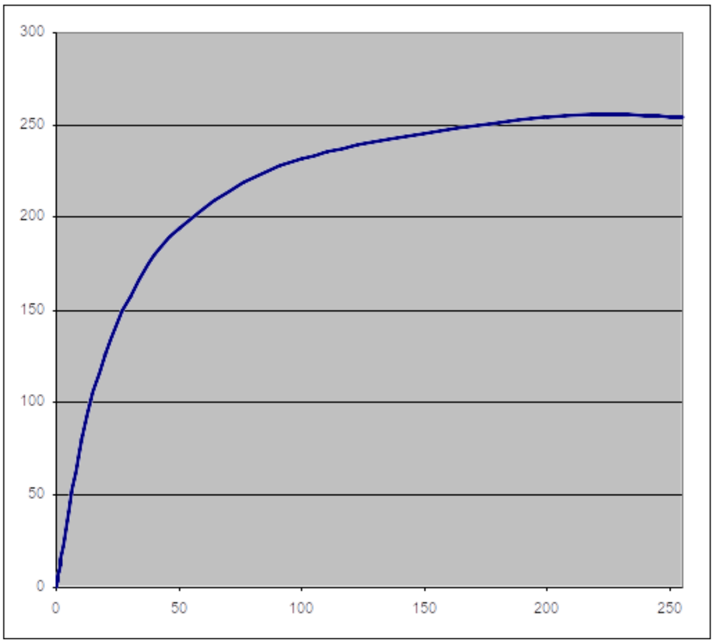
- Set **TCInvert** to “1” for a correction to be applied, otherwise to “0.”
- Set **TCGamma22** to “1” for a gamma 2.2 curve correction. If it is set to “0” and **TCInvert** is set to “1,” Analyzer will look for a tone curve specified by the user in the **Include** section.

Set the **MTFXLSFile** parameter in the **Include** section to the name of the file containing the tone curve of the camera. This file can be the result of a Analyzer measurement of Tone Curve (an exported .xls file), or it can be a text file. If it is a text file, it must contain one line per value, with the following pattern:

- “LUM_ [input value] [output value]”

Lines must be ordered with increasing or decreasing input values.

```
LUM_ 0 0
LUM_ 1 8.9609375
LUM_ 10 80.4296875
LUM_ 30 156.9765625
LUM_ 50 193.6015625
LUM_ 100 232.0078125
LUM_ 200 255
LUM_ 255 255
```



Left: text file of a transfer function ; Right: corresponding transfer function

It is also possible to use the sidecar file to define one to four positions in the image where MTF will be measured. For example with the following sidecar file MTF will be measured at only one point (x = 784; y = 584).

```
[MTF]           // MTF section
X1=784          // x coordinate of a point to compute MTF (optional)
Y1=584          // y coordinate of a point to compute MTF (optional)
TCInvert=...    // set to 1 to apply a transfert function correction
TCGamma22=...   // set to 1 to apply a transfert function correction with a gamma 2.2 curve
```

```
[Include]      // links to exported files section
MTFXLSFile=... // MTF: file of the tranfert function to correct
```

Sidecar file can also be used to select the ROI where MTF will be measured. There should always be a pair of ROI, for horizontal (H) and vertical (V) measurement. There can be one to four pairs of ROI.

```
[MTF_ROI_1_H] // first H ROI
Left=1899
Right=2140
Top=568
Bottom=771

[MTF_ROI_1_V] // first V ROI
Left=2037
Right=2259
Top=638
Bottom=988

[MTF_ROI_2_H] // second H ROI
Left=...
[MTF_ROI_2_V] // second V ROI
Left=...
```

8 – RADMTF: MTF on a radial MTF chart

8.1 Introduction

Camera phone Image Quality (CPIQ) is a set of standards for mobile phone camera quality measurements initially developed by the International Imaging Industry Association (I3A) and taken over by the IEEE (Institute of Electrical and Electronics Engineers) in 2012 (http://grouper.ieee.org/groups/1858/).

CPIQ recently released a new MTF standard, "Camera phone Image Quality – Phase 3: Acutance – Spatial Frequency Response." This measurement uses a chart with low-contrast slanted edges similar to those described in ISO 16067-1, and a slanted edge algorithm that allows angles other than 0° and 90° for tangential and sagittal measurements.

This measurement is similar to the Analyzer standard MTF measurement in most points, e.g., definitions, influencing factors, accuracy, and influencing parameters (described in Section 7 MTF: Modulation Transfer Function). This section focuses on the particularities of the MTF measurement on the radial chart as defined by the standard.

8.2 Measurement on the radial chart (CPIQ SFR chart)

The standard defines a chart with sagittal and tangential transitions, and a new protocol to compute the MTF on a slanted edge from any scanning direction.

The measurement algorithm used by Analyzer follows the various operations described in the standard.

8.2.1 Luminance channel

As written in the standard, the luminance channel is measured. The luminance signal is given by the Y channel of the CIE 1931 XYZ color space. Analyzer also returns measurement results for red, green, and blue channels. On raw images, no luminance channel is computed, and results in the field are given for the green channel instead.

8.2.2 Chart MTF calibration

The standard requires the calibration of the chart MTF.

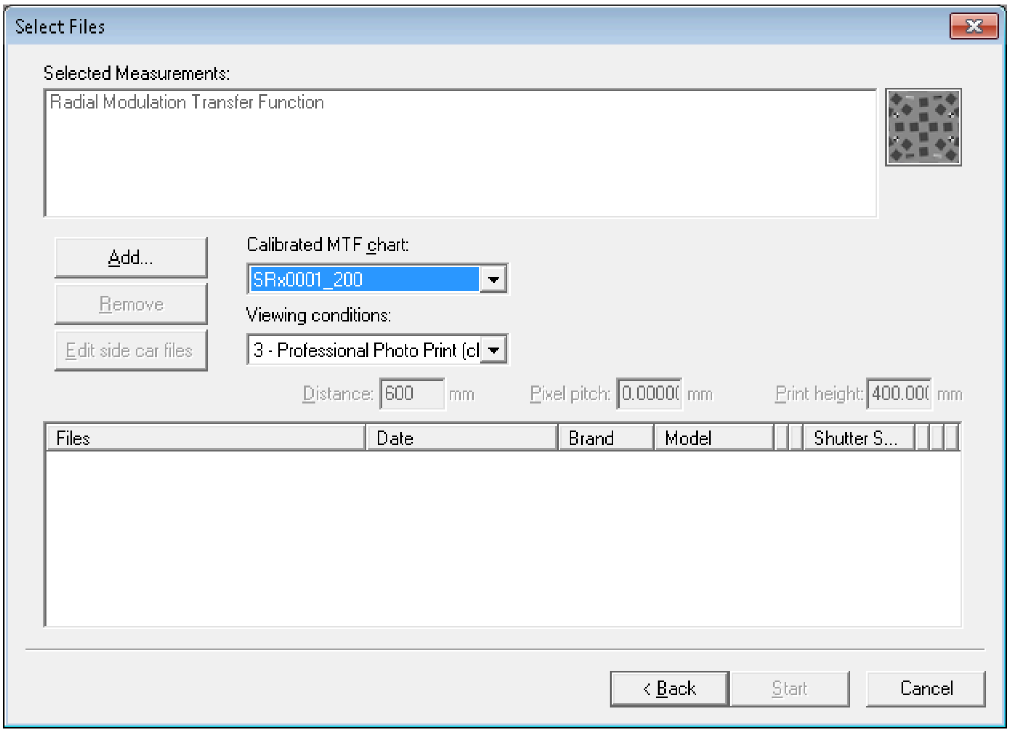
DXOMARK IMAGE LABS has measured the MTF of the printed charts. Analyzer computes the distance between the camera and the chart, and corrects the MTF.

As there are two sizes for the CPIQ SFR chart, you must indicate which one to use for the measurement when selecting the input image files. The choice of the target depends on the resolution of the sensor, and the maximum possible sensor resolution is specified by the standard (12 Mpix for the SRx0002, 24 Mpix for the SRx0001). This specification is very narrow, and it is possible to use these charts with sensors with higher resolutions (up to 24 Mpix for the SRx0002, 48 Mpix for the SRx0001).

The table below gives the contrast on the chart at Nyquist/2, depending on the resolution of the sensor. Correcting a chart attenuation of 40% (60% contrast) increases inaccuracy from 5 points of MTF to 8, which is still acceptable in most cases.

	SRx0001	SRx0002
12 Mpix	86%	75%
24 Mpix	75%	60%
48 Mpix	60%	–

The reference name of the chart is printed on it (i.e., SRU0001_200 or SRU0002_140).



Selection of the radial chart subtype (SRx0001_200 or SRx0002_140)

8.2.3 Gamma correction

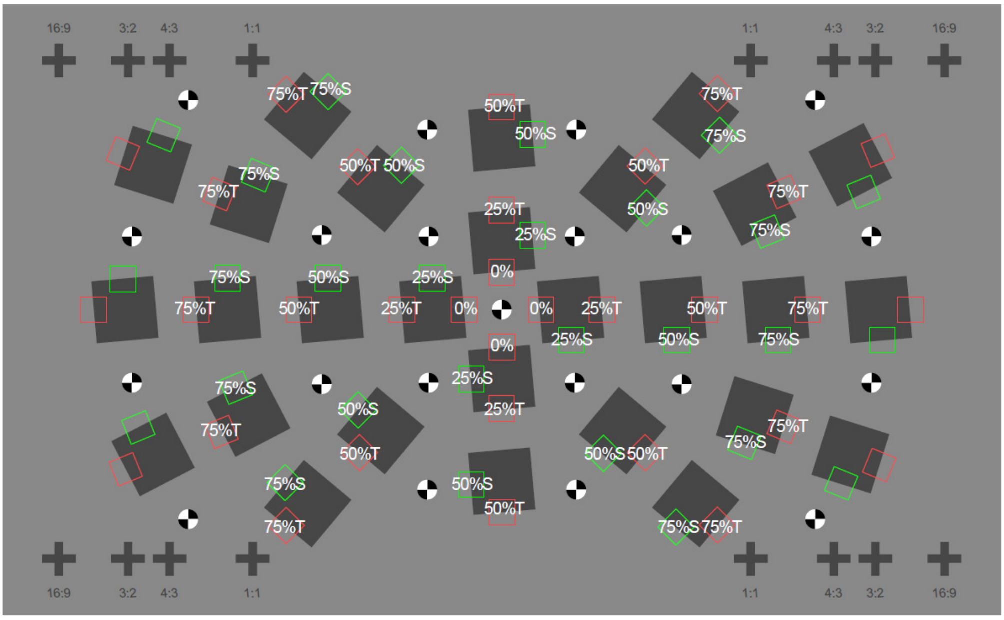
The image must be linearized before computing the MTF on slanted edges. As the slanted edges are low contrast, the linearization implied by the conversion from RGB to CIEXYZ is sufficient to obtain a correctly linearized transition.

For RGB images, this linearization is applied on all channels of the input image. Raw images are considered linear and thus require no further operations.

For other MTF measurements, this linearization is not done by default, so you must activate the gamma 2.2 correction to obtain an equivalent result.

8.2.4 Total acutance number and subjective evaluation

The positions of the different regions of interest (ROI) used for the computation are shown in the chart image below, extracted from the standard document:



Radial MTF chart for cameras with higher resolution than VGA, as displayed in the standard. Green ROI are sagittal transitions, red ROI are tangential transitions

To compute the total acutance number, sagittal and tangential acutance numbers are averaged for each radius. A weighted average of all radii is then computed using the following weights:

Radius	0	25	50	75
Weight	0.3	0.25	0.25	0.2

The weighted average acutance value is then transformed to JND (Just Noticeable Difference) according to formulas 8–10 in the standard:

$$\mathrm{JND} = \frac{3.360 \times 10^{-3} - 2.336B + 164.1B^2 - 191.8B^3 + 16.32B^4}{1.00 - 0.086\,55B + 0.9680B^2 - 2.306B^3}$$

With $B = \max(0, 0.8859 - Q)$ and Q the acutance.

8.3 Measurement in raw format

The CPIQ standard does not define a protocol for measuring MTF in raw format. The subjective evaluation in JND is not adapted to this format, and so is not displayed. Measurements are done for the four channels R, Gr, B, Gb; the luminance channel is not computed.

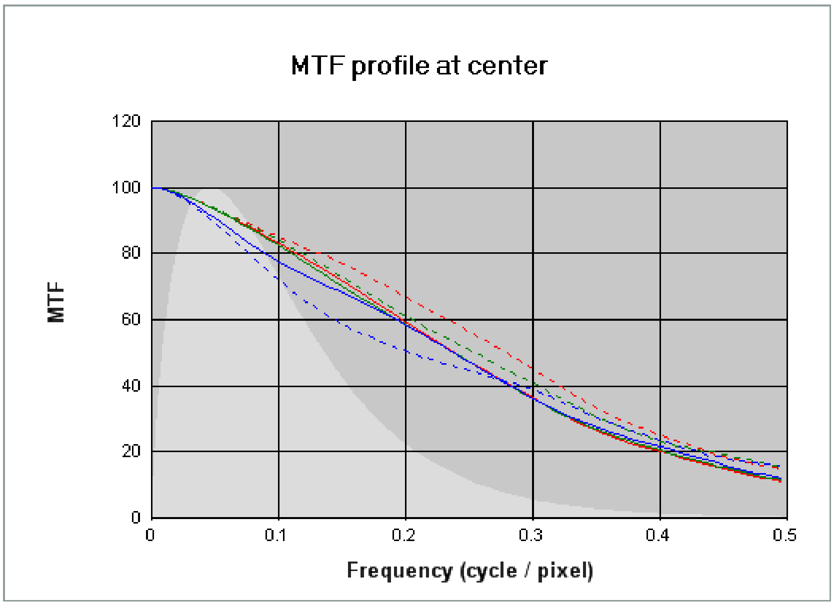
However, the MTF measurement is nonetheless also available in raw format; see the corresponding Section 7.5 in the MTF measurement section for more details.

8.4 Analyzer output

Analyzer returns the following data:

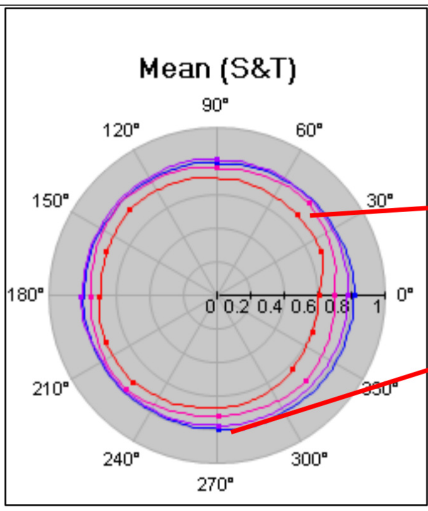
- The summary tab contains two sections:
  - The averaged total acutance number and its corresponding JND loss. This result (JND) is computed for RGB images only.
  - A summary section that displays four key values (acutance, limiting resolution, MTF50, and ringing intensity) for the luminance channel (or the green channel for raw images). The mean values for ROI at radius 0% and 75% are given. See the chart image above to see the position of the averaged transitions. Each value is the mean of the corresponding sagittal and tangential values.
- The Details tab displays the following key values for the four channels:
  - The conversion factor between cycles/pixel and cycles/degree
  - The acutance
  - The frequencies at MTF 10% and MTF 50%
  - The values of the MTF at Nyquist/2 and Nyquist/16
  - The ringing intensity as a percentage of the step edge amplitude

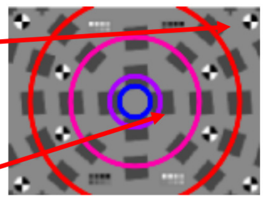
  Each value is the mean of the corresponding sagittal and tangential values for the given radius.
- The MTF graphs tab displays the MTF profiles for the different channels (R, G, B and L for RGB images, and R, Gr, Gb, B for raw images) at the four different radii of the field. The solid line is the MTF in the tangential direction and the dashed line is the MTF in the sagittal direction. The frequencies are expressed in cycle/pixel (the Nyquist frequency is 0.5 cycle/pixel). The CSF used to compute acutance is displayed in light grey.

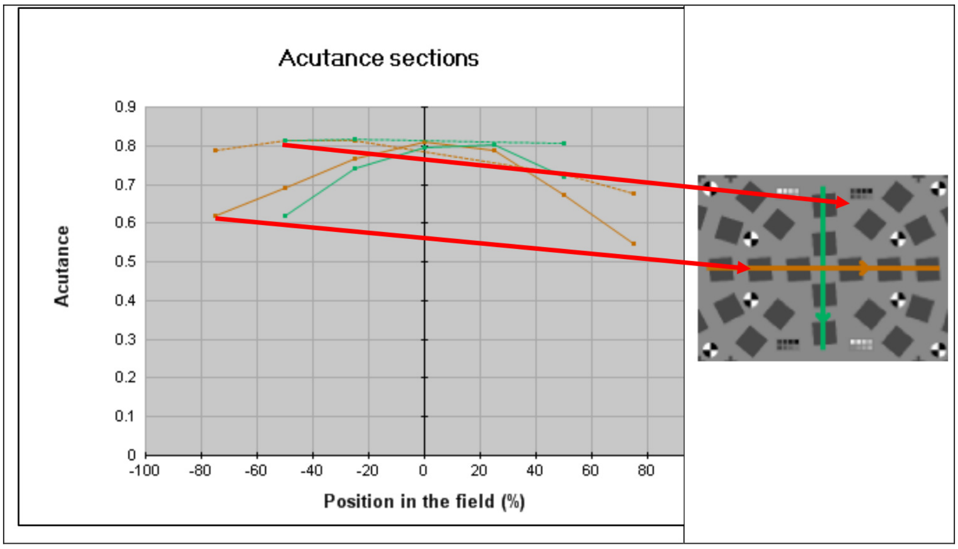


- Six additional tabs contain data for acutance, limiting resolution (MTF 10%), MTF 50%, MTF@Nyquist/2, MTF@Nyquist/16, and ringing intensity. Each one contains graphs of the key values at different positions in the field for the luminance channel (or for the green channel for raw images).

  The table below shows the two kinds of output graphs in these tabs, and the corresponding positions in the image for several measurement points in the graphs:







There are five graphs for each value:

- Four polar graphs that display the key value for each ROI. There is one graph for sagittal values, one for tangential values, one with the mean of the tangential and sagittal values, and the last one with the absolute difference for these values (astigmatism). The radius is given by the color of the graph.
- A 2D graph that displays the value on the horizontal and vertical axes.

8.5 Examples

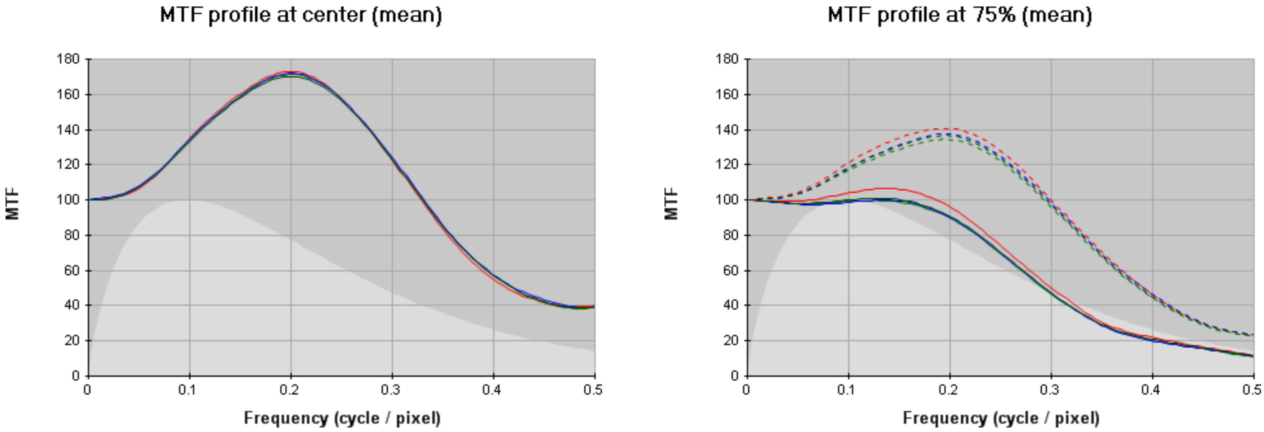
Here is an example of this measurement applied to a smartphone in 16:9 mode that produces 4 Mpix images. This camera has a very strong sharpening algorithm; the measurement results show that the sharpness of edges strongly depends on their direction.

First, the overall measured sharpness (averaged acutance) is 1.09. In the standard, the ideal value is 0.9. The measured value is thus very high, showing over-sharpening.

	Acutance	Subjective Quality (JND)
CPIQ Sharpness	1.09	-0.0

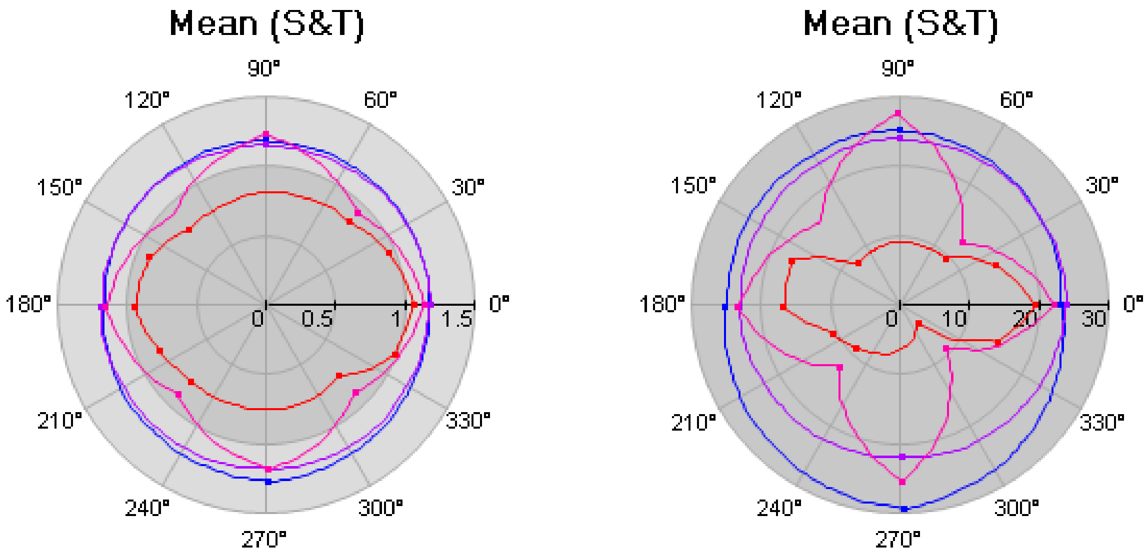
This over-sharpening is also visible in the MTF graphs, which display many values above 100% (170% at

0.2 cycle/pixel). The graphs also show a strong astigmatism in the field, with MTF tangential curves lower than the sagittal ones at radius 75%:



MTF curves in the center and at radius 75%. The plain lines are the tangential curves; the dotted lines are the sagittal curves

This indicates that the sharpening algorithm is directional, and has different effects depending on the direction of the edges. This is even more visible on the graphs in the field (below), which display star-shaped curves when the radius is higher than 50%, meaning that edges will appear sharper if their angle is 0 or 90°.



Acutance (left) and ringing (right) graphs in the field. Values are higher on the horizontal and vertical axes (0°–90°–180°–270°), which show a directional sharpening algorithm

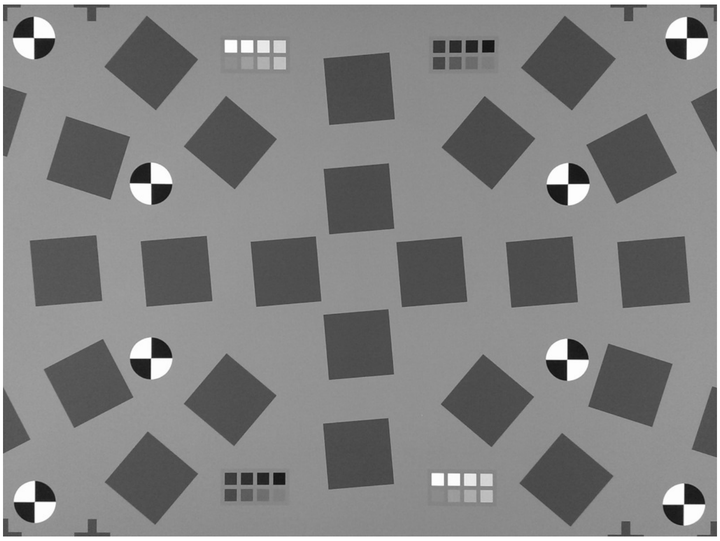
8.6 Shooting

The RADMTF measurement uses a radial MTF chart. Before you begin shooting, you will need to make decisions about the following important parameters: focal length, aperture, focusing, resolution, sharpness, and digital zoom.

8.6.1 Special shooting conditions (see also Section 6.11)

The framing must be such that:

- The test target must fill the image. Use the cross-shaped markers on the chart to select the correct framing, which depends on the W/H ratio of the sensor.



Correct framing of the radial MTF chart on a 4:3 sensor

- The illumination must be uniform over the entire chart.
- The squares must appear sharp and regularly-shaped.
- The whole chart must appear uniformly sharp and must be orthofrontal to the camera.

Take all necessary precautions to avoid shaking the camera when shooting. We recommend using a cable release, or triggering the shot from a computer connected to the camera via a FireWire cable.

8.7 Sidecar parameters

See also Section 4.5.

The following sidecar parameters can be used for the Radial MTF measurement:

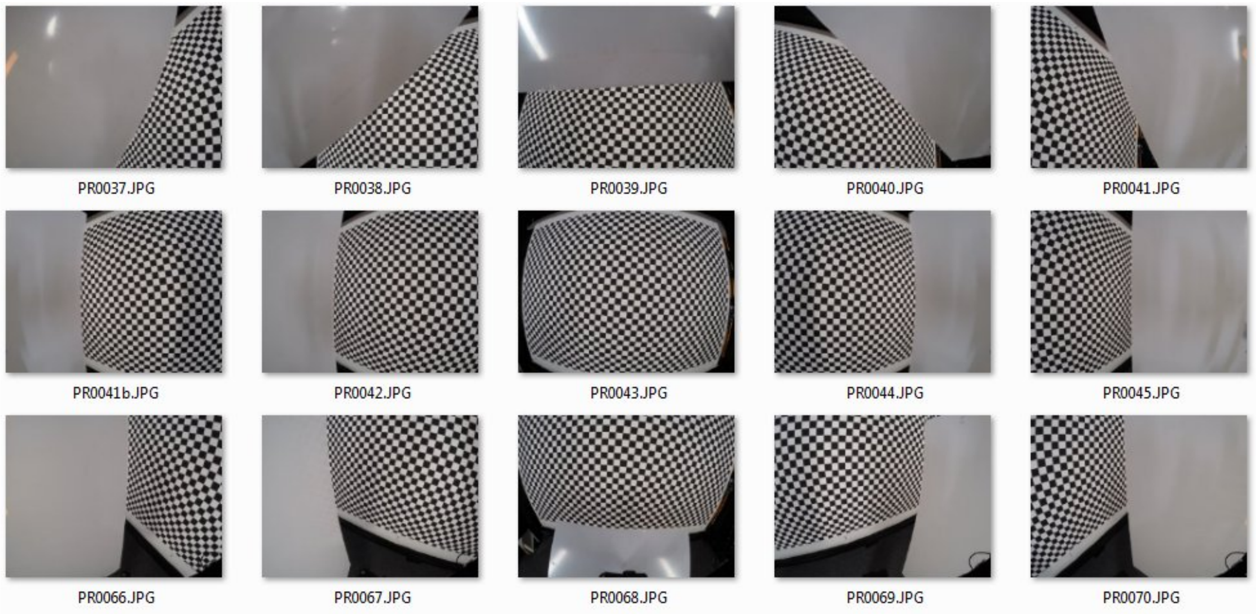
```
[Crop]      // analysis area section
Left= ...   // left position
Right= ...  // right position
Top= ...    // top position
Bottom= ... // bottom position
```

9 – FSHMTF: MTF for fisheye lenses

9.1 Introduction

The MTF measurement in the field of a fisheye lens requires a multi-image protocol to cover a field of view that may be greater than 180° for some devices.

To achieve the measurement, use a spherical panoramic head to make as many images as desired for measurement points. The equivalent of the one-image measurement for standard lenses 5×3 shots.



Fifteen images for the measurement of a fisheye lens in the field

With this method, measurements are made roughly at the same position on the chart for all measurement points in the field. Deformations due to distortion are reduced.

This is also the equivalent of measuring MTF on a spherical chart, with the distance from the chart to the sensor equivalent for all measurement points.

The protocol for using the spherical panoramic head to make Fisheye measurements is described in the protocol manual for Fisheye measurements.

9.2 Influencing factors

Several parameters influence measuring the MTF:

- The focal length of the lens.
- The aperture.
- For some lenses, the focusing distance may also impact the measurement, especially at short distances (in macro mode, for example).
- Shooting distance.

Measurement is limited by the resolution of the sensor and the field of view: on fisheye lenses with a horizontal FoV up to 130°, the minimum image height is 800 pixels. For lenses with a horizontal FoV of around 190°, the minimum image height is 1600 pixels. It is possible to make measurements on lenses with a FoV > 190°, but because of the strong deformation, you must use a high resolution to have measurable edges in the corners. The resolution required will depend on the distortion at the measurement points.

9.3 Measurement points

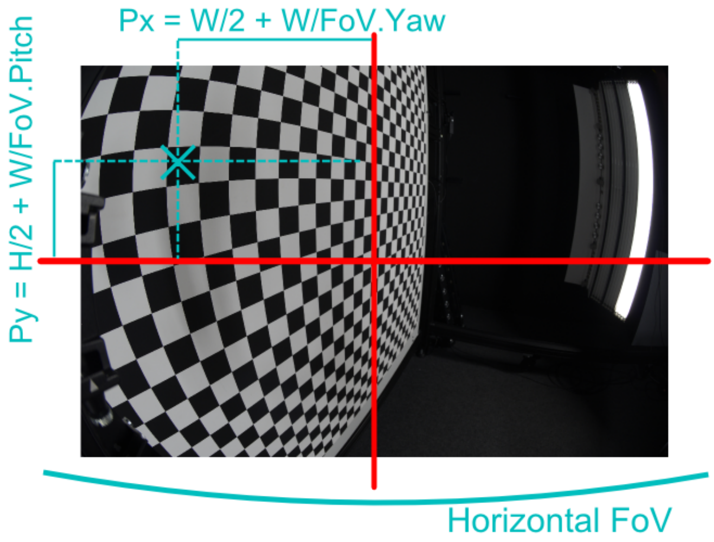
In this measurement, each measurement point is defined by an image and its yaw and pitch angles. You can freely choose the measurement points in the field. The only requirement is that there must be a measurement point in the center of the image field.

9.3.1 Position of measurement points

The position of the measurement points in an image is as follows: if the camera has a horizontal field of view *FoV*, its image size is *Width*×*Height*, and the measurement point position is given by angles *Pitch* and *Yaw*, the position of the measurement in the field is:

$$Px = \text{Width}/2 + \text{Width}/\text{FoV} \cdot \text{Yaw}$$

$$Py = \text{Height}/2 + \text{Width}/\text{FoV} \cdot \text{Pitch}$$



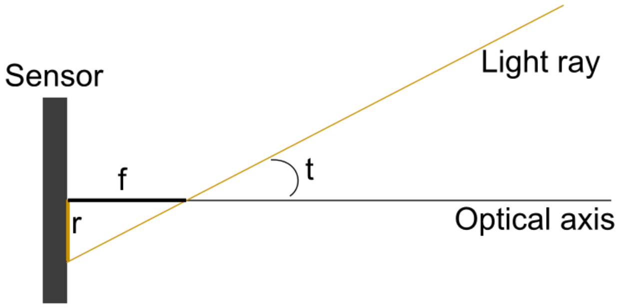
Position of a measurement point

The measurement algorithm searches for the nearest horizontal and vertical edges to the point in the image associated with the given yaw and pitch angles.

Just as you provide the values of *FoV*, *Pitch*, and *Yaw* for the measurement images, you can also fine-tune them to measure MTF at different places in the field independently of the panoramic head angle during the shot.

Note that this definition of the measurement point takes into account the mapping function of the fisheye lens. This means that the measurement point will not be exactly at the same position on the chart for all images because of the mapping function of the lens. Usual mapping functions are:

- Stereographic: $r = 2 \cdot f \cdot \tan(t/2)$
- Equidistant: $r = f \cdot t$
- Equisolid angle: $r = 2 \cdot f \cdot \sin(t/2)$
- Orthographic: $r = f \cdot \sin(t)$

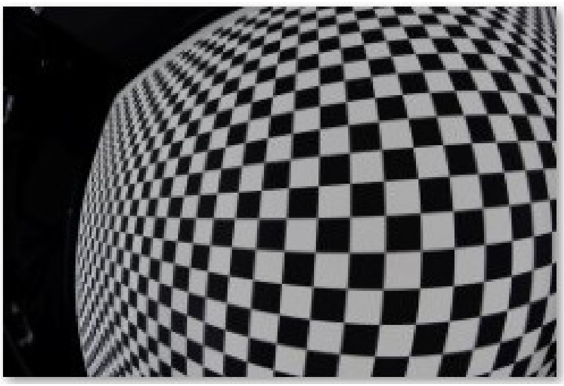


Variables used in mapping function definitions

You need to understand the mapping function of the lens to fine-tune the position of the measurement points. Otherwise the measurement point position is approximated as described above.

9.3.2 Input image order

Be aware that the input order of the images and the order of the resulting measurement points are different.



The result for image showing the head oriented top-left…

0.62	0.85	0.90	0.79	0.67
0.72	0.90	0.90	0.76	0.71
0.58	0.77	0.86	0.78	0.65

…which corresponds to the bottom-right result.

The image input reveals the orientation of the panoramic head. This means that the top-left image in the input matrix is the image in which the panoramic head is oriented to the top-left of the laboratory.

But in the results, the measurement points correspond to their position in the image.

So if the panoramic head is looking at the top left of the laboratory, the measurement point will be at the bottom right of the image. This means that the bottom-right result point corresponds to the top-left image in the input matrix.

9.3.3 Center, borders, corners…

Since you define the number of measurement points, you must also define the different averaged positions in the image.

Center the measurement point in the center of the input matrix. This is the image for which the chart plane and the sensor plane are parallel.

Corners are always the top-left, bottom-left, top-right and bottom-right measurement points.

Borders are the two extreme measurement points with pitch angle equal to zero.

Curves and values at "1/2" are for the two measurement points with pitch angles equal to zero, and the yaw angle nearest to one-third of the image field on each side.

9.4 Selection of the measurement images

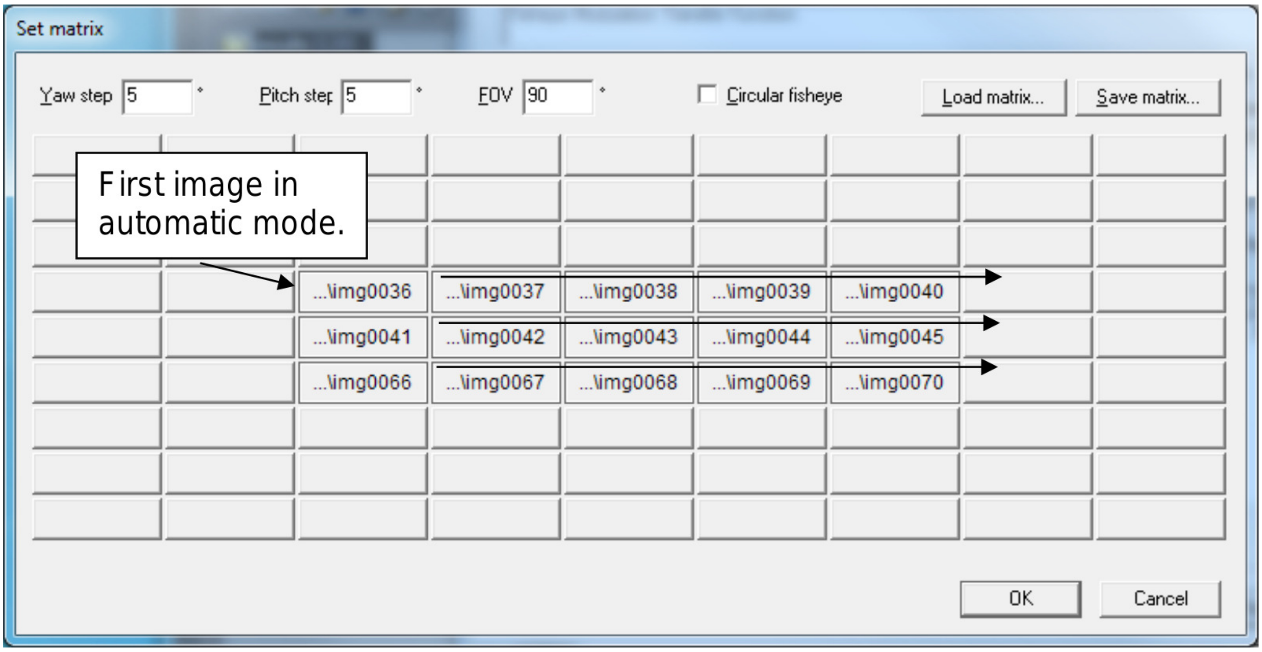
To make a Fisheye measurement, you must select the MTF chart and then "Multiple-shot source" in the measurements dialog.

The next dialog is the same as for the one-shot measurement, which lets you select the chart, the viewing conditions, the smoothing, etc. Refer to the MTF section for a detailed description of these parameters.

To select the images, either push the "Add matrix…" button or drop a selection of image files into the list at the bottom of the dialog.

In the latter case, the matrix will be automatically filled with the given files. You must name the files so that they appear in increasing alphanumeric order, sorted by lines, with the first image corresponding to the one with the panoramic head oriented to the top left. This is the order of the images in the introduction section. A dialog box will then offer a choice of possible matrix sizes.

The "Set matrix" dialog looks like this:



A least one image (the center one) must be in the matrix. Give the angular step for the X (yaw) and Y (pitch) axes of the head and the horizontal FOV of the lens.

To add or replace an image in the matrix, simply drag & drop it into the cell you wish to assign it to, or click on the cell to open the file selection dialog. To remove an image, simply right-click on it. All cells do not need to be filled, but missing cells will reduce the number of measurement points, and thus the accuracy of the measurement.

It is possible to save the matrix as a text file with an .mtx extension for later reuse. It is also possible to directly drop a matrix file into the image selection dialog.

9.5 Measurement in raw format

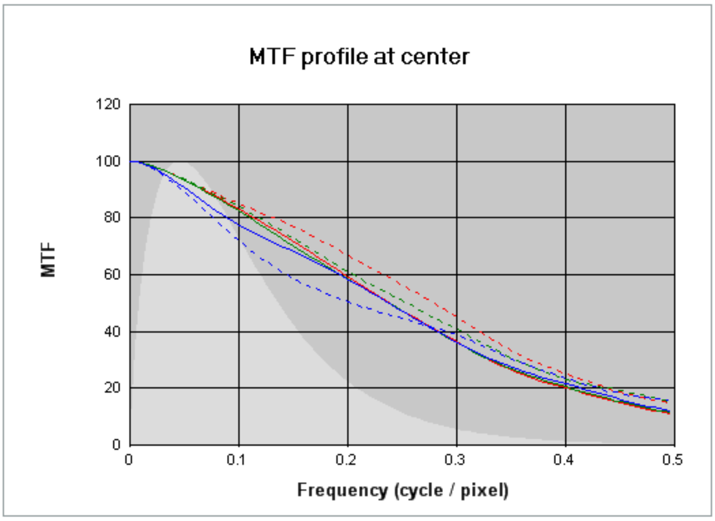
Refer to the Section 7 about MTF for a detailed explanation about the MTF measurement on raw images.

9.6 Analyzer output

Analyzer returns the following data via several tabs:

- The summary tab contains two sections:
  - A summary section that displays four key values (acutance, limiting resolution, MTF50 and ringing intensity) for the green channel. The value at the center of the image and the mean of the values at the corners are given. Each value is the mean of the corresponding vertical and horizontal values.
  - A detailed section that displays the following key values for the three channels:
    * Conversion factor between cycles/pixel and cycles/degree
    * Acutance
    * Frequencies at MTF 10% and MTF 50%
    * Values of MTF at Nyquist/2 and Nyquist/16
    * Ringing intensity as a percentage of the step edge amplitude

    A mean value is given for the corners. Each value is the mean of the corresponding vertical and horizontal values.
- The MTF graph tab displays the MTF profiles for the different channels (R, G, and B for RGB images, and R, Gr, Gb, B for raw images) at four different positions in the field. The solid line is the MTF in the horizontal direction and the dashed line is the MTF in the vertical direction. The frequencies are expressed in cycle/pixel (Nyquist frequency is 0.5 cycle/pixel). The CSF, used to compute acutance, is displayed in light grey.



- The other six tabs are for acutance, limiting resolution (MTF 10%), MTF 50%, MTF@Nyquist/2, MTF@Nyquist/16, and ringing intensity. They contain the key values at the measured positions in the field for each channel. If a measurement point failed, the corresponding cell is empty.
- The last tab displays a composite image made from the input images, with the desired measured point positions in green.

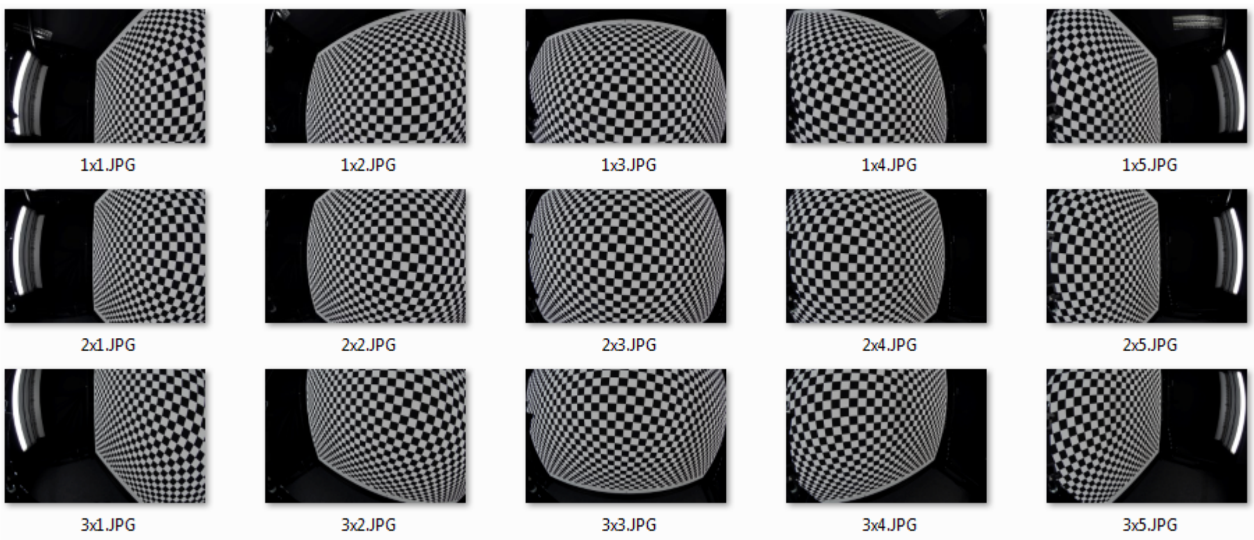
9.7 Examples

This section describes an example of the measurement of a fisheye lens in the field.

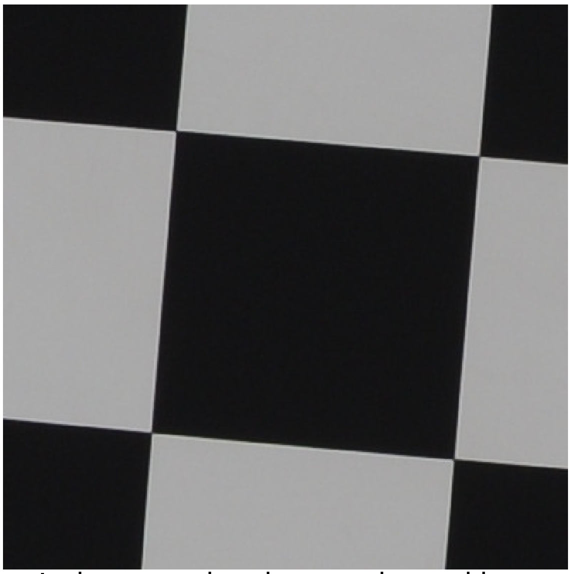
The camera is used in manual mode, with exposure and focus done on the center image, which settings are then retained for the other images. The focal length of this lens is 10.5 mm, aperture f/8, and the chosen shooting distance here is 500 mm. Note that the shooting protocol recommends a shooting distance of 35 times the focal length, but it is possible to be farther away here because the camera has great resolution, and there are no exposure difficulties in manual exposure mode.

The measurement was done on the standard 5×3 measurement points. Following the shooting protocol, the horizontal field view is measured, at 130°. The chosen yaw and pitch step angle are y = 25° and p = 30°, respectively.

The image matrix is displayed below.



Results show a great difference in sharpness between the center and the mean corners, which is clearly visible in the images:



In the center, the edges are sharp, with no chromatic aberration.

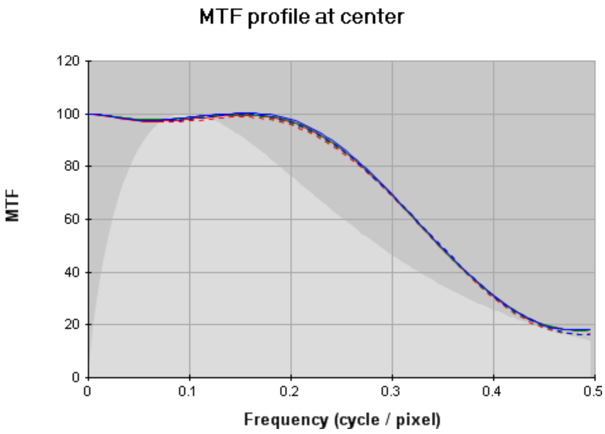
In the corners, the edges are less sharp, and chromatic aberration is visible.

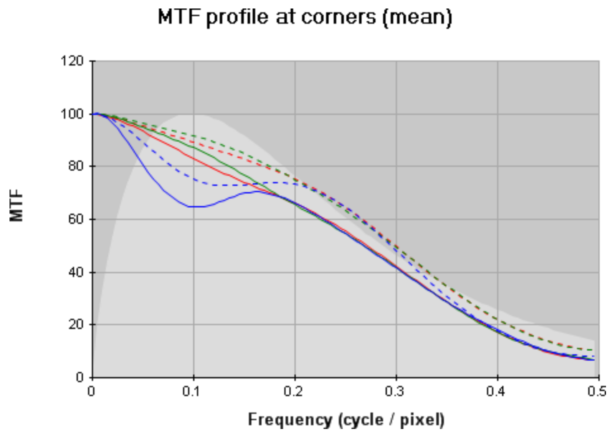
In the overview, the results are as follows:

	Acutance	Limiting resolution (MTF 10%)	MTF 50%	Ringing
		cycles/pixel (lp/mm 24x36mm eq)	cycles/pixel (lp/mm 24x36mm eq)	
Center	0.74	0.50 (66.67)	0.35 (46.00)	7%
All corners (mean)	0.54	0.40 (53.00)	0.22 (29.75)	1%

Acutance is given for "computer display" viewing conditions

The same difference is also visible in the MTF curves:





It is also possible to see the results independently for all the measurement points, and for the six evaluated metrics (acutance, limiting resolution, MTF50%, MTF at Nyquist/2, MTF at Nyquist/16, and ringing). The results for acutance in the field are displayed below.

Shooting conditions | Summary | MTF graphs | **Acutance** | Limiting resolution | MTF 50% | MTF@Nyquist/2 | MTF@Nyquist/16 | Ringing

This table contains the Horizontal and Vertical Acutance [7 - Computer Display] over the image field for all Color Channels.

	Horizontal					Vertical				
Red channel	0.51	0.65	0.76	0.68	0.48	0.57	0.62	0.60	0.60	0.58
	0.50	0.65	0.74	0.66	0.48	0.63	0.76	0.73	0.75	0.60
	0.51	0.69	0.77	0.67	0.47	0.61	0.59	0.61	0.63	0.47
Green channel	0.52	0.65	0.76	0.68	0.50	0.58	0.62	0.60	0.60	0.59
	0.50	0.65	0.74	0.66	0.50	0.64	0.76	0.74	0.76	0.61
	0.51	0.70	0.78	0.67	0.48	0.62	0.60	0.61	0.64	0.48
Blue channel	0.47	0.65	0.77	0.66	0.42	0.53	0.62	0.59	0.59	0.52
	0.47	0.65	0.75	0.64	0.44	0.63	0.76	0.74	0.76	0.60
	0.46	0.71	0.78	0.65	0.41	0.57	0.56	0.58	0.61	0.43

9.8 Measurement repeatability

The measurement repeatability is 4% on average. However, it is more accurate for low frequencies than for high frequencies.

The following table details the measurement repeatability for each frequency interval:

Frequency	Accuracy (RGB)	Accuracy (raw)
[0;0.1]	2%	3%
[0.1;0.3]	4%	6%
[0.3;0.5]	7%	10%

For example, if Analyzer measures MTF(0.25) = 61%, the real MTF value is found in the interval [57;65].

The ringing value is expressed as a percentage of the step edge amplitude and is subject to the image noise and the quantization noise. Therefore, the ringing value is rounded to the closest integer.

9.9 Setting up the parameters influencing the measurement

Refer to the MTF Section 7 for a detailed list of parameters influencing the Fisheye MTF measurement.

9.10 Measurement validity

The MTF measurement (as with the BxU measurement) is meaningful only if all the information about focal length, aperture, exposure correction, noise reduction filter, saturation, and contrast is included.

Giving a MTF curve with no further information is not meaningful. All the values of the influencing parameters should be given. The same limitation holds true for the limiting resolution or astigmatism. However, giving the MTF curve of a 6-Mpix camera with a 24 mm focal length, shooting at f/2.8 with no sharpening filter, is meaningful. You must include any information about exposure correction, noise reduction filter, saturation, and contrast to validate the measurement.

9.11 Comparing two cameras

Comparing the MTF or the limiting resolution of two cameras is possible only if the two cameras have the same resolutions or if the results for the two cameras are expressed in an equivalent resolution — for instance, in line pairs/mm in 24×36 mm-equivalent format.

To convert frequencies as multiples of the Nyquist frequency to frequencies in lp/mm in 24×36 mm equiv. format for a sensor with dimensions WxH, use the following formula:

$$f_{24\times36}(\mathrm{lp/mm}) = f_{Nyq}\sqrt{\frac{WH}{36\times24}}$$

For images whose aspect ratio is different, the conversion takes into account only the direction which actually affects the final resolution (see Section 6.11).

9.12 Shooting

The shooting procedure specific to using the spherical panoramic head for fisheye measurements is described in a separate document, “SphericalHeadProtocol.pdf”.

The document explains how to set up and use the head to shoot multiple pictures.

The center photo must respect the one-shot MTF measurement shooting conditions, so the framing must be such that:

- The chart is horizontal. The sides of the square must form an angle between 5° and 7° with the sensor rows.
- The distance between the sensor and the chart must be roughly 35× the focal length.
- The square sides are at least 40 or 50 pixels long, depending on the resolution. (See Section 5).
- Squares in the center must appear sharp and regularly shaped.

10 – TEX: Texture Preservation and Visual Noise

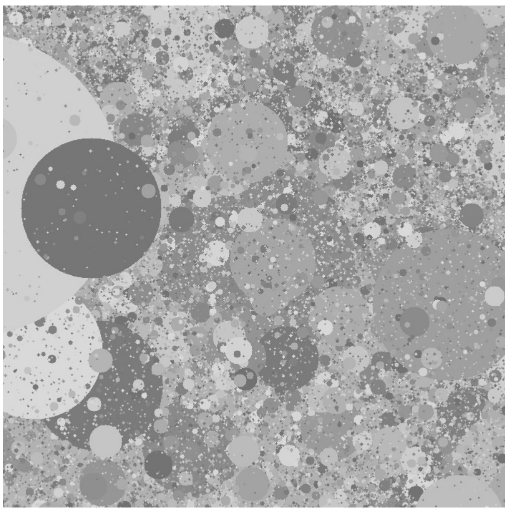
10.1 Introduction

Sharpness is an important part of the quality of an image, but although it is easy to visually determine whether an image is sharp or not, the objective measurement of sharpness is less straightforward. An image can be qualified as sharp if its edges are sharp, and if fine details are visible. But because of digital processing, these two factors are not always correlated.

The ISO standard 12233, as applied in the Analyzer's MTF measurement, measures sharpness by measuring the Spatial Frequency Response (SFR) of the camera to an edge. This method is accurate for measuring edge sharpness, but it has drawbacks when it comes to measuring fine detail preservation. Image processing algorithms can detect edges and enhance their sharpness. They also can find homogeneous areas and smooth them out to reduce noise.

As a result, an edges-only measurement is not representative of the sharpness on the whole image. It is possible to have images with sharp edges but no details.

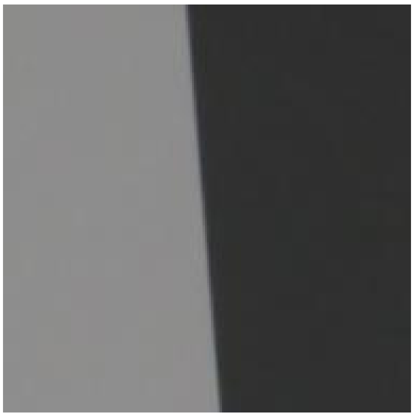
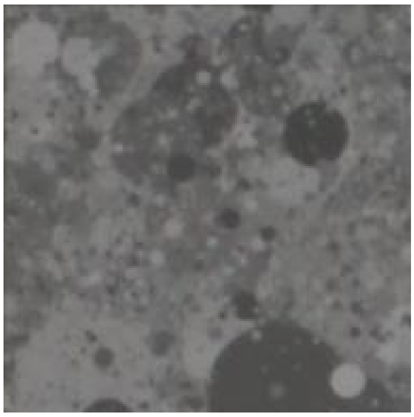
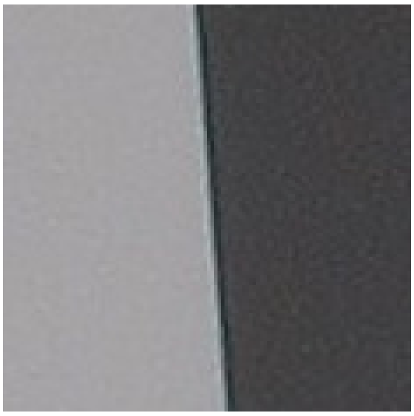
This is why a complementary measurement for sharpness is needed. This measurement should be able to qualify sharpness in terms of preservation of fine details, without being fooled by edge enhancement algorithms. This is the Texture Preservation measurement.



Dead leaves pattern

A target made of a “Dead Leaves” pattern was designed to achieve this measurement. The Dead Leaves model was introduced by Matheron.[2] It is by obtained by drawing random shapes that occlude each other in the plane, similar to Dead Leaves that have fallen from a tree. The statistics of this model follow the distribution of the same statistics in natural images. The use of this model for sharpness measurement has been described by Cao *et al.* in “Measuring texture sharpness of a digital camera” (SPIE, Vol. 7250 (2009)).

Here is an example of the effects of processing:

Camera A: DSL-R without edge enhancement		
Camera B: Bridge camera with high edge enhancement		

On camera A, sharpness seems equal for edges and texture. Many details are visible in the texture.

On camera B, edges have been digitally enhanced, and the SFR transition looks over-sharp. Ringing is also visible as an artifact of the processing. On the texture part, many details that are visible with camera A have disappeared.

[2]Matheron, G., “Random Sets and Integral Geometry,” John Wiley and Sons, New York 1975

At first sight, the images from these two cameras may appear equally sharp. A sharpness measurement on edges will indeed confirm this impression, and will even show that the second camera is sharper. But a closer examination of low-contrast textures shows that camera A has a better preservation of fine details than camera B.

The purpose of the Texture Preservation measurement is to quantify this difference.

10.2 Definitions

As with Analyzer MTF measurement, the main tool used to qualify sharpness in this measurement is the modulation transfer function (MTF).

It measures for each spatial frequency the ratio between the contrast amplitude of the input and the observed image. However, instead of measuring this MTF on an edge (and therefore characterizing edge sharpness), the system MTF is computed on a low-contrast texture.

For more details about MTF, see the MTF measurement chapter (Section 7).

From the MTF measured on the Dead Leaves image, the acutance metric is computed.

10.2.1 Acutance

Acutance is a single-value metric calculated from a MTF result. A higher value means a sharper image.

To compute this value, a contrast sensitivity function (CSF), modeling the spatial response of the human visual system, is used to weigh the values of the MTF for the different spatial frequencies.

The CSF is defined in ISO Standard 15739 for Visual Noise measurement. Its equation is:

$$\mathrm{CSF}(v) = \frac{a \cdot v^{c} \cdot e^{-b \cdot v}}{K}$$

where a = 75, b = 0.2, c = 0.8, K = 34.05 and v is in cycles/degrees. An example of CSF is given in the figure further below.

As the MTF is given in cycles/pixels, the conversion in cycles/degrees is performed by selecting, for instance, the size of the image and its viewing distance (subsequently called “viewing conditions”). When looking closer at an image, fine details are more visible, and thus more weight should be given to high spatial frequencies.

The acutance is defined by

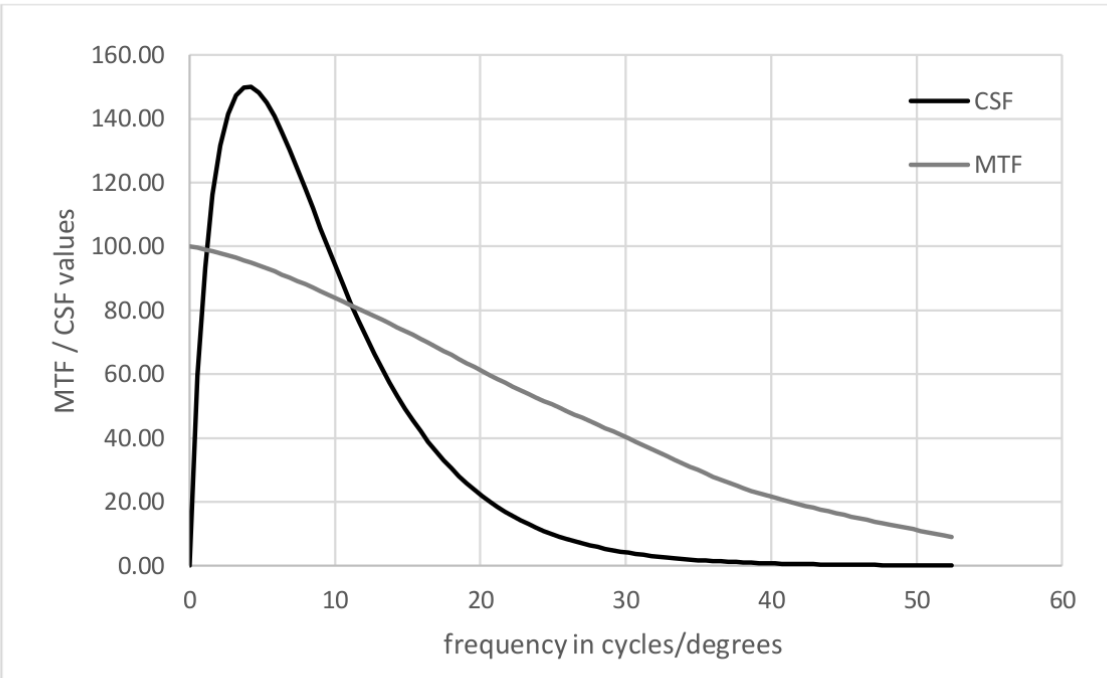
$$\text{Acutance} = \frac{A}{A_r}$$

with

$$A = \int_0^\infty \mathrm{MTF}(v) \cdot \mathrm{CSF}(v) \cdot \mathrm{d}\,v$$

$$A_r = \int_0^\infty \mathrm{CSF}(v) \cdot \mathrm{d}\,v$$

Here is the shape of the contrast sensitivity function depending on some selected viewing conditions:



CSF and MTF for a 40×60 print at 60 cm; obtained acutance is 0.73

This curve promotes a good restitution of quite low frequencies, mostly around Nyquist/4.

10.2.2 Viewing conditions

Viewing conditions must be carefully set as they impact acutance computation. Available configurations are defined in section (Viewing Conditions).

10.2.3 Visual noise

Visual noise is a metric that measures noise as perceived by end-users. From the ISO15739 standard, that specifies methods for measuring level of noise in digital cameras, are derived two Visual Noise measurements, adapted for different use cases.

The Visual Noise measurement referenced in this documentation is adapted for scenes with low dynamic range, like the Deadleaves setup. It is the base-10 logarithm of the weighted sum of the variance values for the CIELab image. These variances are obtained by taking into account the sensitivity of the human eye to different spatial frequencies under differing viewing conditions. The result of this measurement is mapped in a Just Noticeable Difference (JND) of quality loss unit.

In smartphone photography, multi-frame stacking strategies are used to render scenes with high dynamic range. The Visual Noise measurement, which is designed for flat dynamic range scenes, gives unexpected results for different luminance levels than the ones intended for.

The Visual Noise HDR measurement referenced in this documentation is adapted for scenes with low and high dynamic range, like the AF-HDR setup. It is based on the square root of the weighted sum of the L^*, a^*, b^* variances adjusted by a luminance sensitivity function. The result of the measurement in mapped in a JND of noisiness unit.

10.3 Influencing factors

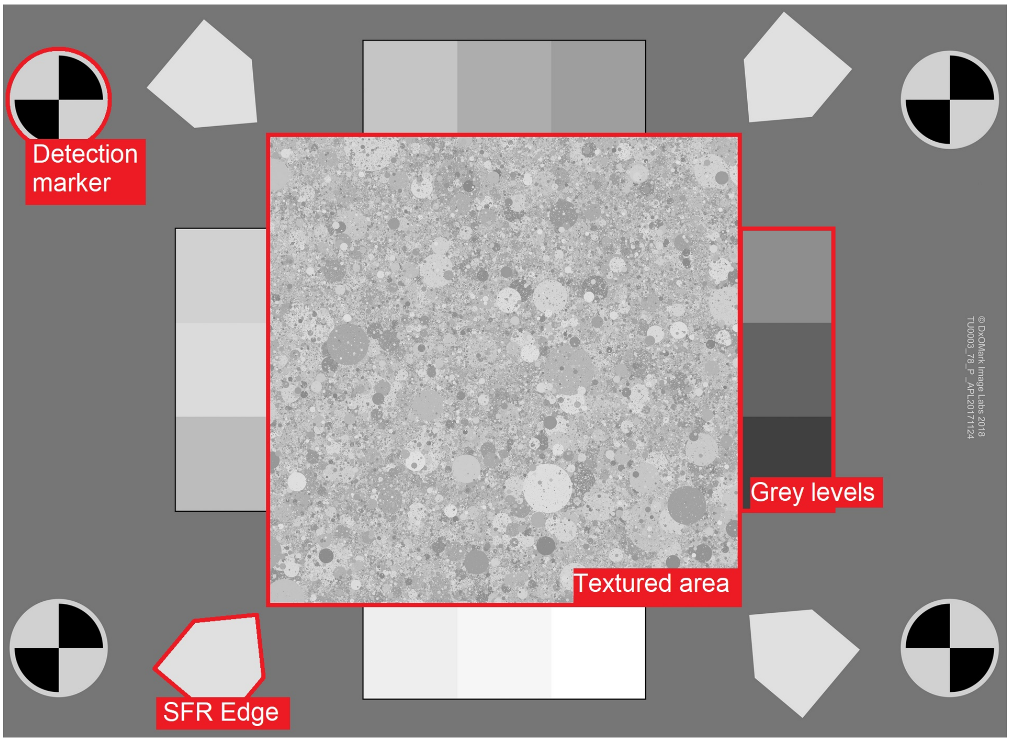
Several parameters influence the measurement of Texture Preservation:

- The focal length of the lens.

- The aperture.
- The focus (an inaccurate autofocus will influence accuracy of the measurement).
- The ISO setting.
- For some lenses, the focusing distance may also impact the measure, especially at short distances (in macro mode, for example).
- The shooting distance for some fixed focal length lenses.
- Noise reduction settings.

10.4 The measurement of Texture Preservation

The Texture Preservation target is designed as follows:



Texture Preservation target

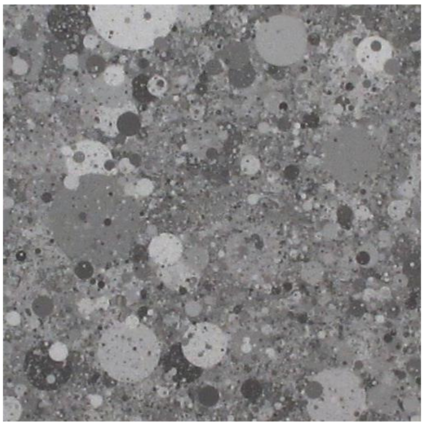
It contains four elements:

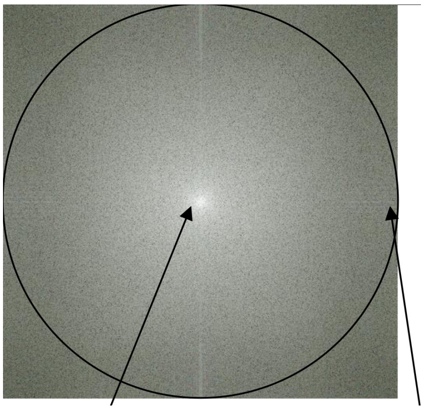
- The texture patch for measuring the texture MTF.
- Four detection markers for automatically detecting the target.
- Four patches with slanted edges for computing a SFR to compare with the texture MTF.
- Twelve grey-level patches for inverting the camera's tone curve (or OECF) and for computing the texture MTF in linear color space.

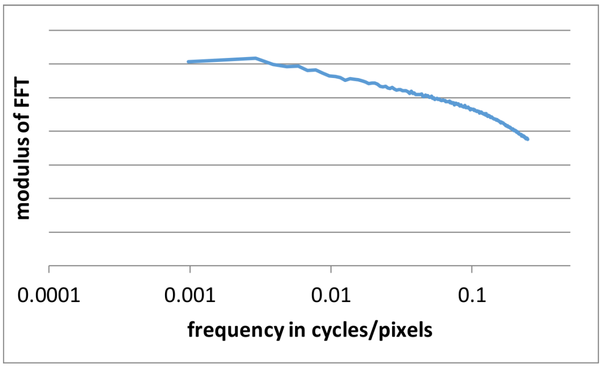
The main steps of the measurement are described below:

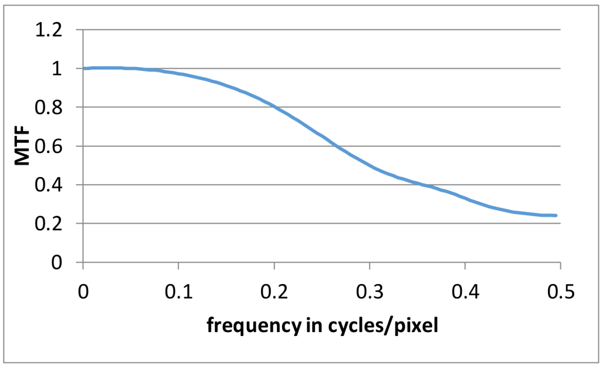
1. The position of the target is automatically detected. If the detection fails (for instance, for very noisy images), the coordinates of the markers can be given in a sidecar file.
2. Grey values on the four SFR patches are used to estimate vignetting and bad lighting. If necessary, a correction is applied.
3. An estimation of the camera's tone curve (or OECF) is computed using the grey patches on the target. This is used to linearize the grey levels of the image so as to compare images with different exposures.
4. Horizontal and vertical SFR are computed on the SFR edges.
5. The fast Fourier transform (FFT) of the texture patch is computed. The result is an image that contains the FFT 2D of the input crop.
6. The profile of the FFT 2D image is computed, and then normalized by the Fourier transform of the ground truth to obtain a MTF.
7. Several values are computed from the MTF, such as acutance.

Here is shown the transformation of the texture crop in a MTF curve:

A crop of the textured area is selected. To allow FFT 2D computation, crop is a square of size. Its size cannot be larger than one third of image's height.	

The FFT 2D of the texture crop is then computed	

Computation of the FFT 2D profile	

Normalization and smoothing of the profile into a MTF	

The normalization of the FFT profile in a MTF has been described by Cao *et al.* in "Dead leaves model for measuring texture quality on a digital camera" (SPIE, Vol. 7537 (2010)). Noise is measured on the OECF patches around the texture area and used to remove the influence of noise in the MTF. This procedure has been described by J. McElvain et al. in "Texture-based measurement of spatial frequency response using the Dead Leaves target: extensions, and application to real camera systems" (SPIE vol 7537, 2010).

Here are the metrics computed by the measurement; MTFs are given in terms of attenuation for a frequency in cycle/pixels.

10.4.1 Texture MTF including noise

MTF computed on the dead leaves crop, without noise correction. Thus the MTF may be overestimated if the image is very noisy.

10.4.2 Texture MTF

MTF computed on the dead leaves crop, with noise removed from the power spectrum of the textured patch.

10.4.3 Texture MTF clipped

MTF computed on the dead leaves crop and clipped to remove values above 1. This limits the effect of over-sharpening on the texture metric. Noise has also been removed from the power spectrum of the texture patch. If you select the OECF standard of -18%, the measurement algorithm applies a gamma 2.2 function to linearize the input image.

10.4.4 Edge MTF (or SFR)

It is the mean of the MTF computed on the edge patches. These MTF are computed horizontally and vertically, as in the Analyzer MTF measurement.

10.4.5 Acutance

Acutance is computed for four MTF:

- Texture MTF
- Texture MTF including noise
- Texture MTF clipped

- Edge MTF (SFR)

"Acutance loss" is the difference between SFR and texture MTF, with noise removed and not clipped, measured on the luminance channel. Texture Preservation is good if sharpness values are similar for edges and texture.

10.4.6 Visual noise

Visual Noise is measured on the uniform grey patches around the textured area.

The measurement is built with the following steps:

1. Input image linearization, by OECF inversion and exposure correction
2. Conversion from linear RGB into opponent color space AC_1C_2. RGB primaries are read from input image if an ICC profile is present in Exif metadata. sRGB primaries are used otherwise.
3. Spatial filtering in the frequency domain (2D FFT), using Johnson & Fairchild type CSF, display/printer MTf and high pass filter
4. Transformation of the spatially-filtered AC_1C_2 data into CIELab 1976 color space
5. Determination of L^*, a^*, b^* variance and covariance values
6. Final Visual Noise metric computation

The DXOMARK IMAGE LABS Visual Noise is the base-10 logarithm of the weighted sum of the L^*, a^*, b^* variances. The result of this measurement is mapped in a JND of quality loss unit.

$$\Omega = K \cdot \log_{10}\left[1 + \sigma^2(L^*) + \sigma^2(a^*) + \sigma^2(b^*)\right]$$

The K-factor is set at 6.87.

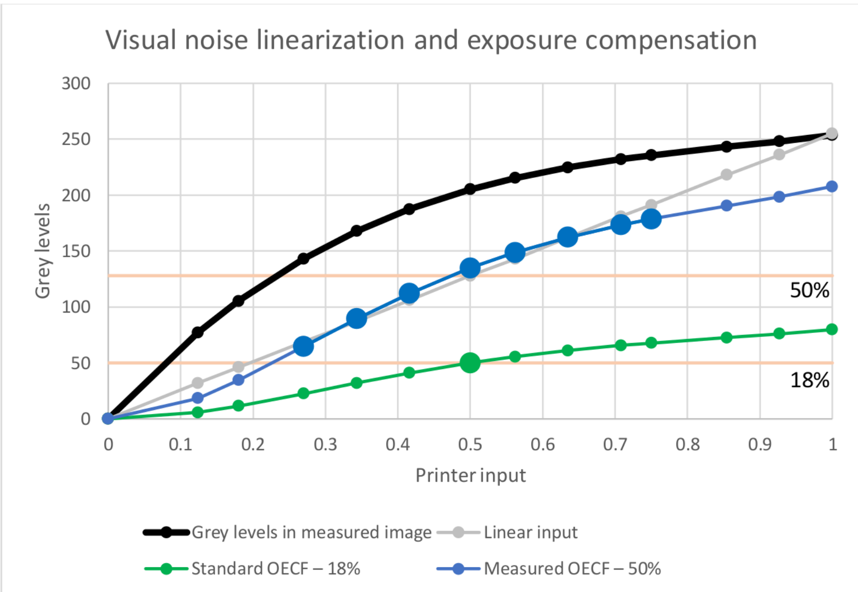
In the "Select Files" dialog, you can choose between two linearization methods:

- **Measured OECF – 50%**
  This is the recommended linearization method. It is also the only one used for the Texture measurement and it is a straightforward inversion of the opto-electronic conversion function (OECF). The

measurement algorithm assumes the OECF to be in the form $y = \alpha x^{\gamma}$, with α and γ to be determined. Notice that despite the continuous model, the OECF will be a function that maps integers into integers. The parameters are chosen to minimize the mean square error between the average patch values measured in the image linearized with these parameters and the known patch reflectances. This estimated OECF is then reversed to obtain a linear image.

- **Standard OECF – 18%**
  This is a now deprecated linearization method, included for compatibility with legacy workflows. It follows the same model $y = \alpha x^{\gamma}$, with γ assumed constant and equal to 2.2, while α is determined in such a way that the 18 % reflectance uniform patch is as close as possible to $L^* = 50$. Notice that it is not always possible for it to be exactly equal to 50, since the function can only map integers onto integers. With this algorithm, the L^* values will generally follow the reflectance quite closely around $L^* = 50$, but they may diverge considerably for high or low values. For these reasons, we recommend that this algorithm is not used, except for some very specific applications.

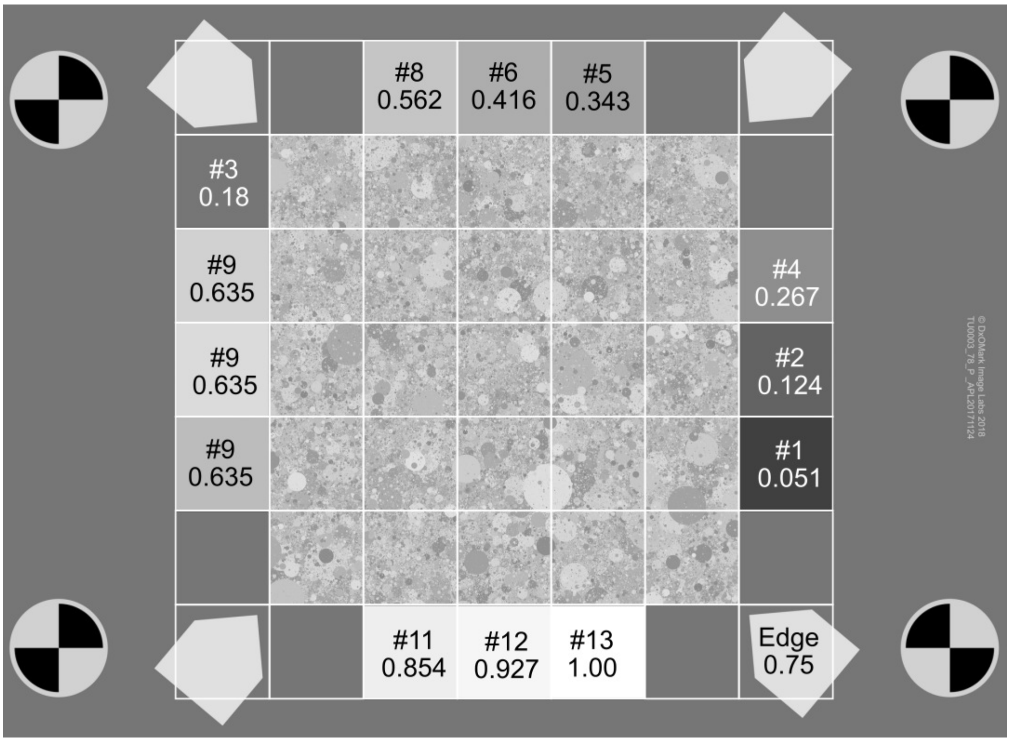
The graph below displays an example of an image grey levels before and after linearization using the two methods. Larger points are those that have been used to estimate the parameters of the OECF (α and γ for method one, only α for method two).



The noise is given for CIELab $L^* = 50$, linearly interpolated from the two closest uniform grey patches to lightness value $L^* = 50$.

Default relative reflectance[3] values of the patches, sorted from the darkest to the brightest (white of the paper), are:

Patch #1	Patch #2	Patch #3	Patch #4	Patch #5	Patch #6	Patch #7	Patch #8	Patch #9	Patch #10	Patch Edge	Patch #11	Patch #12	Patch #13
0.051	0.124	0.18	0.27	0.343	0.416	0.5	0.562	0635	0.708	0.75	0.854	0.927	1.00



10.4.7 Visual Noise HDR

Visual Noise HDR is measured on the uniform grey patches around the textured area.[4]

The measurement is built with the following steps:

1. Input image linearization, by gamma inversion.

[3] The reflectance values indicated are relative to the White of the paper (Patch #13)
[4] Visual Noise HDR measurement is only available through the Workflow Manager.

2. Conversion from linear RGB into opponent color space AC_1C_2. RGB primaries are read from input image if an ICC profile is present in Exif metadata. sRGB primaries are used otherwise.
3. Spatial filtering in the frequency domain (2D FFT), using normalized CSF, display/printer MTF and high-pass filter.
4. Transformation of the spatially-filtered AC_1C_2 data into CIELab 1976 color space.
5. Determination of *L**, *a**, *b** variance and covariance values and *L** mean value.
6. Final visual noise metric computation.

The DXOMARK IMAGE LABS Visual Noise HDR is based on the square root of the weighted sum of the *L**, *a**, *b** variances adjusted by a luminance sensitivity function.

$$V = S_L(L^*)\sqrt{\sigma^2(L^*) + w_{a^*}\sigma^2(a^*) + w_{b^*}\sigma^2(b^*)}$$

with w_a = 0.04977 and w_b = 0.27905 , and where $S_L(L^*)$ is the luminance sensitivity function.

The coefficient w_a and w_b have been found through optimization to fit a perceptual JND of noisiness dataset. The DXOMARK JND of noisiness dataset is a ruler of 93 patches annotated by increasing level of perceived noisiness on a JND scale. The dataset was built during a perceptual experiment according to ISO-20462 methodology. 25 experts and 6 non experts were asked to compare noisy grey patches in a controlled environment. The patches used were extracted from real images of the AF-HDR setup, in several conditions (HDR and non HDR), taken with various smartphones. This results in an annotated ruler interpretable in terms of Just Noticeable Difference value. A JND of 0 means that noise in not perceivable. A difference of 1 JND means that 75% of people will report a difference in terms of perceived noise.

The luminance sensitivity function used in the Visual Noise HDR measurement is defined as follows:

$$S_L(L^*) = a + bL^* + cL^{*2} + dL^{*3}$$

with

- a = 0.068641
- b = 0.048546862
- c = -7.786422 E-4

- d = 3.5483275 E-6

Results are mapped in a JND of noisiness unit:

$$\Omega = \frac{w_1 V^3}{1 + w_2 V^{\frac{8}{3}}}$$

with w_1 = 323.39010 and w_2 = 45.91672

The noise is given for all patches of the chart.

10.5 Measurement in raw format

The main purpose of this measurement is to qualify the impact of image processing algorithms on sharpness. Thus it makes sense for 8-bit RGB images only, and measurement on raw images is not available.

10.6 Analyzer output

Analyzer returns the following data [5]:

- The shooting conditions tab contains general shooting condition values, and also the selected viewing conditions:

Image format	RGB
Image depth	8 bits/channel
Width	4256 pixels
Height	2832 pixels
Date	11/02/2016 - 11:11:52
Color space	sRGB
Description	03 - Professional Photo Print (closer)
Distance	600 mm
Print height	400 mm
Use MTF display	Yes
Exposure compensation	Standard OECF – 18%

Brand	NIKON CORPORATION
Model	NIKON D3S
Aperture	5.6
Focal length	50.00 mm
Shutter speed	50.00 ms
ISO speed	200
Ev bias	-0.67
White balance	Auto white balance

[5] Analyzer does not return any data for Visual Noise HDR

- The summary tab contains two sections:
  - A summary section that contains acutance values for the four MTF measurements (texture, texture including noise, texture clipped, and SFR). Acutance loss is the difference between Edge acutance and Texture acutance. Acutance is given for red, green, blue, and luminance channels. The pixels/degree coefficient, determined by the viewing conditions, is also given.

		Acutance loss
Y	Luminance Channel	0.000

		Texture acutance	Texture acutance including noise	Texture acutance clipped	Edge acutance (SFR)
R	Red Channel	0.872	0.873	0.843	0.872
G	Green Channel	0.892	0.894	0.853	0.884
B	Blue Channel	0.879	0.880	0.848	0.880
Y	Luminance Channel	0.885	0.886	0.851	0.881

The Visual Noise is given with $L^*a^*b^*$ variance and covariances based on a linearly-interpolated estimate for an L^* mean of 50, depending on the selected viewing conditions.

Estimated visual noise at 50 L* Mean for viewing conditions [6 - Custom Print]

Visual noise	Variance			Covariance		
	L*	a*	b*	L*a*	L*b*	a*b*
0.849	0.096	0.134	0.110	-0.027	0.009	-0.088

  - A detailed section that displays key values for the four channels on three MTF graphs (texture, texture including noise, and SFR). These values are the spatial frequencies at MTF 50%, and the values of the MTF at Nyquist/2.

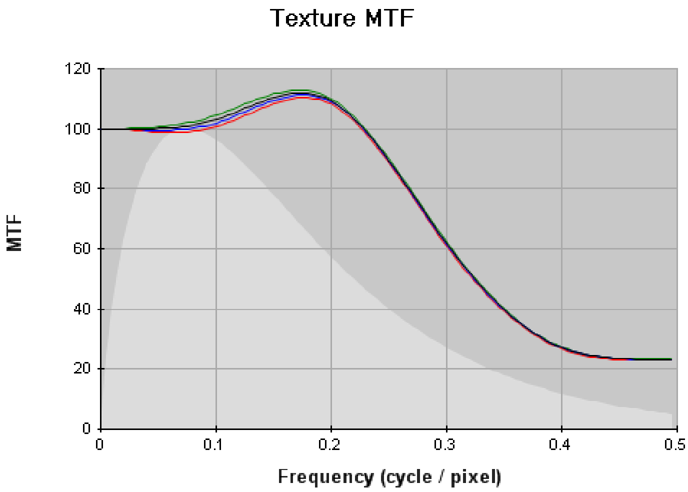
This table contains the values of the MTF, expressed in cycles/pixel and in lp/mm (24x36mm eq)

		MTF 50%		
		Texture	Texture including Noise	SFR
R	Red Channel	0.33 (38.39)	0.33 (38.39)	0.33 (38.98)
G	Green Channel	0.33 (38.98)	0.33 (38.98)	0.34 (39.57)
B	Blue Channel	0.33 (38.39)	0.33 (38.39)	0.33 (38.98)
Y	Luminance Channel	0.33 (38.39)	0.33 (38.98)	0.33 (38.98)

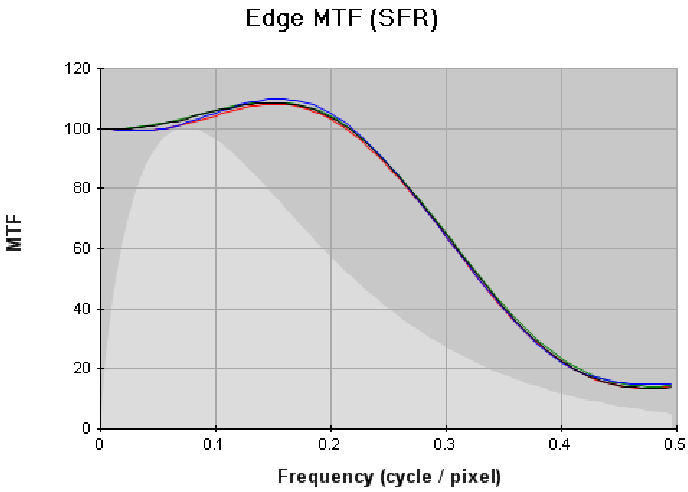
This table contains the values of the MTF (in %) at Nyquist/2 (or 29.53 lp/mm (24x36mm eq))

		MTF @ Nyquist/2		
		Texture	Texture including Noise	SFR
R	Red Channel	89%	89%	87%
G	Green Channel	90%	90%	88%
B	Blue Channel	89%	89%	88%
Y	Luminance Channel	90%	90%	88%

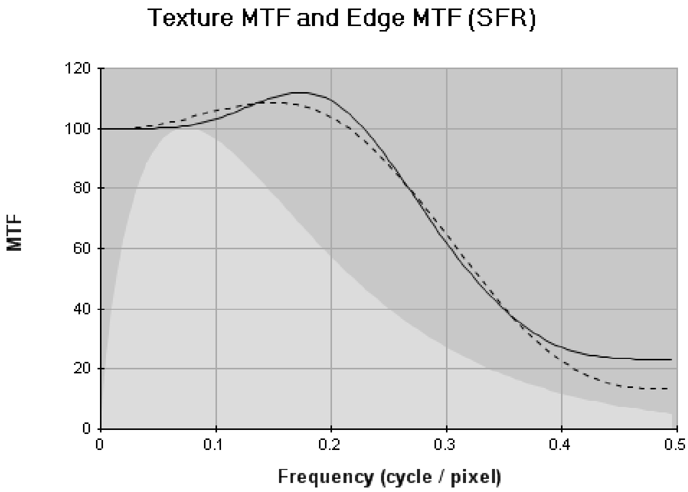
- The MTF and MTF including Noise tabs each contain three graphs:
  - The MTF graph for texture, with or without noise depending on the selected tab. All color channels are displayed on this graph.



  - The MTF graph for edges. Each color channel is printed. This graph is the same on both tabs.



– The comparison of Texture MTF graph and Edge MTF graph, for green channel only. Depending on the selected tab, texture MTF will or will not include noise.



The CSF is also represented as a filled light grey curve. It changes with the viewing conditions.

- The Visual Noise tab displays detailed visual noise results for each uniform grey patch, and an estimate of visual noise for a CIELab L^* value at 50, obtained by linear interpolation.
- The CPIQ texture tab displays results of texture blur following CPIQ standards. See the CPIQ section for a description of these results.

10.7 Running Visual Noise HDR measurements with Workflow Manager

The Visual Noise HDR measurement can be run using Workflow Manager. The VisualNoiseHDRMeasure supports a wide variety of input parameters. For more information about these inputs, please read the inline help of the function:

```
from dxomark.core.measure import VisualNoiseHDRMeasure
help(VisualNoiseHDRMeasure.Inputs)
```

The Visual Noise HDR measurement can be run like this:

```
# Import the needed modules
from dxomark.core.measure import VisualNoiseHDRMeasure
from dxomark.core.measure import ViewingConditionType
from dxomark.corewrappers import Measure

# Choose image to measure
img = r"C:\Path\To\AFHDRImage"

# Coordinates of the grey patches
# [[top left corner], [bottom right corner]]
# (can be obtained through TextureMeasure in the WorkflowManager)
posPatches = [
    [[2163, 2091], [2347, 2276]],
    [[2164, 1884], [2347, 2068]],
    [[919, 1463], [1104, 1649]],
    [[2165, 1677], [2348, 1861]],
    [[1753, 1261], [1937, 1445]],
    [[1545, 1259], [1730, 1444]],
    [[915, 2088], [1101, 2275]],
    [[1337, 1258], [1522, 1442]],
    [[917, 1671], [1103, 1857]],
    [[916, 1880], [1102, 2066]],
    [[1331, 2506], [1516, 2692]],
    [[1539, 2506], [1724, 2692]],
    [[1747, 2505], [1932, 2691]]]

# Set viewing conditions
viewingConditions = Measure(Measure.MODULE.ViewingConditions)
viewingConditions.inputs = {
    "GetAllCSF": True,
    "NbPointsCSF": 150,
    "NormalizeCSF": True,
    "ViewingConditions": ViewingConditionType.CustomPrint(distance=1000, height=1200)
}
viewingConditionsResults = viewingConditions.execute(img).outputs

# Compute the Visual Noise HDR
obj = VisualNoiseHDRMeasure()
obj.Inputs({
    ImgObj": img,
    "PosPatches": posPatches
    "PixelsDegrees": viewingConditionsResults["PixelsToDegrees"],
    "MTF": viewingConditionsResults["MTFPrinter"],
```

```
    "AllCSF": viewingConditionsResults["AllCSF"],
})
obj.Process()
out = obj.Outputs()
```

10.7.1 Workflow Manager output

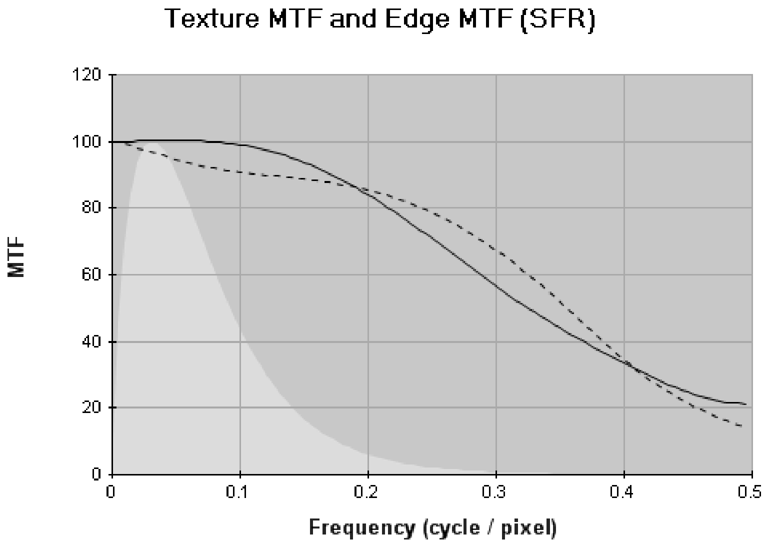
The output of the Visual Noise HDR measurement available in the Workflow Manager has the following structure:

- MeanA: Average CIE-*a** level for each patch
- MeanB: Average CIE-*b** level for each patch
- MeanL: Average CIE-*L** levle for each patch
- VarA: Variance of the CIE-*a** level for each patch
- VarB: Variance of the CIE-*b** level for each patch
- VarL: Variance of the CIE-*L** level for each patch
- ChromaticityRatio: Ratio of the visual noise chromatic component compared to the total visual noise
- LabImages: *L*a*b** images if the input option ReturnLabImages is True
- VisualNoise: Visual noise metric, before jnd mapping applied
- VisualNoiseJnd: Visual noise metric in JND unit

10.8 Examples

Here are several examples of results obtained with the Texture Preservation measurement. The selected viewing condition is "Professional Photo Print (closer)."

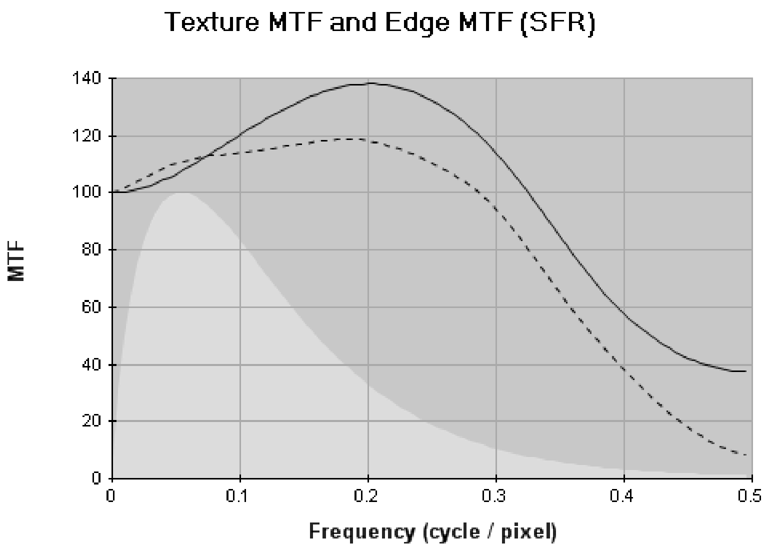
The first example is a good camera without a sharpness enhancement algorithm enabled. Because no sharpness has been added by the body, it may look a bit soft compared to post-processed images.



MTF curves without sharpness enhancement

Results are similar on textures and edges. The acutance value is 0.83, which means that the images appear slightly blurry, but with a natural aspect, since this blur may be due to the lens, or to the autofocus.

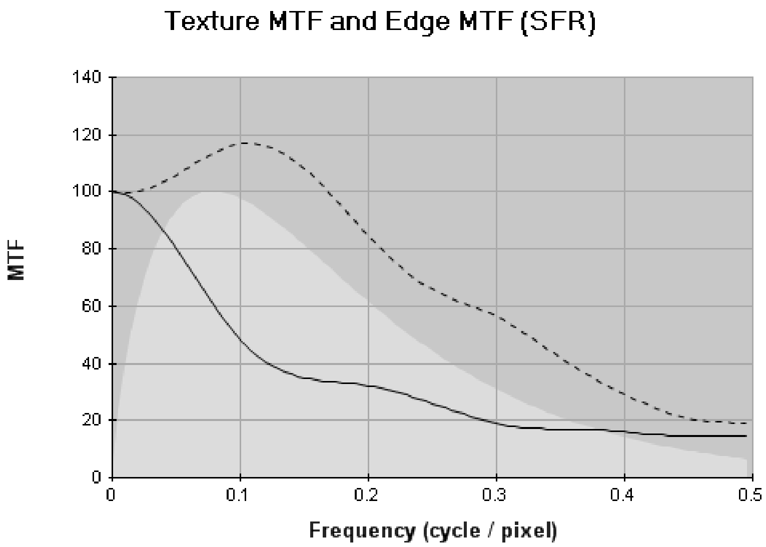
The second example is a camera with sharpness enhancement enabled. In this configuration, it gives more crispy images that may look particularly appealing for small prints.



MTF curves with sharpness enhancement

Results are still similar on textures and edges, but this time the acutance value is 1.03, which means that the images appear very sharp. MTF values above 100 mean that some sharpness enhancement artifacts, such as ringing, may be visible on images.

The last example is a lower-end camera.



MTF curves for fine details loss

Curves for textures and edges are different. Acutance value for edges is 0.78, while acutance value for textures is 0.4. Edges appear slightly blurry but much more detail is lost in the texture part.

10.9 Measurement accuracy

For measurement accuracy of MTF graphs, see MTF measurement section (Section 7).

The repeatability of the acutance measurement is ±0.04. However, it is dependent on the following measured camera characteristics:

- If autofocus is inaccurate or not repeatable, as for some camera phones, results may have low repeatability even for consecutive images taken under the same shooting conditions. Shooting several images and selecting the sharpest one can increase measurement accuracy.
- For long focal lengths (≥ 100 mm), small vibrations on setup may induce variations in measurement results. Locking the camera mirror can increase measurement precision.

Repeatability of the Visual Noise measurement is ±0.6 if visual noise result is higher than 1. Else it is ±0.3.

10.10 Measurement scale

The following table gives a subjective scale of acutance results:

Acutance	Level of sharpness
Above 0.95	The image is very sharp. Sharpness enhancement algorithms have been used, and ringing artifacts are very likely.
Between 0.85 and 0.95	The image is sharp.
Between 0.70 and 0.85	The image is slightly blurry.
Between 0.60 and 0.70	The image is blurry. Many fine details are lost.
Below 0.60	Most fine details are lost.

This one gives a subjective scale of acutance loss results, which is a characteristic of the quality of digital processing.

Acutance Loss	Degradation due to sharpening
Below 0.10	No significant loss of fine details.
Between 0.10 and 0.15	Visible loss.
Above 0.15	Loss is objectionable.

Tables below provide a subjective scale of visual noise results depending on the shooting conditions.[6] In low-light conditions, a slightly higher amount of noise is considered acceptable.

[6]This only applies for Visual Noise measurement, not for Visual Noise HDR measurement.

In bright-light conditions (300–1000 lux):

Visual noise	Subjective evaluation
Below 1	No visible noise.
Between 1 and 3	Visible noise.
Above 3	Noise is objectionable.

In low-light conditions (5–300 lux):

Visual noise	Subjective evaluation
Below 3	No noise or acceptable noise for the shooting conditions.
Between 3 and 6	Visible noise.
Above 6	Noise is objectionable.

The Visual Noise HDR measurement output is given in a Just Noticeable Difference (JND) of noisiness unit. A JND of 0 means that noise in not perceivable. A difference of 1 JND means that 75% of people will report a difference in terms of perceived noise.

10.11 Setup parameters influencing the measurement

Following set up parameters may change the results of the Texture Preservation measurement:

- Digital zoom function: you must normally deactivate this, unless it is the subject of the test.
- Resolution: set this to the highest available value to obtain accurate measurements.
- Framing of the image in 4:3, 16:9, etc.: take the photograph with maximum use of the sensor, unless it is the subject of the measurement.

- Special camera settings such as noise reduction filter, saturation filter, contrast enhancer, and so on should be deactivated.
- Exposure quality: the image must be neither over- nor under-exposed, usually by setting the camera to aperture priority.
- Deactivate the exposure correction (EV must be set to zero).
- The compression ratio should be as low as possible (TIFF format is preferred to JPEG)

10.12 Validity of the measurement

Texture Preservation measurement (as with MTF measurement) is meaningful only if you mention all the information about focal length, aperture, ISO speed, exposure correction, noise reduction filter, saturation, and contrast. You must also mention the selected viewing conditions (for acutance value).

Giving a MTF curve or an acutance value with no further information is not meaningful. All the values of influencing parameters should be given.

On the other hand, giving the Texture Preservation results of a 6-Mpixel camera, with a 24 mm focal length, at f/2.8 and ISO 400 for a 40×60 cm print viewed at 60 cm, and with no sharpening filter is meaningful. You must mention any information concerning exposure correction, noise reduction filter, saturation, and contrast to validate the measurement.

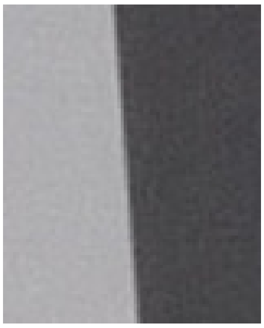
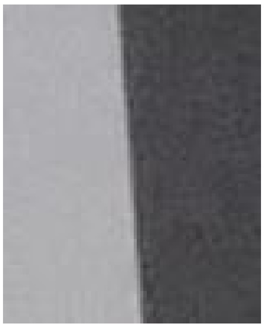
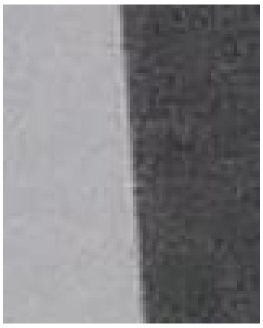
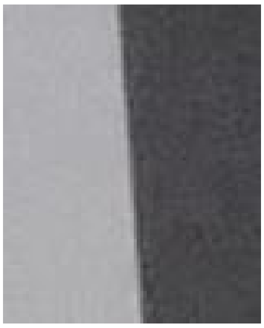
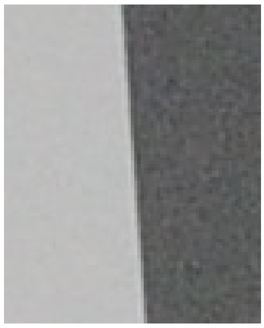
10.13 Comparing two cameras

It is possible to directly compare the acutance of two cameras, if the viewing conditions are the same.

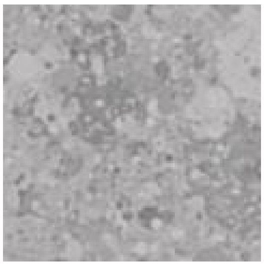
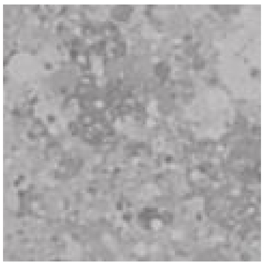
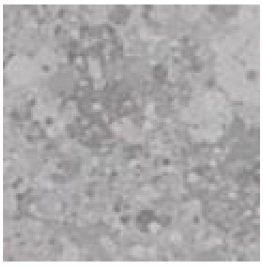
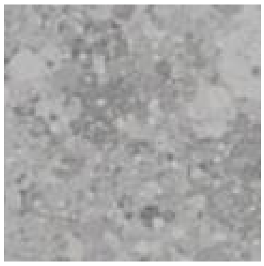
However, comparing MTF results of two cameras is possible only if they have the same resolutions or if the results for the two cameras are expressed in an equivalent resolution. The MTF measurement section describes how it is possible to express MTF results in an equivalent resolution (for instance, in lp/mm in 24×36 equivalent format).

Here is a comparison of results obtained with two cameras at different high ISOs. The first camera is the Nikon D3s, with a 50 mm lens, and the second one is the Panasonic G2 with a kit lens at focal length 50 mm. The selected aperture is f/5.6, and body parameters are set to the default mode (noise filter, sharpness, contrast). Measurements are done using “Professional Photo Print (closer)” viewing conditions. The comparison is deliberately unfair in order to show the results of a professional camera (Nikon D3s) versus those of a camera for amateur photographers (Panasonic G2).

The following table shows a crop of an edge for each ISO:

	ISO 800	ISO 1600	ISO 3200	ISO 6400
G2	 Acutance = 0.80	 Acutance = 0.78	 Acutance = 0.77	 Acutance = 0.63
D3s	 Acutance = 1.00	 Acutance = 1.00	 Acutance = 0.98	 Acutance = 0.95

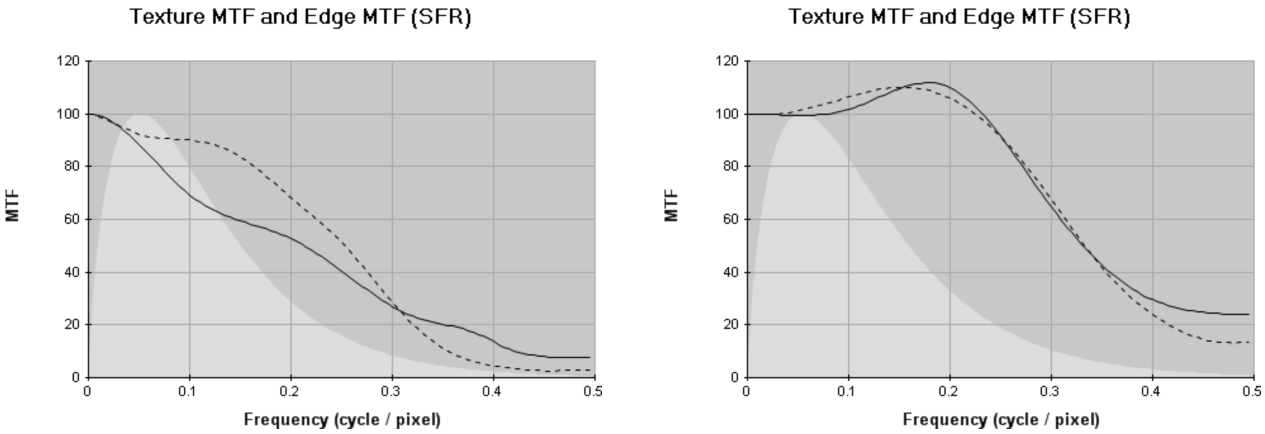
On the Nikon D3s, edges remain sharp at all ISO, while the loss of sharpness is highly visible on the edges of the G2. Edge acutance values follow this behavior: edge acutance values of the G2 decrease regularly with ISO, and are quite low for ISO 6400 (edge acutance=0.63). On the D3s, edge acutance values decrease very slowly, and remain high at ISO 6400 (edge acutance=0.95).Here is the same table for a crop of the textured patch:

	ISO 800	ISO 1600	ISO 3200	ISO 6400
G2	 Acutance = 0.68	 Acutance = 0.62	 Acutance = 0.59	 Acutance = 0.44
D3s	 Acutance = 1.00	 Acutance = 1.00	 Acutance = 0.98	 Acutance = 0.93

The loss of fine details for the G2 is clearly visible. At ISO 6400 there are no details visible. The D3s has essentially the same detail preservation for all these ISOs.

All in all, the D3s shows a very slight loss of acutance both on texture and edges at higher ISOs. The camera may lower the sharpening or apply a noise reduction that also decreases the image sharpness. On the G2, noise reduction already decreases the edge acutance at higher ISOs (edge acutance = 0.63 at ISO 6400). The loss in low-level details in the texture is even worse (texture acutance = 0.44 at ISO 6400), showing a very aggressive noise reduction.

In the MTF curves at ISO 800 (figure below), the difference between these cameras is also clearly visible, showing the low sharpness of the G2 compared to the D3s.



MTF curves for Panasonic G2 (left) and Nikon D3s (right), at ISO 800

10.14 Shooting

The Texture Preservation measurement uses a texture chart.

- ***Decide on the important parameters:*** focal length, aperture, focusing, resolution, ISO, sharpness, digital zoom, etc.
- ***Special shooting conditions (see also Section 4.12)***
  - Target must be centered in image
  - Visible background behind the target must be uniform (18% grey is recommended).
  - Borders of the target must be parallel to the borders of the image.
  - Texture area must fill one third of the image's height.
  - Lighting must be uniform.

Note: It is important to keep a record of all the parameters and settings associated with each shot. Depending on the model, not all cameras record all the EXIF data, and if the measurement is to be used to compare two cameras, the records of shooting conditions for the image files must be strictly identical.

10.15 Sidecar parameters

If automatic detection fails, you can use the [Common] section to manually provide the position of the markers.

```
[Common]
// Manual texture chart position
X1=... // x coordinate of the bottom-right marker
Y1=... // y coordinate of the bottom-right marker
X2=... // x coordinate of the bottom-left marker
Y2=... // y coordinate of the bottom-left marker
X3=... // x coordinate of the top-right marker
Y3=... // y coordinate of the top-right marker
X4=... // x coordinate of the top-left marker
Y4=... // y coordinate of the top-left marker
```

11 – VIDEO-TEX: Video Texture

11.1 Introduction

Measuring image sharpness is an important component of still image quality evaluation, and the same goes for video quality evaluation.

The Video Texture (VIDEO-TEX) measurement extends the “TEX” measurement to video inputs. The Texture Preservation measurement is applied on all frames of the video, and a summary of all results is displayed.

It is interesting to apply the measurement to video frames, and not just to still images, because the image processing chain is different for these two formats, and thus there may be some differences in image quality as well.

Moreover, comparing the sharpness over the frames of a video gives information about the behavior of the camera and its stability: if the sharpness or zoom factor vary during measurement, despite the chart and the camera being attached and unmoving, there is probably a problem with the focus stability. This measurement also makes it possible to measure the focusing time when the focus is lost.

11.2 Definitions

11.2.1 YCbCr or Y'CbCr color space

The Y'CbCr is a color space part of the digital video color pipeline. Y' is the luma component and Cb/Cr are the chroma components. This color space is the one used by the MPEG standard for video compression.

In many video codecs, this format is the output format after decompression, which is then converted into the RGB color space to be displayed on-screen. The YCbCr/RGB conversion is defined in the ITU-R BT.601 standard.

This color space is often mistaken for the YUV color space, which is the equivalent for analogous signals. This said, we will nonetheless use the terms YUV and YCbCr as equivalents.

11.2.2 Edge MTF

Edge MTF is a measurement of sharpness that conforms to the ISO standard 12233. A more detailed definition is given in the chapter on MTF measurement (Section 7).

11.2.3 Texture MTF

Texture MTF is a measurement of sharpness performed on a structured image (i.e. the dead leaves chart). It quantifies the ability of a camera to reproduce details in an image. A more detailed definition is given in the chapter on TEX measurement (Section 10).

11.2.4 Acutance

The acutance is a single value metric calculated from a MTF result. The value is a weighted average of the MTF, with weights dependent on the CSF and the viewing conditions (image size and distance to subject). The metric therefore takes into account only the visible frequencies for a given viewing condition. A more detailed definition of the acutance is given in the chapter on TEX measurement (Section 10).

11.2.5 Viewing conditions

A viewing condition defines the visualization conditions of an image: image size, distance etc. These conditions are used during the computation of acutance. A more detailed definition of the viewing conditions is given in the chapter on TEX measurement (Section 10).

11.2.6 Zoom variation

Zoom variation is defined as the variation of the perimeter delineated by the 4 markers on the Dead Leaves chart. The comparison is done for a given video frame (i to the first frame (0) of the video:

$$\text{Zoom}(\%) = \frac{\text{Perimeter}_i - \text{Perimeter}_0}{\text{Perimeter}_0}$$

The result is positive if the perimeter of the markers in the tested frame is larger than the perimeter of the markers of the first frame, and negative otherwise. A value close to 0 means that the field of view did not evolve.

Zoom variation can be used to quantify lens breathing, which is usually associated with a change to the field of view.

11.3 Measurement in raw format

The main purpose of the Texture Preservation measurement is to quantify the impact of image processing algorithms on sharpness. Thus it makes sense to perform these measurements on RGB images only, so measurement on raw images is not available.

11.4 Measurement in YCbCr color space (YUV)

Analyzer performs Video Texture measurements on YCbCr data. When the option is selected, all the texture measurements are performed on the Y channel of the YCbCr color space, and thus before the RGB conversion, which is done during video decompression.

The reasons for doing so are:

- The YCbCr to RGB conversion defined by the ITU-R BT.601 standard supposes a reduced dynamic for each channel (16–239 for the Y channel); however, some manufacturers use the whole dynamic in their compression process (0–255). The direct consequence is a clipping of the blacks and whites during the RGB conversion, resulting thus in a loss of information. Measurements performed in the YCbCr color space avoid this possible clipping and therefore potential measurement errors.
- The measurement is performed on the video output just after decompression, before any processing or conversion for displaying the stream on-screen. This is the format that all video players use as input, provided that the codec is the same.

11.5 Measuring Video Texture

The Video Texture measurement is a Photo Texture measurement performed on each frame of a video file. For each output parameter of the Video Texture measurement, the following values are computed:

- The average value for all the video frames.
- The standard deviation computed for all the video frames.
- The minimum value for all the video frames.
- The maximum value for all the video frames.

In addition to the Texture measurements, the Video Texture measurement provides an evolution of the field of view defined by the four markers of the dead leaves chart. These zoom variations give information about lens breathing (and thus refocusing).

The measurement can use either video files or a series of images as input. In the case of an image series, the images are considered as if they were frames in a single video.

Finally, the measurement is available in YCbCr format, which helps avoid possible incorrect YCbCr to RGB conversions 11.4.

11.6 Analyzer output

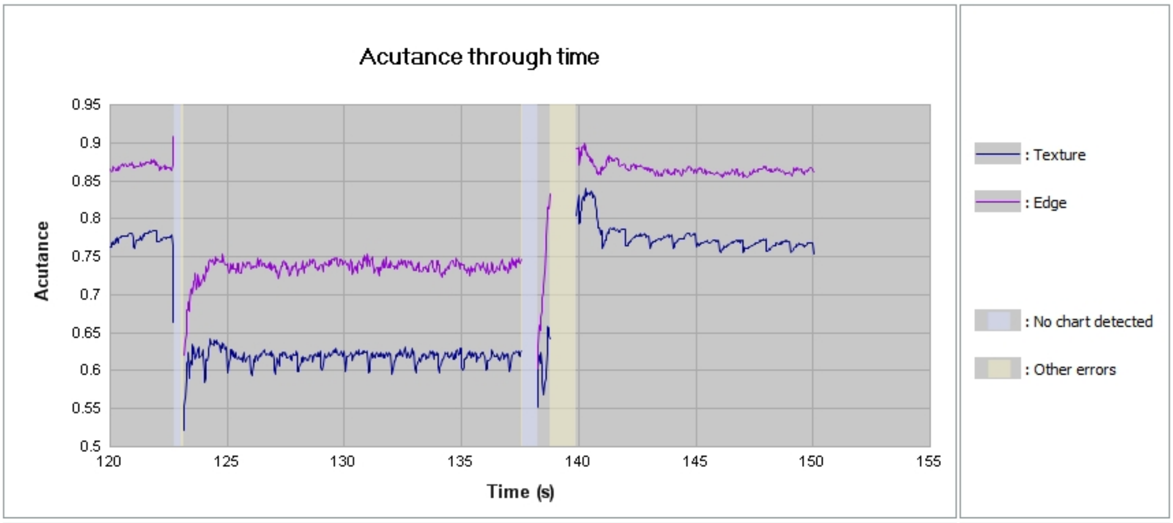
Analyzer returns the following:

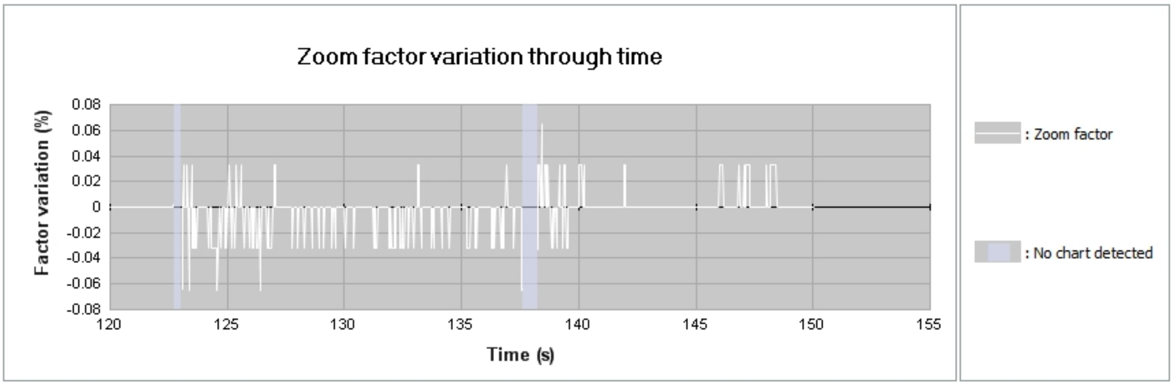
- The shooting conditions tab contains values describing general shooting conditions (including information about the video file), the viewing condition selected for the measurement, and the sidecar parameters.
- The Summary tab contains:
  - The pixels/degree coefficient determined by the viewing conditions.
  - The acutance loss, which is the difference between mean Edge acutance and mean Texture acutance for the green channel (the Y channel is used when the YUV option is activated).
  - A table containing statistical values (mean, standard deviation, minimum and maximum) texture and edge MTF acutance. The statistics are computed on all the frames of the video that produced no measurement errors. Acutance is given for red, green, and blue channels (and only for the Y channel when the YUV option is activated).

		Mean acutance loss
G	Green channel	0.106

		Texture acutance				Edge acutance (SFR)			
		Mean	Std. Dev.	Max	Min	Mean	Std. Dev.	Max	Min
R	Red Channel	0.659	0.106	0.865	0.433	0.762	0.091	0.974	0.515
G	Green channel	0.701	0.076	0.846	0.534	0.807	0.060	0.912	0.597
B	Blue Channel	0.722	0.091	0.950	0.401	0.823	0.067	0.982	0.556

- A graph displaying edge and texture acutance for each frame of the tested video. Frames in which the markers were not detected are indicated in light blue. Frames for which the measurement raised an error (other than for marker detection) are indicated in light yellow.
- A graph displaying the variation of the zoom as a percentage for each frame of the video. Frames in which the markers were not detected are indicated in light blue.





- The detail tab contains:
  - A table displaying the mean grey level at 18% (average computed on all the video frames without error) for each color channel R, G, B, and Y, where Y stands here for the Luminance of the *XYZ* color space (when the YUV option is activated, only the Y channel of YCbCr color space is given).
  - A table containing statistical values for the frequency corresponding to MTF at 50% for texture and edge. The frequencies are expressed both in cycle/pixels and line pairs per millimeters, and are given for red, green and blue channels (and for the Y channel only when the YUV option is activated).

This table contains the values of the MTF, expressed in cycles/pixel and in lp/mm (24x36mm eq)

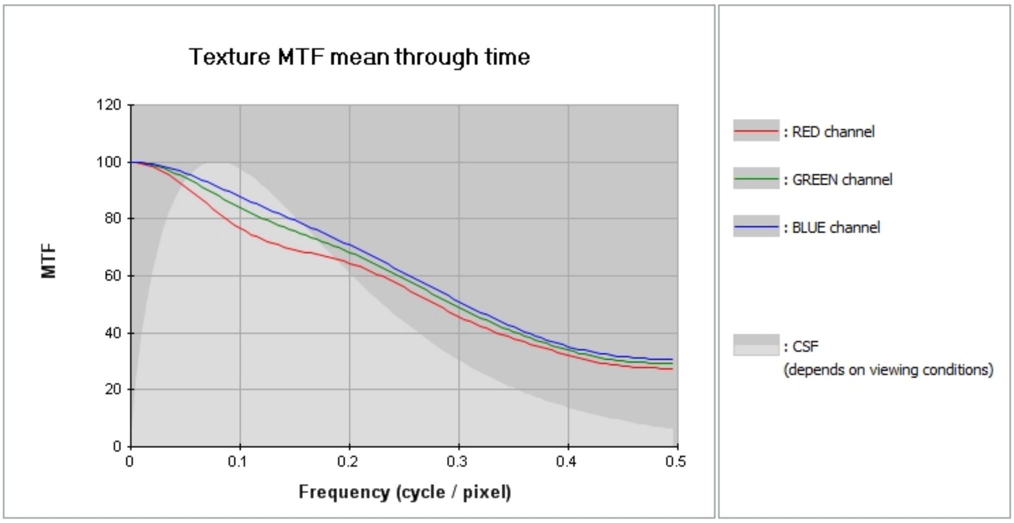
	MTF 50%							
	Texture				SFR			
	Mean	Std. Dev.	Max	Min	Mean	Std. Dev.	Max	Min
R Red Channel	0.27 (13.29)	0.10 (4.70)	0.41 (20.09)	0.11 (5.14)	0.36 (17.44)	0.07 (3.24)	0.45 (21.80)	0.15 (7.35)
G Green channel	0.29 (14.18)	0.08 (4.01)	0.42 (20.33)	0.16 (7.59)	0.38 (18.51)	0.05 (2.38)	0.45 (21.80)	0.19 (9.31)
B Blue Channel	0.30 (14.46)	0.08 (4.06)	0.42 (20.58)	0.09 (4.41)	0.38 (18.83)	0.05 (2.33)	0.49 (24.01)	0.18 (8.57)

  - A table containing statistical values for MTF at Nyquist/2 for texture and edge for each color channel (and for the Y channel only when the YUV option is activated).

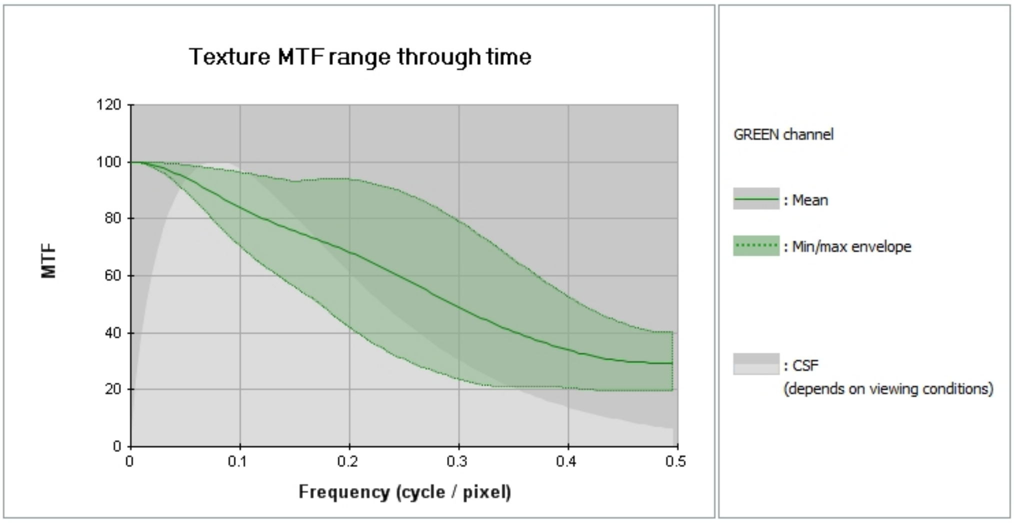
This table contains the values of the MTF (in %) at Nyquist/2 (or 12.25 lp/mm (24x36mm eq))

	MTF @ Nyquist/2							
	Texture				SFR			
	Mean	Std. Dev.	Max	Min	Mean	Std. Dev.	Max	Min
R Red Channel	56%	20%	88%	25%	73%	17%	109%	30%
G Green channel	59%	19%	89%	30%	78%	13%	98%	34%
B Blue Channel	61%	18%	91%	24%	81%	13%	102%	30%

- The MTF graphs tab contains:
  - A graph displaying the texture MTF averaged on all the video frames. The MTF is displayed for R, G and B color channels (and for the Y channel only when the YUV option is activated).



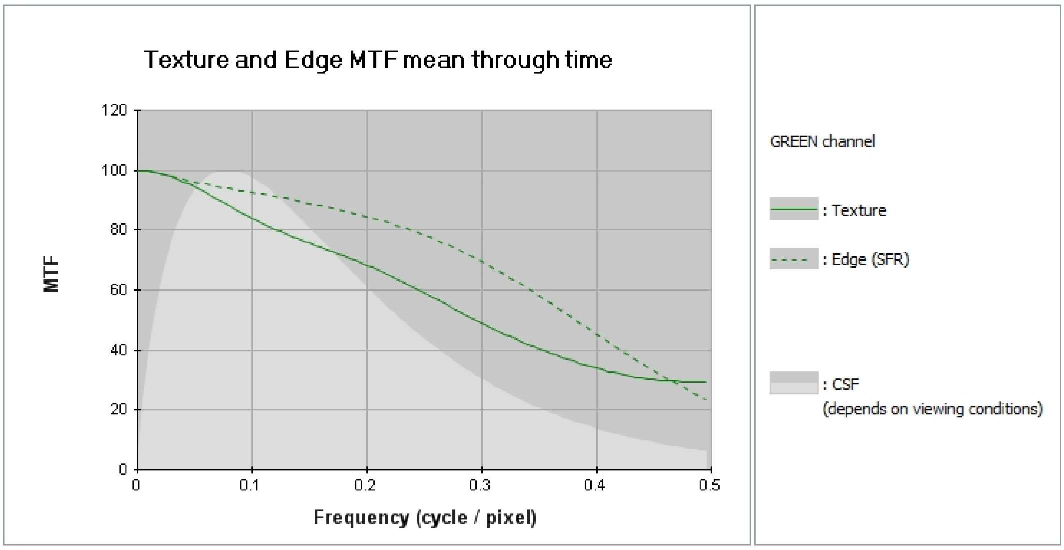
– A graph displaying the maximum and minimum texture MTF on all video frames for the green channel only (and for the Y channel only when the YUV option is activated).



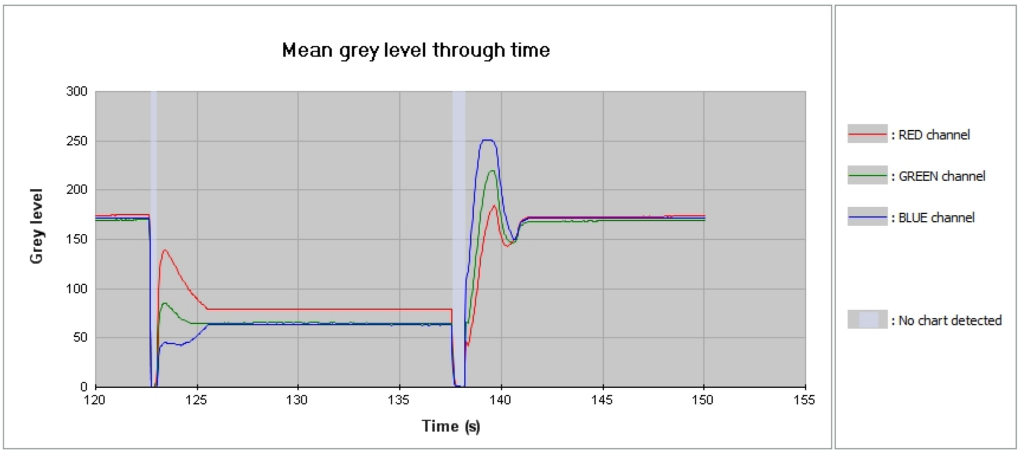
– A graph displaying the edge MTF averaged on all video frames. The MTF is displayed for R, G and B color channels (and for the Y channel only when the YUV option is activated).

– A graph displaying the maximum and minimum edge MTF on all the video frames for the green channel only (and for the Y channel when the YUV option is activated).

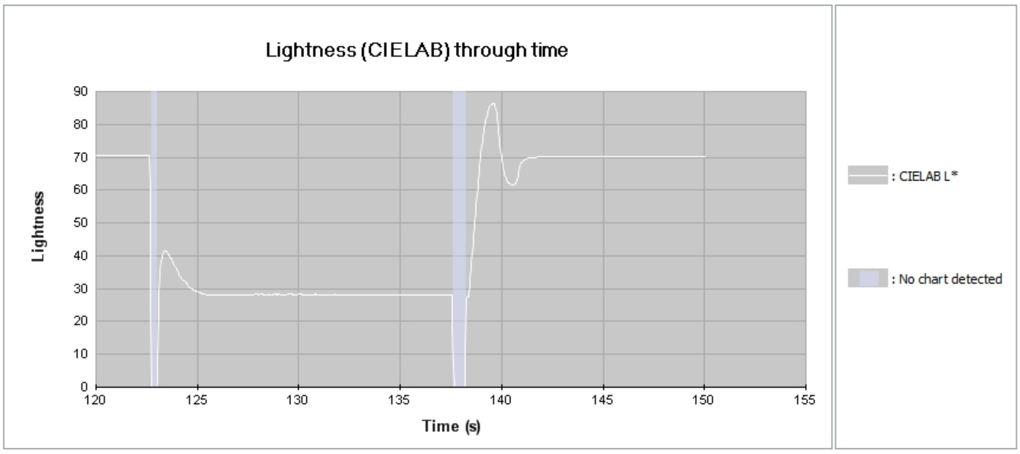
– A graph displaying the difference between average texture and average edge MTF for the green channel (and for the Y channel when the YUV option is activated).



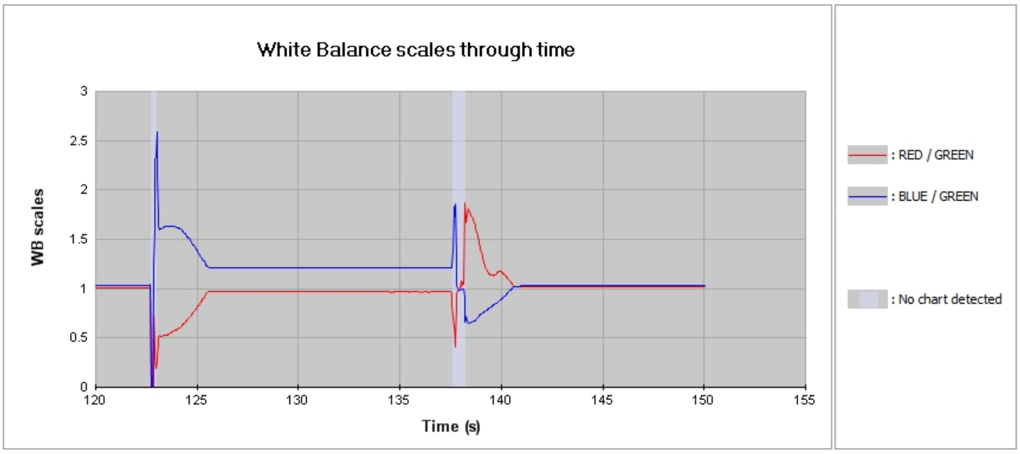
- The CPIQ texture tab displays the results of texture blur according to CPIQ standards. (See the CPIQ section 36 for a more complete description.) Here the results are averaged for all valid video frames.
- Finally, the Exposure and White Balance tabs contain mean grey level values computed on an ROI for each video frame. The default ROI is the texture area; however, you can specify a different ROI in a sidecar file. The following graphs are given:
  - Mean R, G, B values as functions of time (Y, Cb and Cr if the YUV option has been selected).



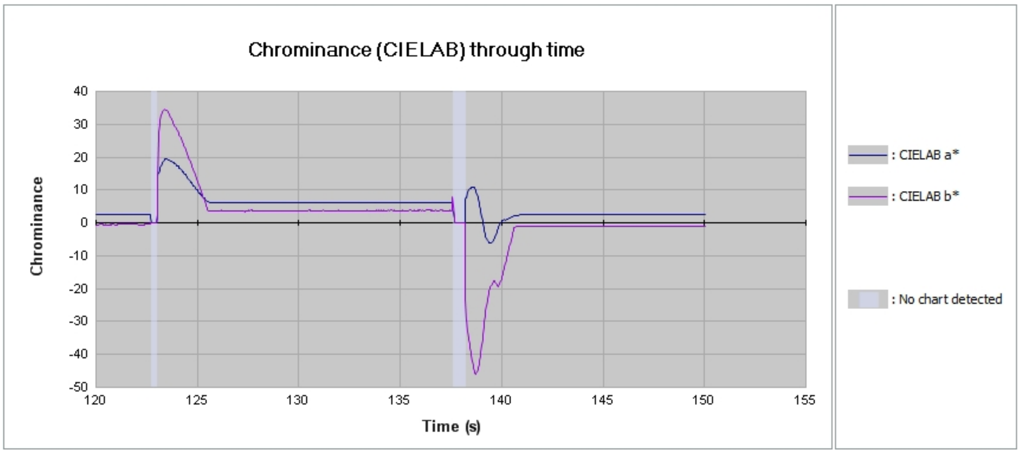
  - Mean CIELAB L* as a function of time.



– Mean Red/Green and Blue/Green as functions of time.



– Mean CIELAB a* and b* as functions of time.



11.7 Measurement accuracy

The accuracy of all the measurements related to the MTF are provided in the chapters on MTF measurement and TEX measurement (see Section 7 and Section 10).

The accuracy of the zoom factor variation can be computed from the accuracy of marker detection (±1 pixel). Since the zoom factor variation is deduced from the perimeter of the 4 markers and the framing is fixed, we obtain the following accuracy:

Resolution	Zoom variation accuracy
3840×2160 (4K)	±0.04%
1920×1080 (Full HD)	±0.07%
1280×720 (HD)	±0.11%

11.8 Measurement scale

The scales for texture acutance measurements are the same as those given in the chapter on "TEX measurement" (Section 10.10):

Acutance	Level of sharpness
Above 0.95	The image is very sharp. Sharpness enhancement algorithms have been used, and ringing artifacts are very likely.
Between 0.85 and 0.95	The image is sharp.
Between 0.70 and 0.85	The image is slightly blurry.
Between 0.60 and 0.70	The image is blurry. Many fine details are lost.
Below 0.60	Most fine details are lost.

And for acutance loss:

Acutance Loss	Degradation due to sharpening
Below 0.10	No significant loss of fine details.
Between 0.10 and 0.15	Visible loss.
Above 0.15	Loss is objectionable.

11.9 Set-up parameters influencing the measurement

The following camera settings may influence the Video Texture measurement:

- Compression rate: set this to the smallest possible value unless it is the subject of the test. Indeed, a strong compression can lower the acutance results.
- Video resolution: set this to the highest available value to obtain accurate measurements.
- Video framing: take the images so as to make maximum use of the sensor, unless the sensor is the subject of the measurement.
- The digital zoom function: deactivate this unless it is the subject of the test.
- Exposure quality: the image must be neither over- nor under-exposed.
- Stabilization system: turn this off unless it is the subject of the test.

11.10 Validity of the measurement

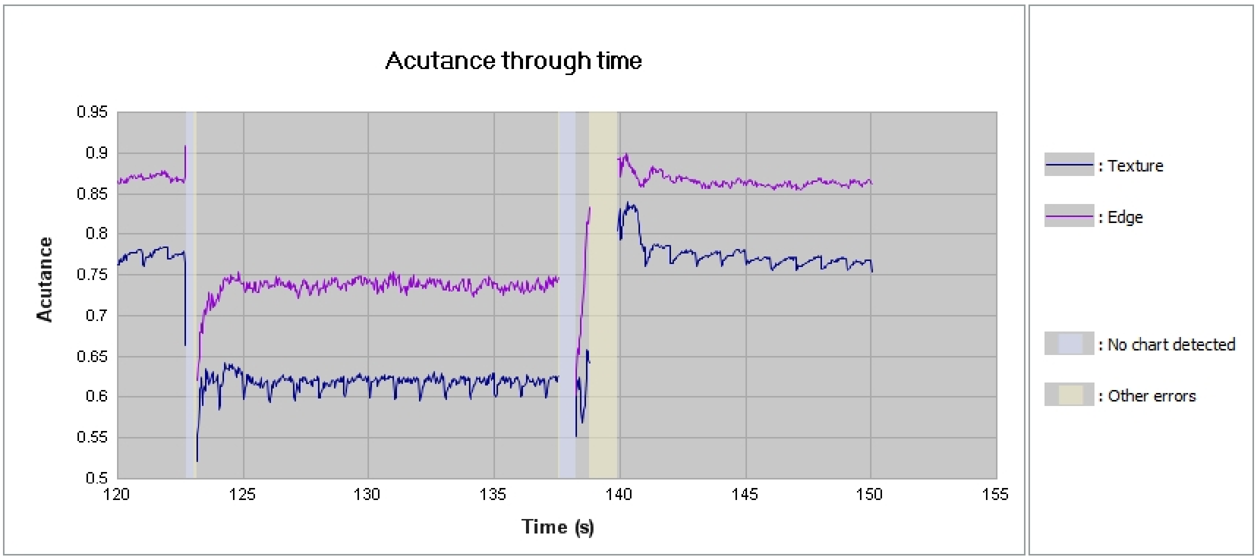
Analyzer lets you perform Texture measurements on video files and on series of images. As with the Photo Texture measurement, the Video Texture measurement is meaningful only when associated with a given set of test conditions: lighting conditions, focal length, aperture, ISO speed, noise reduction filter, stabilization on or off. You must also mention the selected viewing conditions (to obtain an acutance value).

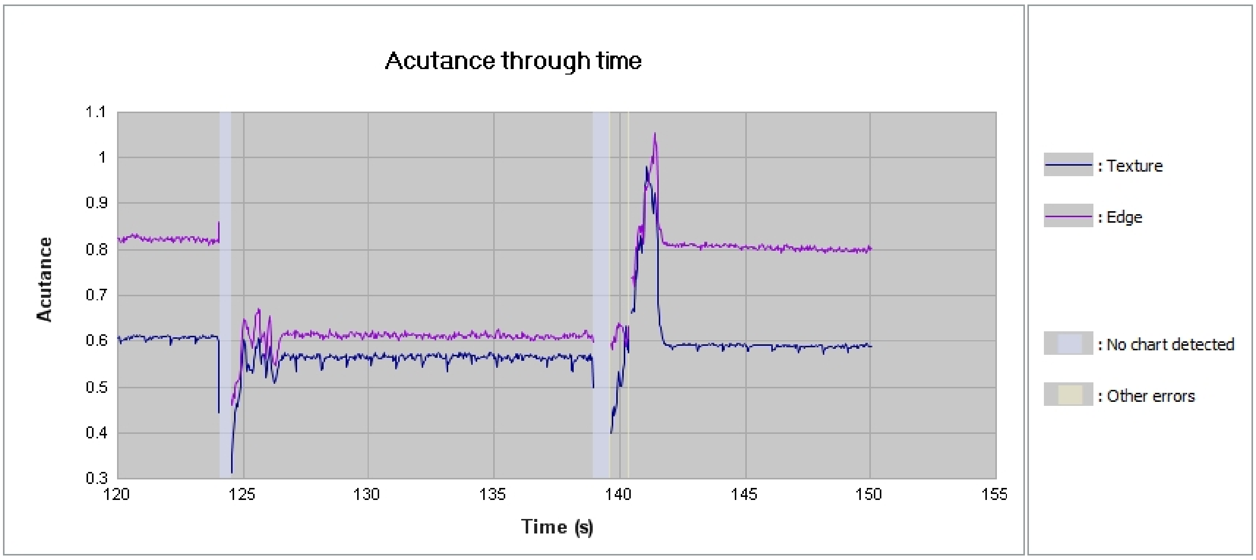
Since this measurement is meant to analyze videos, the scenario you choose (lighting condition evolution, chart framing) is very important and can reveal different things: time required to refocus, processing stability, reactivity to lighting changes, etc. It is up to you to define the proper scenario to test each of these points.

11.11 Comparing two cameras

In this section, we compare the reaction of two cameras to a specific scenario. In this scenario, the lights change from 700 lux to 30 lux and then back to 700 lux. The illuminant stays the same (D54). The two cameras are on a tripod.

If we compare the acutance evolution, we observe several things:

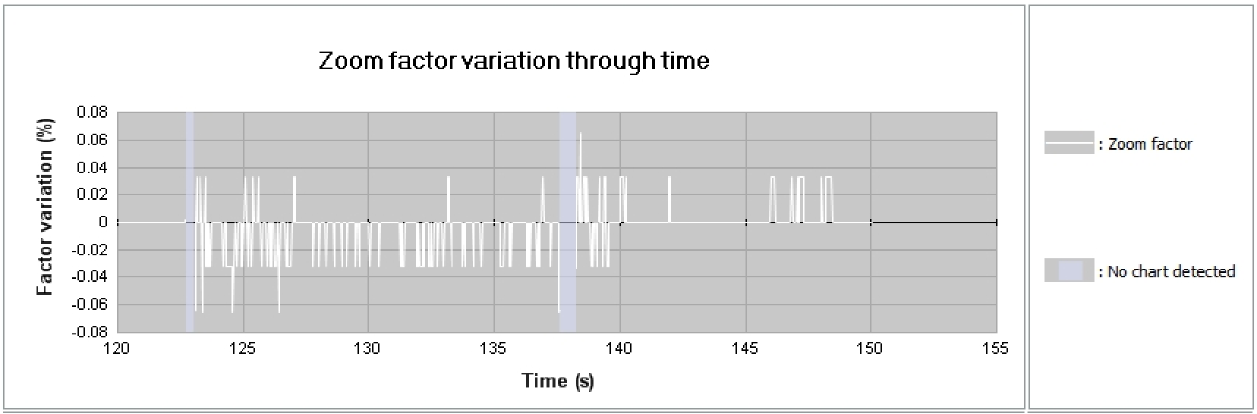


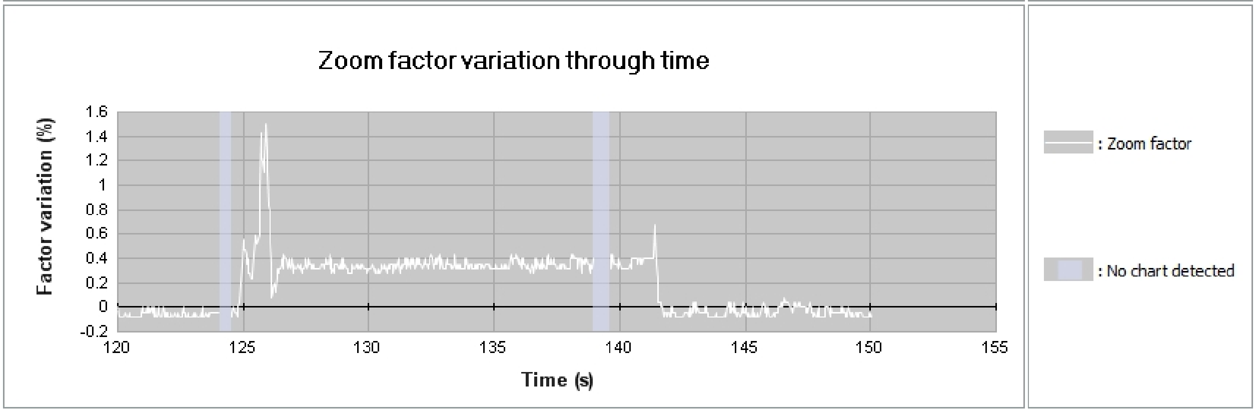


- For the two cameras, the edge acutance is significantly better than the texture acutance.
- The two cameras seem to be repeatable for a given light intensity (i.e., the same level of acutance at 700 lux is present at the beginning and at the end of the video).
- Camera 1 is significantly better at 700 lux than Camera 2.
- Detail preservation in Camera 2 is poor, but seems to be constant at 700 and 30 lux.
- For both cameras, there is a periodic loss of texture acutance. This is related to the reference frames in video compression, which are periodic and are encoded differently than other frames in the video stream.

- Camera 2 seems to be refocusing at the 30 lux transition, based on strong oscillations in the acutance values.

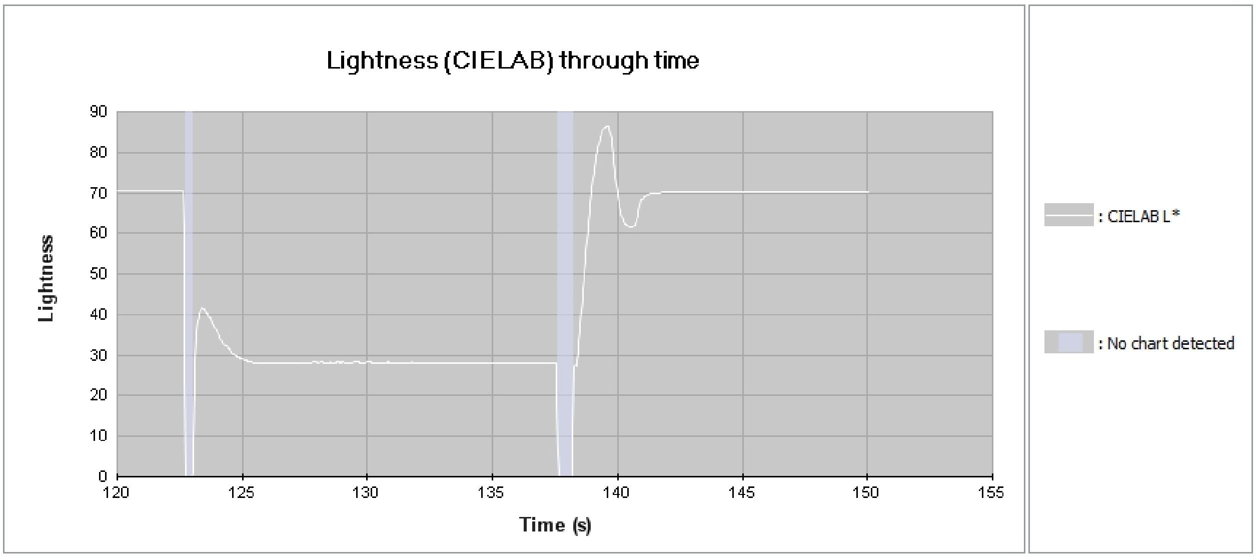
If we now compare the zoom variation oscillations, we can observe:

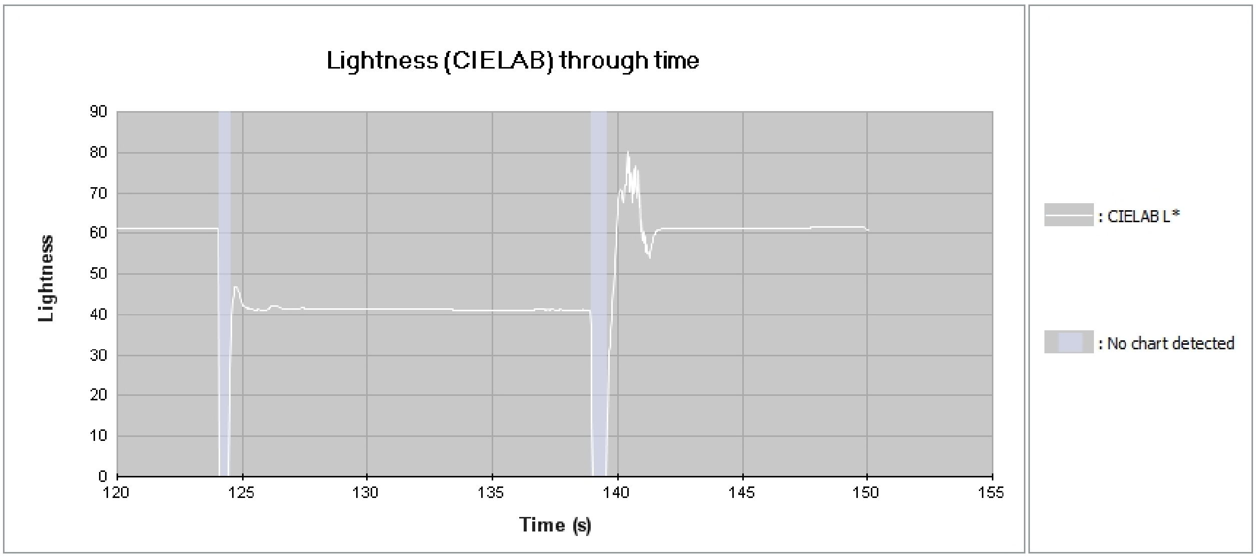




- Camera 1 is stable and does not refocus (no significant zoom variations means that the field of view is stable).
- Camera 2 does not have the same field of view at 30 lux as at 700 lux. The change in the field of view confirms what was observed with the acutance evolution: the camera is refocusing when the lighting changes.

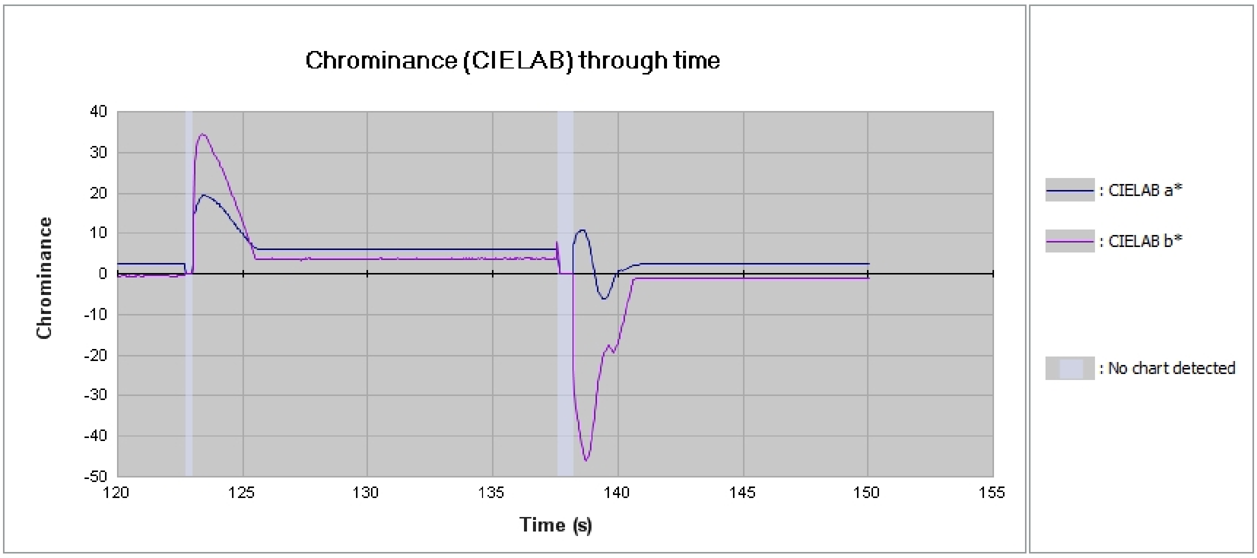
Let's now compare the average CIELAB *L** in the Dead Leaves ROI:

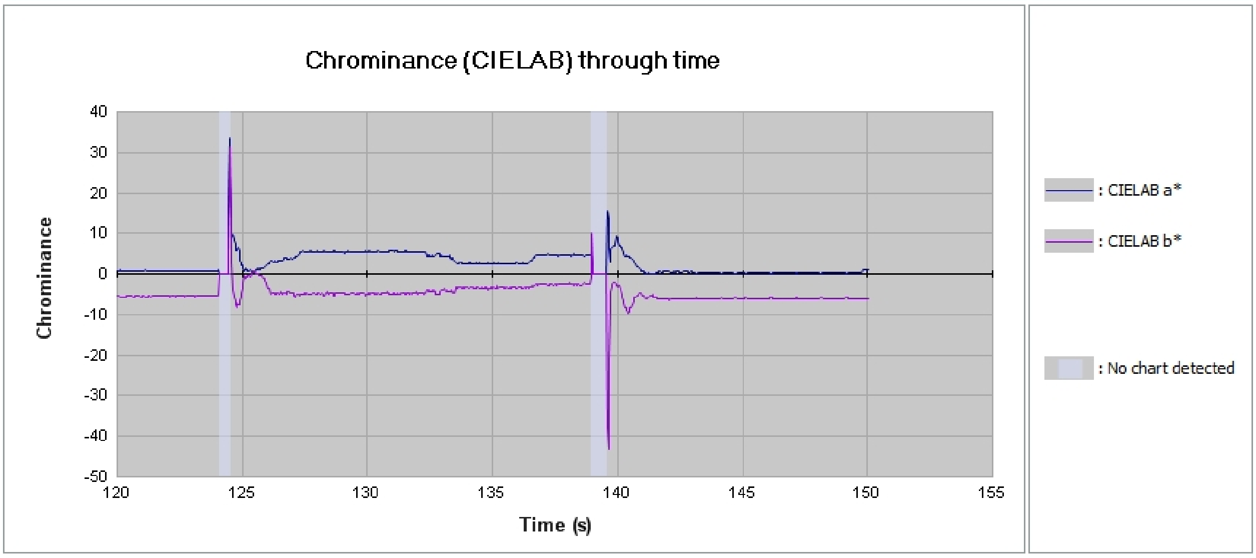




- For both cameras, there is a change in target exposure between 30 lux and 700 lux.
- Both cameras are repeatable at 700 lux (i.e., same grey level).
- The difference between the two target exposures is stronger for Camera 1 than for Camera 2.

Finally, let's compare the average CIELAB *a** and *b** in the Dead Leaves area:



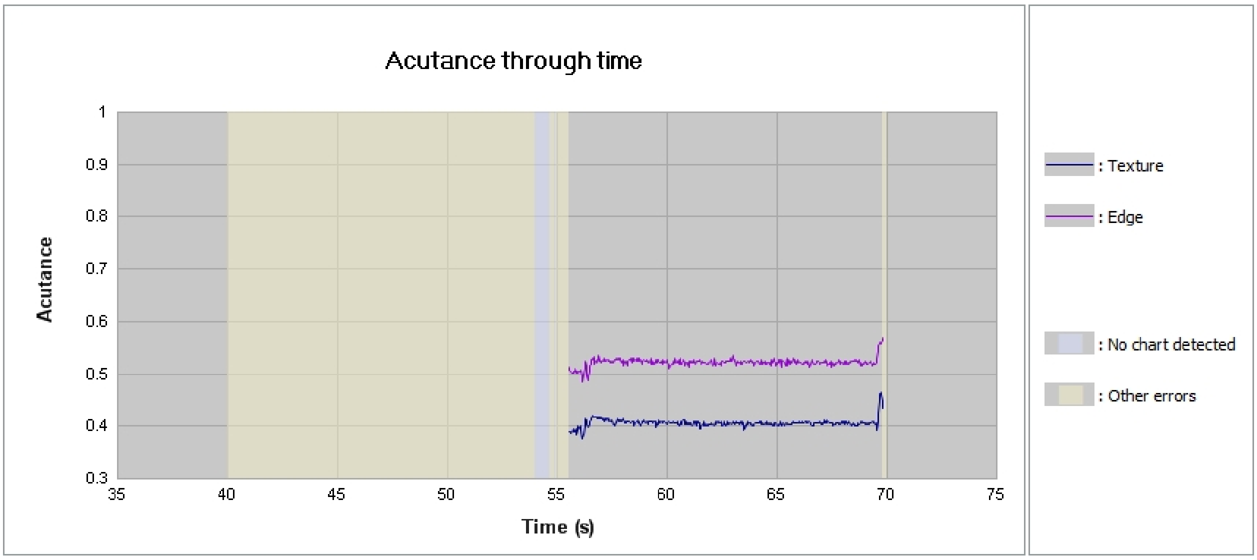


- The white balance is different at 700 lux and 30 lux for both cameras.
- Camera 1 is more stable than Camera 2 at 30 lux.

11.12 Comparing RGB to YCbCr (YUV) measurements

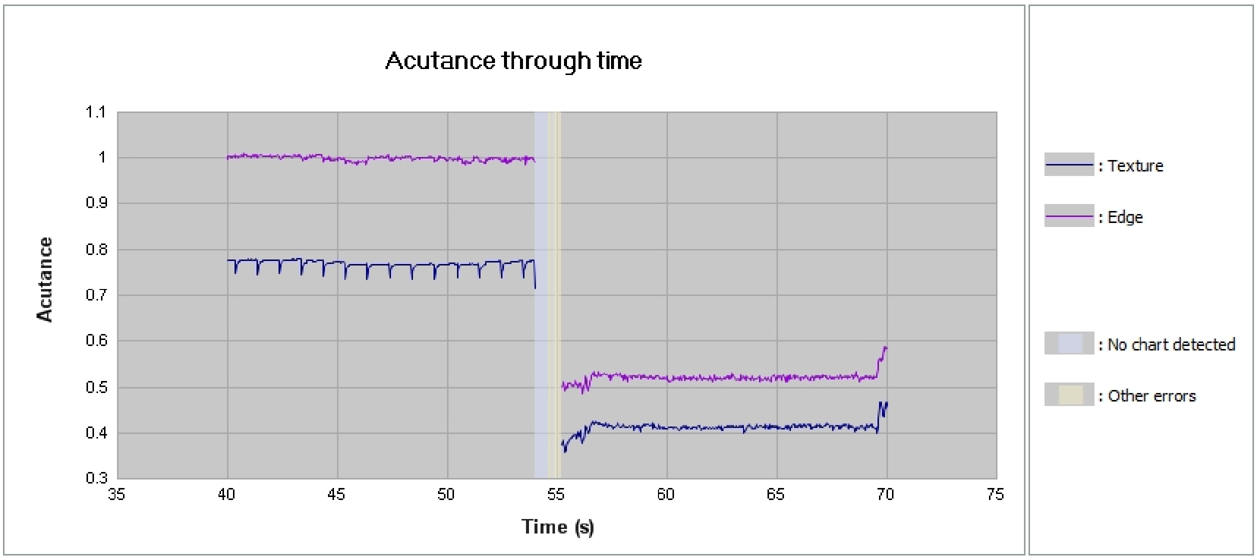
In this section, we show an example of when it is preferable to use YUV measurements. In this example, the lights change from 700 lux to 30 lux (using a D54 illuminant). However, the camera here does not use the YCbCr to RGB conversion proposed by the ITU-R BT.601 standard.

If we run the measurements with the RGB option, we obtain the following acutance evolution:



The first part of the video (700 lux) produces errors and the second part (30 lux) is OK. A simple check of the warning tab shows that half of the frames raised an exposure error. The explanation is that the YCbCr to RGB conversion used during decompression (ITU-R BT.601 standard) assumes a reduced dynamic compared to what the manufacturer used during compression. The result is a clipping of dark and bright areas which makes the measurements impossible here.

If we now run the measurements with the YUV option, we obtain:



Since there is no YCbCr to RGB conversion, the measurements can now be run at 700 lux. Moreover, if we compare the acutance results at 30 lux, we see that they are very close to what was obtained before with the RGB option. The small variations are mostly due to the fact that different color channels are used.

11.13 Shooting

For optimal measurements, follow the detailed instructions for shooting the Dead leaves targets defined in the Texture measurement Section 10.

It is up to you to determine what lighting conditions or lighting scenarios to use, depending on what needs to be tested. In all cases, however, we recommend using uniform lighting for the measurement.

11.14 Sidecar parameters

The Video Texture measurement does not need sidecar parameters to be launched. However, sidecars can be used for several interesting options:

- You can use the `[VideoTemporalCrop]` section to crop the video and run the measurement within a limited time span. You can define the duration of the measured video by filling the start and end times, or the start and duration times, but not both simultaneously.

```
[VideoTemporalCrop] // section for temporal crop of videos
StartTimeSec = ...  // start time of the measurement, in sec
EndTimeSec   = ...  // end time of the measurement, in sec
DurationSec  = ...  // duration, in seconds
StartFrame   = ...  // start time of the measurement, in frames
EndFrame     = ...  // end time of the measurement, in frames
FrameNumber  = ...  // duration, in frames
```

- You can use the `[ROI]` section to specify another region for computing average grey levels:

```
[ROI]
Left   = ... // coordinate of the left side of the ROI
Right  = ... // coordinate of the right side of the ROI
Top    = ... // coordinate of the top the ROI
Bottom = ... // coordinate of the bottom the ROI
```

- If automatic marker detection fails, you can use the `[Common]` section to provide these positions manually:

```
[Common]
X1=...  // x coordinate of the top-left marker
Y1=...  // y coordinate of the top-left marker
X2=...  // x coordinate of the top-right marker
Y2=...  // y coordinate of the top-right marker
X3=...  // x coordinate of the bottom-left marker
Y3=...  // y coordinate of the bottom-left marker
X4=...  // x coordinate of the bottom-right marker
Y4=...  // y coordinate of the bottom-right marker
```

12 – FR: Color Fringing

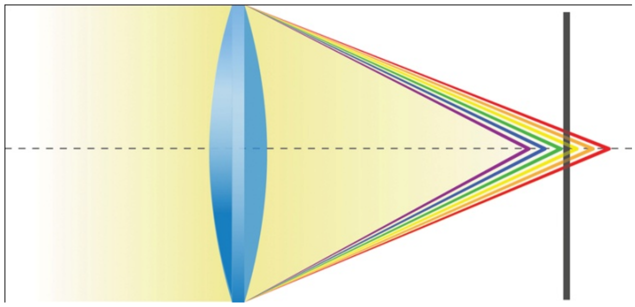
12.1 Introduction

Color fringing can be observed on images showing very high contrast between very dark and bright areas. The image below shows a real camera phone image exhibiting very strong blue fringing.

Example of Blue Fringing, on a highly saturated sky

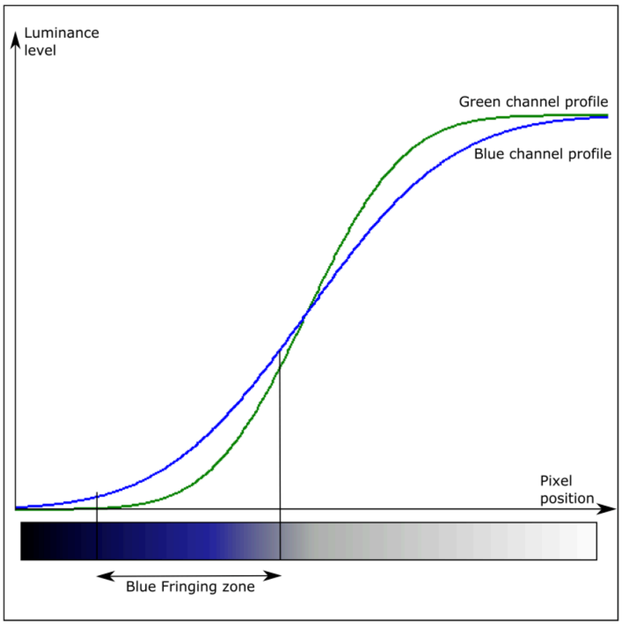
The optical path of a light ray depends on its wavelength. This physical phenomenon can lead to chromatic aberration, either lateral (see the Section on 13) or longitudinal (see the Section on 7). However, a camera with an optical system that has very low chromatic aberration under normal conditions may exhibit colored fringes under conditions with a very high exposure, as backlit areas. Photographers often refer to this as "purple fringing," but the same phenomenon can lead to other fringing colors, which we will refer to generically as "color fringing".

Lateral and longitudinal chromatic aberrations are first-order aberrations, but higher-order chromatic aberrations may lead to slightly different blur spots or MTF. A more detailed description of color fringing has been published in "Characterization and measurement of Color Fringing," by F. Cao, F. Guichard, H. Hornung and C. Sibade, *Proceedings of the SPIE*, volume 6817, pp. 68170G-68170G-9 (2008).



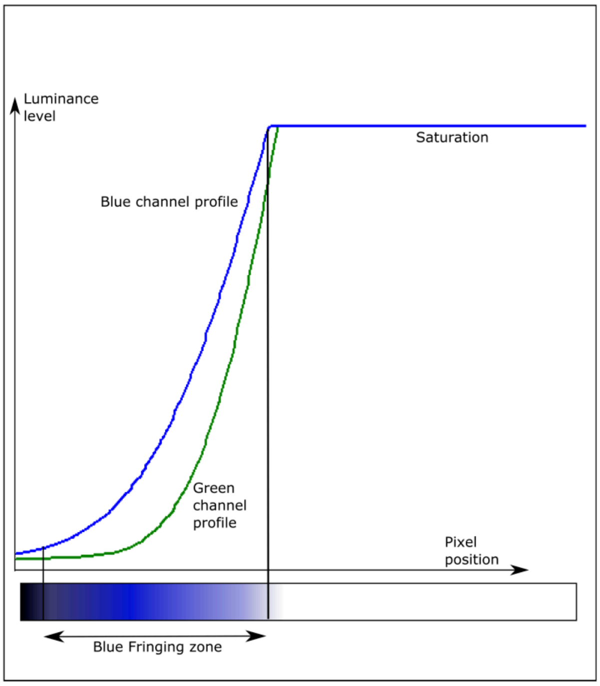
Longitudinal chromatic aberration

The next figure presents an ideal non-noisy and correctly-balanced luminance response of the blue and green channels along a black-to-white transition. If the blue channel is not as sharp as the green channel, the pixels located in the darker part of the transition show a blue hue, as the blue level is greater than the green one. This zone of excessive blue level represents blue fringing.



Example of an edge transition, showing blue fringing, linear regime with no sensor saturation

For saturated signals, the color channel profiles are all amplified and clipped at the saturation level. The amplitude difference due to the difference in focus also becomes larger and the fringing becomes more visible. Because the color fringing appears in situations of very high sensor exposure, the knowledge of the camera MTF is in general not accurate enough to predict the amount of color fringing. So to measure color fringing, the Analyzer protocol reproduces high contrast and saturation that are characteristic of backlit scenes and directly examines the behavior of the camera across black and white transitions.



Example of an edge transition, showing blue fringing. The sensor is saturated in the highlights

12.2 Definitions

Line profile comparison

The Color Fringing measurement is based on comparing the levels of the different color channels across a transition with very high contrast and possibly very high saturation levels. Depending on the profile compared to the green profile, we define:

- Blue fringing as the excess of blue level over green.
- Red fringing, by equivalently comparing the red channel with the green channel.
- Purple fringing, when both blue and red channels have significantly higher levels than the green channel.

Color fringing amounts can also be negative, meaning a lack of blue or red hue instead of an excess, and leading to yellow (negative blue fringing), cyan (negative red fringing) or green fringing.

Saturation Value
See definition in the Dark Signal chapter.

12.3 Influencing factors

Several parameters influence the measurement of color fringing:

- The camera exposure.
- The lens aperture.
- The lens focusing.
- The shooting distance.
- The spectral distribution of the light source.

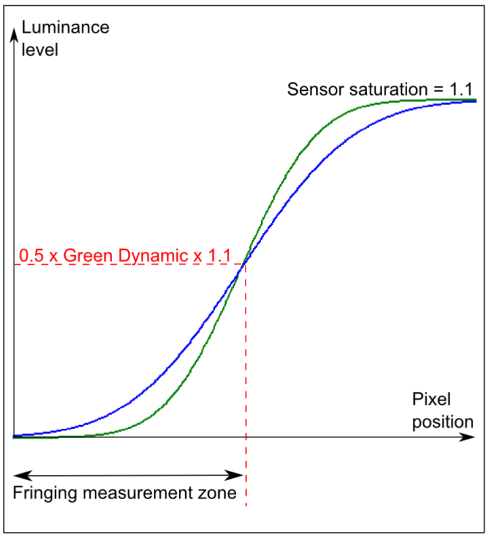
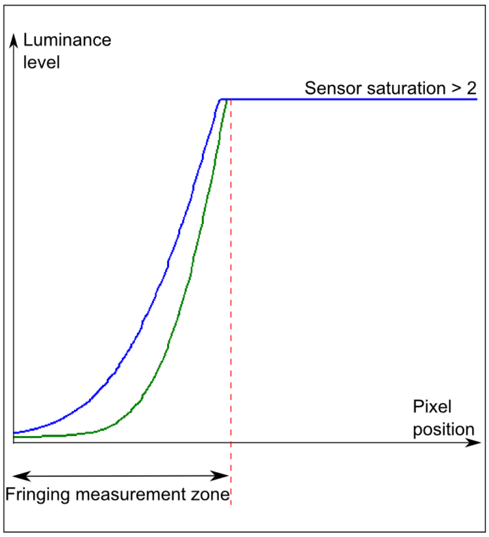
Image processing algorithms can impact color fringing. In particular, color rendering, tone curve, and digital sharpening modify the fringing. Lateral chromatic aberration can also modify the measurement of color fringing, depending on the quality of the lens and the position of the measured transition in the image field.

12.4 The measurement of color fringing

Profile extraction
The method for measuring color fringing is based on the same principle of profile extraction as the method used for the MTF, which follows the ISO 12233 standard. As the chart contains a single slanted square, the profile extraction is performed for each square edge, providing horizontal and vertical fringing measurements for black-to-white and white-to-black transitions.

Blue and red fringing are evaluated by comparing blue and red profiles respectively to the green profile (or the mean of Gr and Gb for raw images). The output value is the amount of color fringing within this fringe (see the definition below).

Color fringing is measured on the black side of the transition. Depending on the sensor saturation level, the limit of the Color Fringing measurement area will differ:

<table>
<tr><th>Sensor saturation <2</th><th>Sensor saturation ≥2</th></tr>
<tr><td>
</td><td>
</td></tr>
<tr><td>Limit is at $\frac{1}{2} \cdot D \max(1, \text{saturation})$,
with D the green dynamic</td><td>Limit is at green saturation</td></tr>
</table>

Fringing measurement

Looking for instance at blue fringing, for each pixel x, the following ratio $f(x)$ function is computed:

$$f(x) = \frac{B(x) - G(x)}{\max G - \min G}$$

where $B(x)$ and $G(x)$ are the blue and green levels at pixel x, and $\max G$ and $\min G$ are respectively the maximum (i.e. white value) and minimum values of the green channel in image. When the green channel saturates, $\max G$ is equal to the saturation value.

At each x position, if $f(x)$ is greater than a threshold α, this pixel is tagged as a fringing pixel. Such consecutive pixels located near the transition define a fringing zone; its width in absolute pixels gives the extent of blue fringing width (W). The amount of fringing is defined as:

$$A = \sum_{x \in W} (f(x) - \alpha)$$

The threshold α is set by default at 0.05, meaning that the blue fringing is detected when the relative difference of blue and green is larger than 5%. The value can be changed in the user interface when loading the images.

If there are several fringing areas for one channel, the result is given for the widest area only.

The same measurement is also performed for red fringing by comparing the red and green channels. Purple fringing, as a combined blue and red fringing, is the minimum values of the blue and red fringing. Purple amount is computed as:

$$A_{purple} = \sum_{x \in (W_{blue} \cap W_{red})} \left(\min \left(f_{blue}(x), f_{red}(x) \right) - \alpha \right)$$

Saturation factor
The rectangular T4105 Stouffer transmission step wedge placed under the slanted square is used to evaluate the saturation factor. This factor indicates how many times the input signal exceeds the sensor saturation. You can take multiple shots at different exposures to measure the fringing at different saturation factors. For instance, if the 6^{th} patch (optical density 0.3) is the first one saturated, the saturation factor is $10^{0.3} = 2$.

If this Stouffer step wedge is not saturated, the saturation factor is less than 1.

12.5 Measurement in raw format

Fringing can be measured both on RGB or raw images. The results provide completely different information.

The fringing phenomenon is due to the optical response of the system, amplified by the sensor saturation. The measurement in raw qualifies the color fringing on the optics and the sensor, without any image processing.

On the other hand, measurement in RGB format takes image processing into account. Image processing modifies the color fringing and sometimes tries to attenuate subsequent artifacts. In particular, the following steps of the raw conversion affect fringing:

- Color rendering.

- Demosaicing.
- Tone curve correction.
- Sharpening.

12.6 Analyzer output

Analyzer returns the following data:

- The Shooting Conditions tab contains general shooting conditions values, the selected fringing threshold, and the target used in the image (1 - target 001):

Image format	RGB
Image depth	8 bits/channel
Width	3008 pixels
Height	2000 pixels
Date	11/05/2011 - 15:14:37
Color space	Adobe RGB
Fringing threshold	5 %
Fringing target	1

- The Summary tab contains four sections:
  - The saturation factor, given for the green channel

Saturation factor (green)	7.13

  - The average fringing, computed by averaging fringing of the four transitions, for the three fringing colors (blue, red and purple)

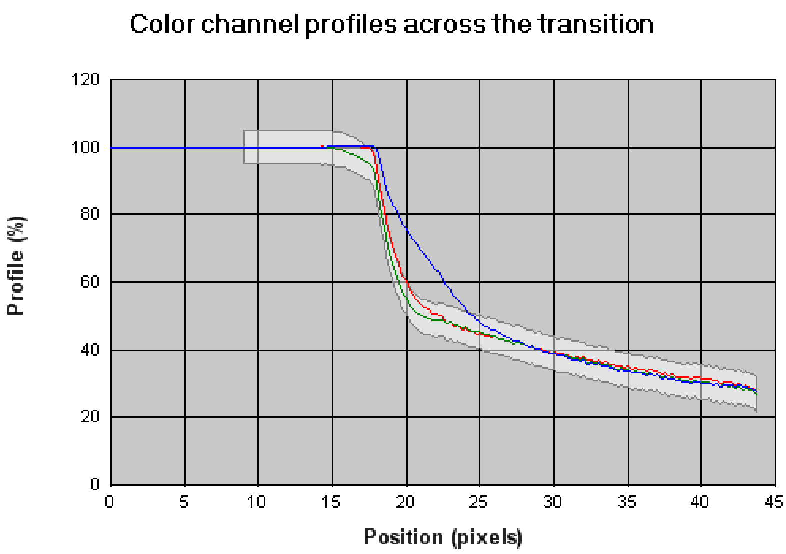
	Blue	Red	Purple
Average amount	54.6 (7.48)	0.4 (0.06)	0.4 (0.06)

  For each color, the fringing amount is given in pixels multiplied by intensity, and in mm multiplied by intensity on a 20×30 cm equivalent format. A negative amount means a lack of the measured color.

- The maximum fringing is also given, for each color. For blue, red and purple, the results of the transition that exhibits maximum fringing (intensity) are selected. The three color results are independent: the transition of maximum blue fringing may not be the same that the one with maximum red fringing.
- Eventually, the fringing for each transition (horizontal or vertical, white to black or black to white) is shown.

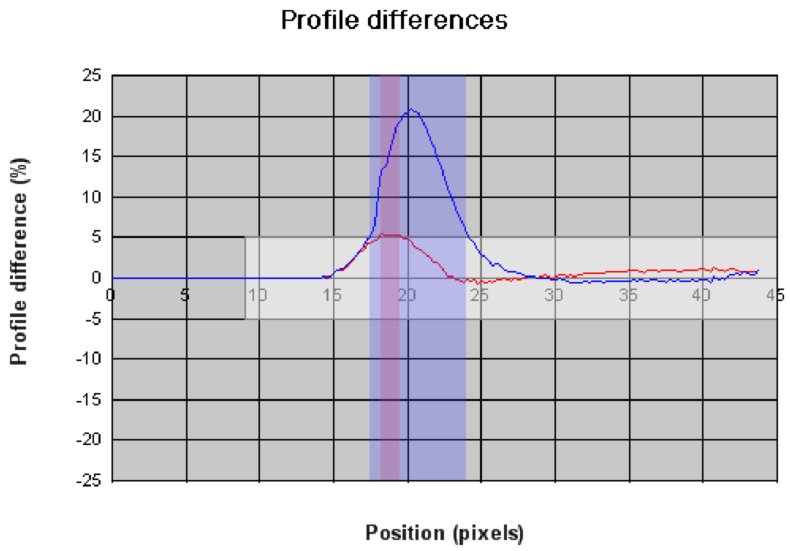
• The profiles and profiles differences are given for each transition, with one transition per tab

- The first graph shows the color channel profiles.



The light grey area around the green channel represents the fringing threshold.

- The second graph shows the profiles differences



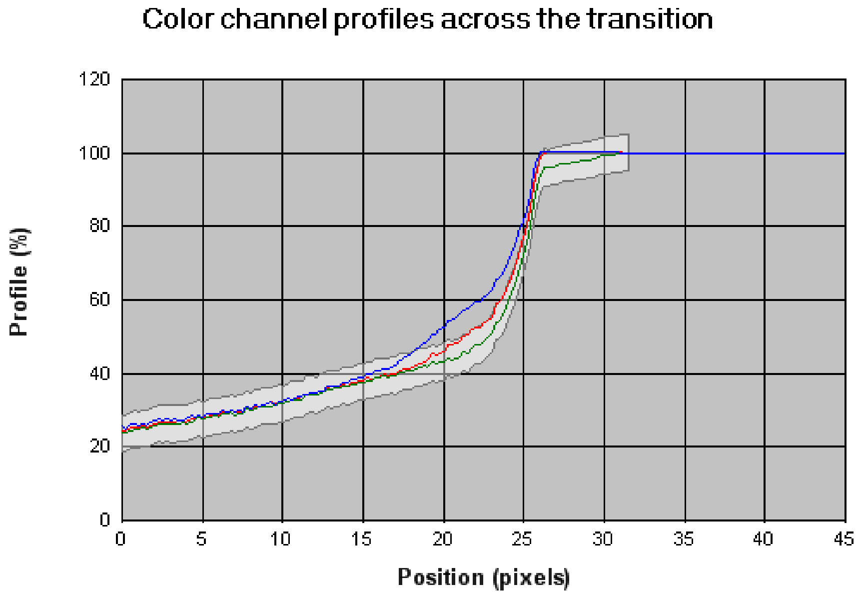
12.7 Examples

The figure below shows an example of blue fringing on a transition.

Illustration of blue fringing

The image has been shot with a camera phone at a shooting distance of two meters. Saturation factor is 11.22 for the green channel.

The graph of color channel profiles exhibits this fringing:

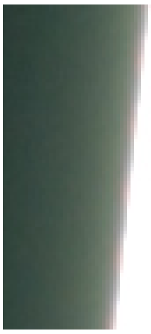


The blue channel is clearly higher than the green and red channels. The phenomenon is also visible in the average fringing results at 56.4 pixels (7.48 mm, 20×30 cm equivalent), which is a clearly visible color fringe:

	Blue	Red	Purple
Average amount	54.6 (7.48)	0.4 (0.06)	0.4 (0.06)

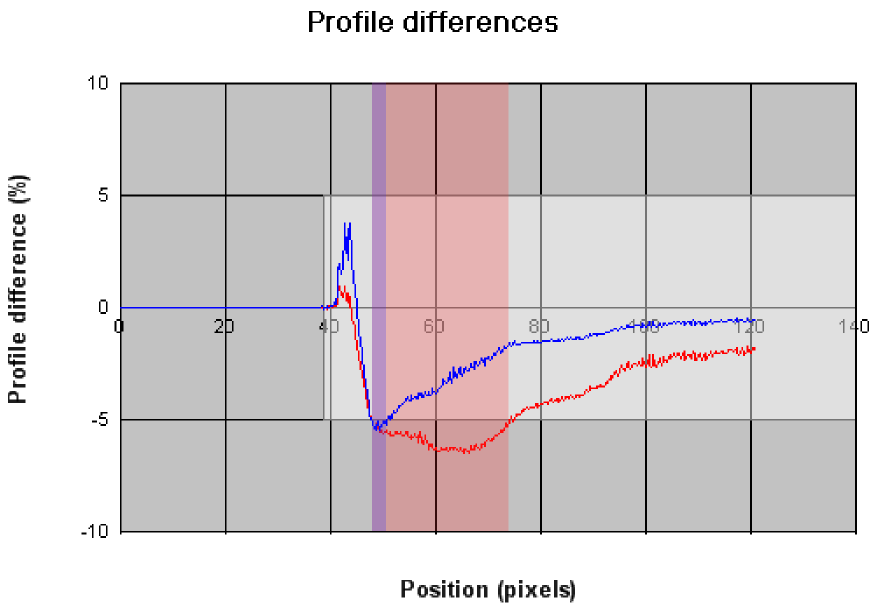
Red and purple fringing are negligible.

The second example comes from a DSLR. DSLR cameras usually have few color fringes, but some can appear when the sensor is highly saturated. The following image was shot on a 6 Mpix with a kit lens, at focal length 18 mm, and aperture f/3.5 at 2.5 m. The saturation factor is 22.39.



Color fringing on a D-SLR

Some blue/green hue is visible in the black part of the transition. This also appears in the profile differences:



A lack of red channel is visible on this graph. This lack leads to an excess of green and blue. The same behavior is also visible in the averaged results. While the fringing width is large, a low amount (meaning low hue) is detected:

	Blue	Red	Purple
Average amount	-0.7 (-0.07)	-24.0 (-2.39)	-0.8 (-0.08)

12.8 Measurement accuracy

The accuracy of the saturation measurement is related to the quantization of the step wedge. As the step is 0.05 density, a saturation factor X is known with a 12% precision. For example, if the measured saturation is 11.22, it means that the saturation is between 10 and 11.22.

The accuracy of the fringing amount is ±8 pixels.

The following parameters may reduce the accuracy of the measurement:

- A white balance error for RGB images
- A focusing error, either from autofocus or manual focus.

12.9 Measurement scale

The fringing amount qualifies the visibility of the phenomenon, but not the hue: a large fringe with a medium amount of fringing will be less colored than a small fringe with the same amount of fringing.

Absolute fringing amount (with α = 5%)	Qualitative level
Below 30	Hardly noticeable
Between 30 and 100	Visible
Over 100	Disturbing

12.10 Set up parameters influencing the measurement

The following setup parameters may change the results of the Color Fringing measurement:

- Digital zoom function: deactivate this unless it is the subject of the test.
- Resolution: set this to the highest available value to obtain accurate measurements.

- Deactivate such special camera settings as noise reduction filter, saturation filter, contrast enhancer, and so on, unless they are the subject of the test); the compression ratio should be as low as possible (TIFF format is preferable to JPEG).
- Color temperature: the image should be as "neutral" as possible, so that there is identical contrast between the three RGB channels.
- Settings that apply special color processing (sepia, B&W, saturation, color temperature, etc.), should be set to off or to neutral.

12.11 Validity of the measurement

The Color Fringing measurement is meaningful only if all the information about focal length, aperture, shooting distance, exposure (exposure time or saturation factor) is mentioned. If you have used specific setup parameters (noise reduction filter, contrast enhancer, and so on), you must mention them, too.

Giving the amount of color fringing with no further information is not meaningful. Give all the values of influencing parameters.

On the other hand, giving the fringing results of a camera with a 24 mm focal length, at f/2.8 with no sharpening filter, at a distance of 5 meters, is meaningful. You must also mention any information concerning noise reduction filter, saturation or contrast to validate the measurement.

12.12 Comparing two cameras

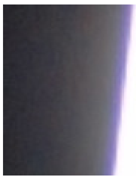
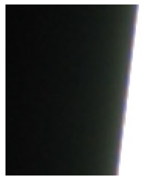
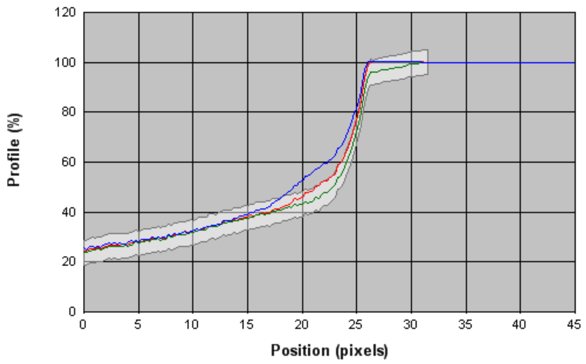
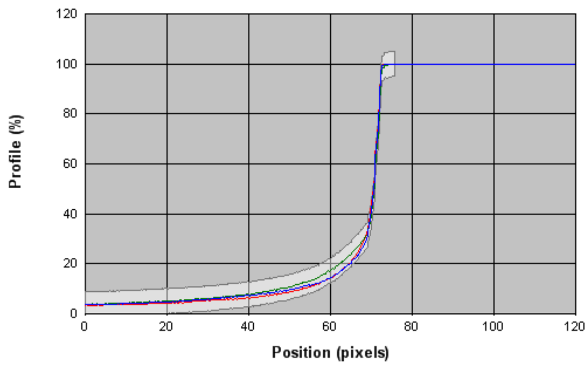
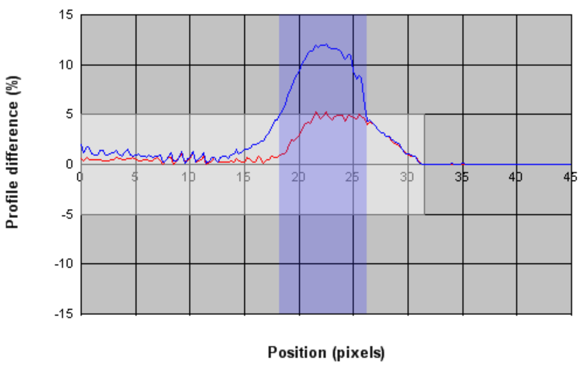
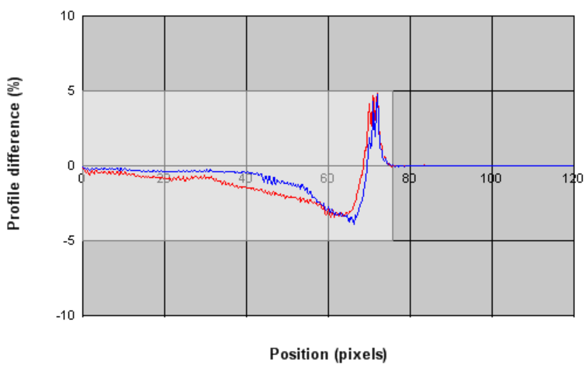
Comparing two cameras with different resolutions and/or different sensor sizes may seem difficult, because measurement is primarily computed in pixels.

As explained in the BxU measurement, which also gives results in pixels, a comparison of results of this kind will depend on whether the images issued from the two cameras are observed on a print or on a display.

If you print the images in the same single format, you can compare the results given in 20×30 cm equivalent format.

If you view the images on a display with zoom 1:1, the results in pixels should be preferred.

The following example shows the comparison of two cameras. The first one is a 3 Mpix camera phone, known for its high level of blue fringing; the second one is a 6 Mpix DSLR using a kit lens at focal length 18 mm, aperture f/3.5 (which produces the worst color fringing for this camera). Exposure for both cameras has been set to have pixels at eleven times the sensor saturation. Shooting distance is 2 m for both cameras.

<table>
<tr><th>Camera phone (3 Mpix)</th><th>D-SLR (6 Mpix)</th></tr>
<tr><td></td><td></td></tr>
<tr><td>
</td><td>
</td></tr>
<tr><td>
</td><td>
</td></tr>
<tr><td><table><tr><th>Blue</th><th>Red</th><th>Purple</th></tr><tr><td>38.68 (5.29)</td><td>0.00 (0.00)</td><td>0.00 (0.00)</td></tr></table></td><td><table><tr><th>Blue</th><th>Red</th><th>Purple</th></tr><tr><td>0.00 (0.00)</td><td>0.00 (0.00)</td><td>0.00 (0.00)</td></tr></table></td></tr>
</table>

On the profiles, the slant of the camera phone shows a lack of sharpness, while the DSLR slant is quite straight. A difference between color profiles is visible on the camera phone graphs.

The measurement confirms that the first camera has high blue fringing, while the DSLR, like most DSLRs, shows no color fringing.

12.13 Shooting

The Color Fringing measurement uses a color fringing chart.

You should usually center the target in the image field. But you can perform measurements anywhere in the field, provided that the detection markers are visible.

- ***Decide on the important parameters:*** focal length, aperture, focusing, resolution, ISO, sharpness, shooting distance, etc.
  - The exposure time setting depends on the sensor saturation desired.
- ***Special shooting conditions (see also Section 5)***
  - The target must be the only source of light.
  - The chart must be horizontal so that the angle between the square edges and the horizontal or vertical transitions is between 5° and 7°.
  - The target should be as orthofrontal as possible. Use the mirror method to position the camera suitably (see the protocol on page 75).
  - Markers should be at least 30 pixels high for a RGB image, and 60 pixels high for a raw image.
  - Ensure an acceptable white balance for RGB images.
  - Be careful with focusing: a bad or non-repeatable focusing will change the results.

The size of the saturated part on the step wedge indicates the saturation level:

Step wedge saturation	Sensor saturation
No saturation	<1×
One quarter	3×
One half	10×
Three quarters	30×

Note: It is important to keep a record of all the parameters and settings associated with each shot. Depending on the model, not all cameras record all the EXIF data, and if the measurement is to be used to compare two cameras, the recording conditions for the image files must be strictly identical.

12.14 Sidecar parameters

If automatic marker detection fails, you can use the `[Common]` section to provide these positions manually.

```
[Common]
// Manual color fringing chart position
X1=... // x coordinate of the top-left marker
Y1=... // y coordinate of the top-left marker
X2=... // x coordinate of the top-right marker
Y2=... // y coordinate of the top-right marker
X3=... // x coordinate of the bottom-left marker
Y3=... // y coordinate of the bottom-left marker
X4=... // x coordinate of the bottom-right marker
Y4=... // y coordinate of the bottom-right marker
```

It is also possible to define the offset in the image. This is mostly useful for raw images.

```
[Black]         // Black value section
BlackValue= ... // value to subtract to have 0 black (must be in 15b for raw images)
```

The following section, specific to the fringing measurement, allows applying a color matrix on color channels before measurements:

```
[Fringing]          // Fringing section
ColorRedRed= ...    // coeff. a
ColorRedGreen= ...  // coeff. b
ColorRedBlue= ...   // coeff. c
ColorGreenRed= ...  // coeff. d
ColorGreenGreen= ...// coeff. e
ColorGreenBlue= ... // coeff. f
ColorBlueRed= ...   // coeff. g
```

```
ColorBlueGreen= ... // coeff. h
ColorBlueBlue= ...  // coeff. j
```

This matrix is applied on red, green and blue channel as in this formula:

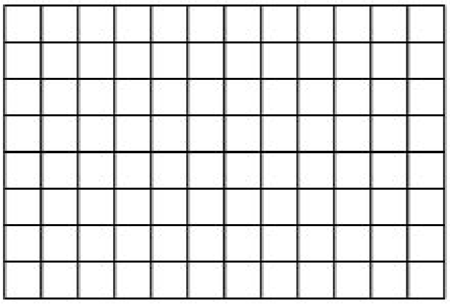
$$\begin{bmatrix} R' \\ G' \\ B' \end{bmatrix} = \begin{bmatrix} a & b & c \\ d & e & f \\ g & h & j \end{bmatrix} \cdot \begin{bmatrix} R \\ G \\ B \end{bmatrix} = \begin{bmatrix} a \cdot R + b \cdot G + c \cdot B \\ d \cdot R + e \cdot G + f \cdot B \\ g \cdot R + h \cdot G + j \cdot B \end{bmatrix}$$

By default this matrix is: $\begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$

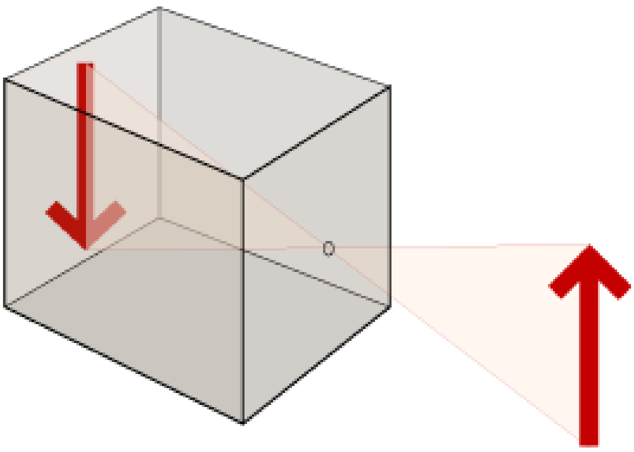
13 – DC: Distortion and Lateral Chromatic Aberrations

13.1 Introduction

A perfect optical system would be capable of projecting the image of a regular grid onto the camera sensor without distortion.



The pinhole camera, probably conceived by the Chinese around 500 BC, was described by Aristotle in ancient times. It allowed Renaissance painters to define the rules of perspective and enabled Nicéphore Niepce to produce his first photographic images. It consists of a light-excluding box pierced on one side by a small-diameter hole. Due to a basic principle of geometry, a distortion-free image is projected onto the inside wall of the box opposite to the hole.



If the observed scene is planar, then the scene and the projected image differ from a homography. In particular, all straight lines remain straight. Moreover, if the plane of the scene is orthofrontal, then the two images differ from a similarity transformation. In particular, all the parts of the scene are magnified in the same way.

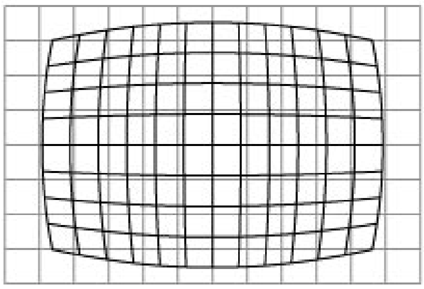
However, real cameras are not pinhole cameras. Lenses are not infinitely small, and nor are light sources. Distortion arises when the magnification is not uniform in the image field. In particular, straight lines do not remain straight. Moreover, the local magnification also depends on the wavelength, because refraction indices of lens materials classically depend on the wavelength, yielding lateral chromatic aberration.

13.2 Definitions

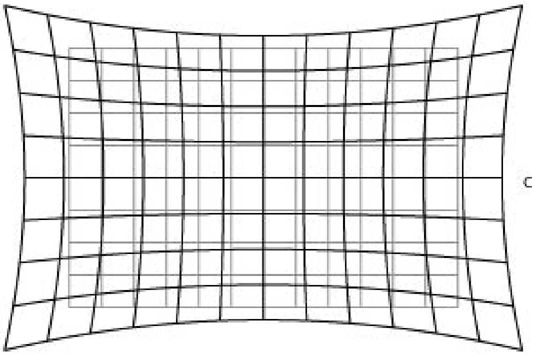
13.2.1 Geometric distortion

Two types of geometric distortion may arise, depending on the optical formula of the lenses:

- Barrel distortion, when the grid takes the form of a barrel (lines near the edges curve outwards)



- Pincushion distortion, when the grid takes the form of a pincushion (lines near the edges curve inwards)

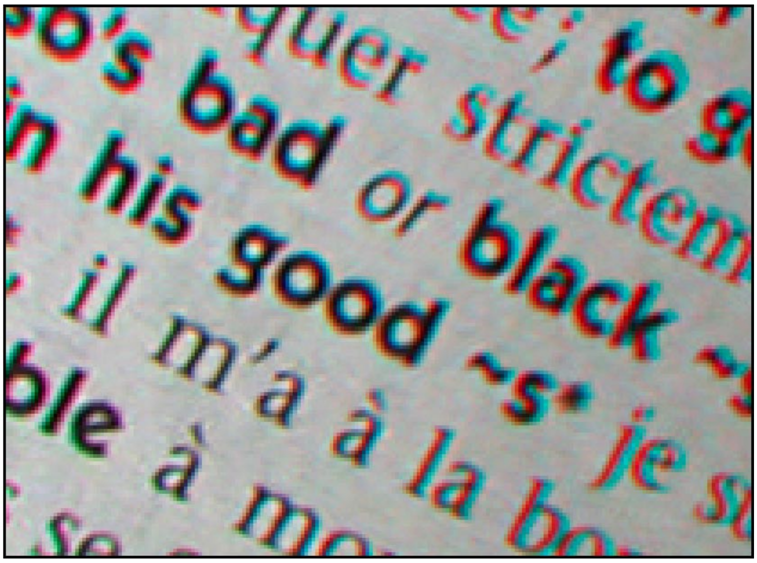


More complex lenses actually show a mix of these two behaviors.

The degree of distortion may not be even over the image area.

13.2.2 Lateral chromatic aberrations

The optical path of a light ray depends on its wavelength. A lateral displacement arises that is dependent on the wavelength of the light. These lateral chromatic aberrations are the object of interest of the present measurement.



Example of chromatic aberration

13.2.3 Measurements in arcminutes

Depending on the viewing condition of the images, the same measured chromatic aberration may or may not be visible. This is why chromatic aberration results are also displayed in arcminutes for several conditions: on a website, on a HD screen, and an 8 Mpix image equivalent. Arcminutes are considered in the object plan, between user and observed image.

The use of Arcminutes is motivated as it is a common unit for human eye resolution.

As a reference value, for a human eye with good acuity, the maximum resolution is about 1 arcminutes.

The formulas for these three conditions are:

- Web: Images are scaled to SVGA and viewed at 25 cm. Equivalent to a 61×46 mm image viewed at 25 cm.

  $$\text{Web LCA measurement (arcmin)} = \frac{180}{PI} \cdot \text{atan}\,(\text{LCApixel} \cdot 200/\text{image\_width}/2/750) \cdot 60$$

  where

  - 200 in mm is the default width for a 42-inch diagonal screen
  - 750 in mm is the screen viewing distance

- HDTV: Images are scaled to fit on a HD screen (width=93 cm) and viewed at 1.7 m.

  $$\text{HD LCA measurement (arcmin)} = \frac{180}{PI} \cdot \text{atan}\,(\text{LCApixel} \cdot 929/\text{image\_width}/2/1740) \cdot 60$$

  where

  - 929 in mm is the default width for a 42-inch diagonal HD screen
  - 1740 in mm is the screen viewing distance

- 8 Mpix equivalent: Images are scaled so that an 8 Mp image is viewed at 1:1 size on a 0.25 mm pixel-pitch screen at 60 cm.

  $$\text{LCA measurement (arcmin) 8 Mpix} = \frac{180}{PI} \cdot \text{atan}\,(\text{LCApixel} \cdot 0.25/2/600) \cdot 60$$

  where

  - 0.25 in mm is the default size for screen pixel pitch
  - 600 in mm is the screen viewing distance

13.3 Influencing factors

The following parameters have an influence on the measurement of distortion and lateral chromatic aberrations:

- The focal length of the lens (or the chosen focal length on a zoom lens).
- The focus distance of the lens.
- The distance of the subject (if different from the focus distance).

13.4 Measurement of distortion

13.4.1 Geometric distortion

Non local method

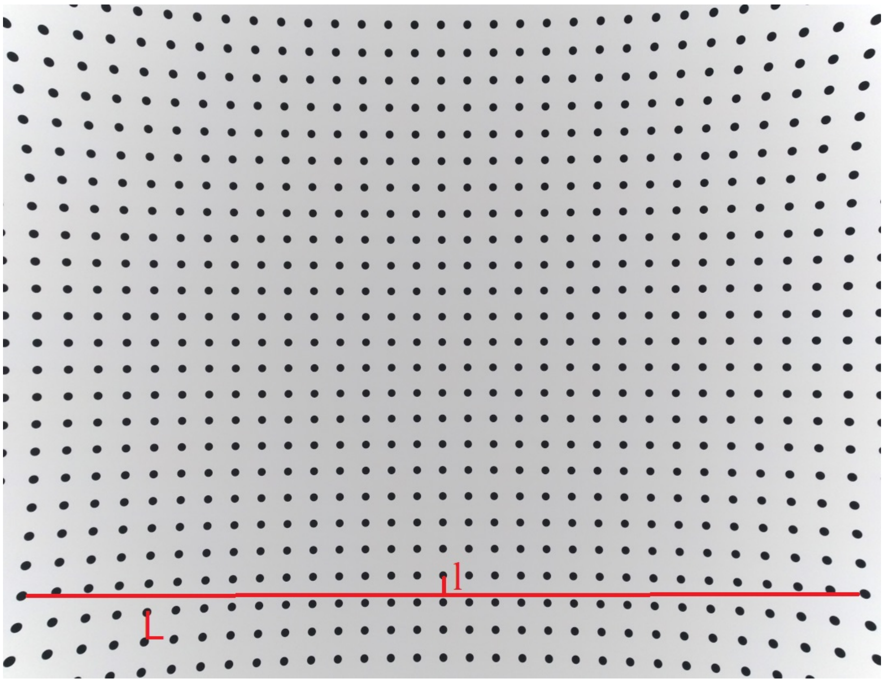
Analyzer characterizes distortion by measuring the positional errors associated with a series of points that are aligned on the test target (but not necessarily aligned in the image because of the distortion) as follows:

- Computation of the largest distance l between points that should belong to the same straight line, defined by the two points located at its ends (at a distance L).
- The positional error measurement relating to this series of points is the ratio l/L, expressed without units, but as a percentage (since it is a distance ratio).
- The result is positive in the case of barrel distortion, and negative in the case of pincushion distortion. It is close to 0 when there is no distortion.

Note: positions of points in the image, and therefore distortion, depend on the wavelength of the light (cf. Section 7). By convention, the measurement of distortion is based on only one color channel of the image. In case of a RGB picture (JPEG, etc.), the measure is directly done on the green channel.

> In case of a raw image, the measure is done on a computed green channel obtained with a linear interpolation of pixels surrounded by a green color filter.

The following diagram illustrates a positional error measurement on a set of points located at the edge of the image:



Non local measure of distortion

The average positional error measure represents the average of all the positional error values of all the points with respect to a virtual reference grid covering 95% of the field. The maximum positional error measure represents the largest positional error calculated over the all these points.

An image may contain a mixture of barrel and pincushion distortion. In this case, the measurement indicator will display the distortion that has the higher value.

Local method

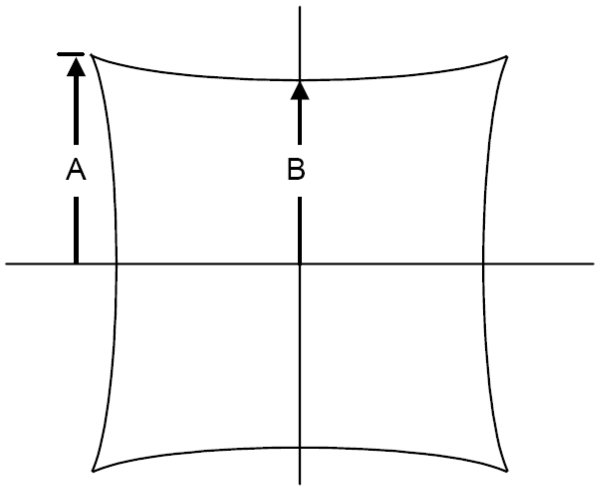
Analyzer also proposes another measurement of distortion obtained from the following considerations: The position of a dot center in the observed (distorted) image is also known in the undistorted image. For any other point, the undistorted position can be interpolated with a high-degree polynomial. The ratio between the distance of a point to the image center in the observed image and the theoretical image is a relative measure of distortion.

This measurement is the ratio of two distances and has no unit. It is close to 1 when there is no distortion. This value is averaged on circles centered at the image center. Note that this measure is related to the effective focal length measure (Section 16).

There is no mathematical identity relating the local and non-local distortion. However, because the non-local distortion is usually measured on the image border, the two measurements are approximately related by $d_{\text{local}} = 1 + \alpha d_{\text{non local}}$, where α is a numerical constant close to 1.

TV Distortion

Analyzer also computes the TV Distortion, which is a measure of the perceived distortion described in the SMIA standard. It is described below:



The value of TV Distortion for a corner is $D_{\text{TV}} = 100 \cdot \frac{A - B}{B}$

This value is computed for each of the four corners, and the total TV Distortion is the mean of these four values.

There is an explicit relation between the TV Distortion and the Analyzer maximum distortion. For a camera with maximum distortion located in the center of the image top border or bottom border, we have

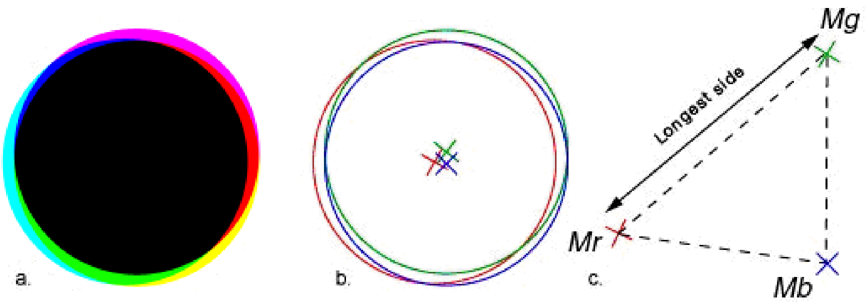
$$D_{\mathrm{TV}} = \frac{D}{\frac{H}{2 \cdot W} - \frac{D}{100}}$$

W is the width of the image, *H* its height and *D* the distorsion computed by Analyzer.

Be aware that for barrel distortion, the TV distortion value will be negative, and positive for a pincushion distortion, thus the opposite of the Analyzer distortion (i.e., positive for barrel and negative for pincushion).

13.4.2 Lateral chromatic aberration

Analyzer stores three positions for each image spot, associated respectively with the red plane (point Mr), the green plane (point Mg) and the blue plane (point Mb) of the analyzed RGB image. For a measurement performed on a raw image, R, G, and B channels are first computed with a linear interpolation of pixels with the same color filter: there is no mix between the information of pixels with different color filters. The lateral chromatic aberration, associated with point Mg, is defined as the length (in pixels) of the longest side of the triangle Mr-Mg-Mb.



Definition of chromatic aberration

The result of the measurement is displayed in three forms:

- In absolute pixels (along with the measurement accuracy).
- As a proportion of the image width (expressed in ‰).

- In a 24×36 equivalent, in order to compare cameras whose sensors have different resolutions and sizes.

13.5 Measurement in raw format

The geometrical distortion and the lateral chromatic aberrations are optical phenomena. Raw and RGB measures should give similar results (and usually do).

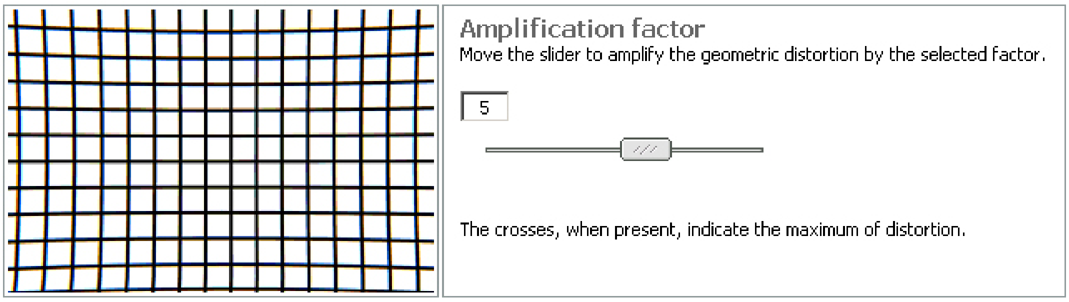
However, several steps of raw conversion may mix information from different channels, and affect lateral chromatic aberration. These steps include:

- Demosaicing
- Denoising filter
- Color rendering
- Image compression

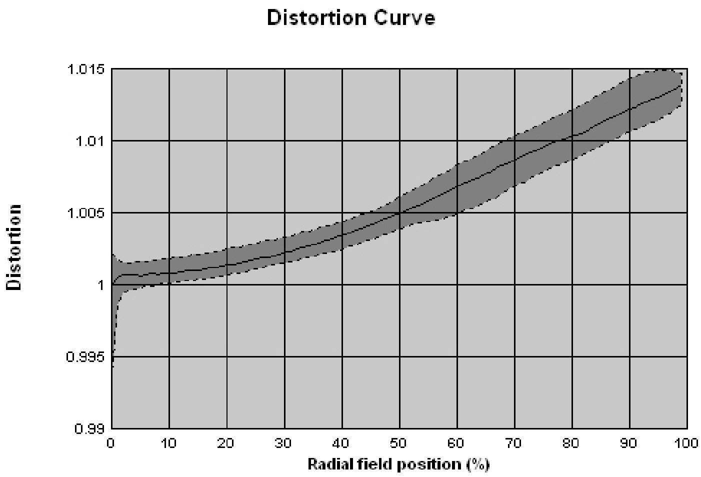
13.6 Analyzer output

Analyzer returns the following data:

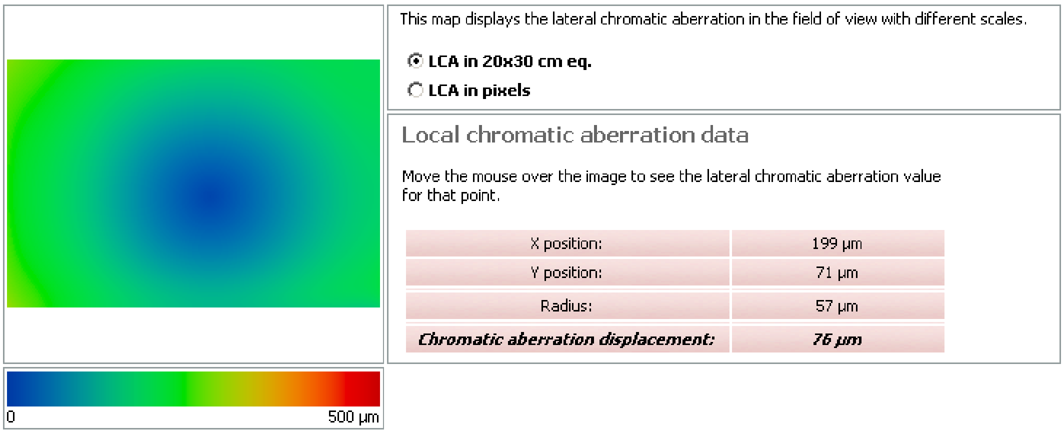
- The Summary tab contains the mean value and the maximum value of distortion obtained by the global method, and the value of TV Distortion. It also contains the maximum and mean lateral chromatic aberrations in different units: in pixels; as a proportion of the image; and as a 20×30 cm equivalent (results in μm).
- The geometric distortion tab presents a virtual view of the regular grid after application of the measured distortion. For better visibility, you can set the amplitude of the distortion by moving the slider. When the amplification factor is equal to 1, the location of the maximum distortion is displayed. The grid is a three-channel image, so that lateral chromatic aberration can also be visualized (usually only when using an amplification factor, however).



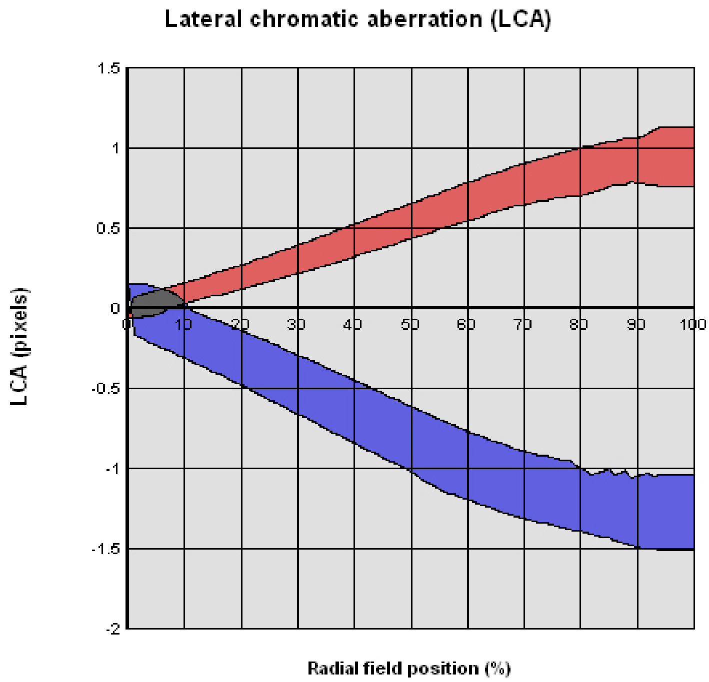
- The distortion curve tab presents the variation of the distortion in the image field, computed with the local method. The origin on the *x* axis is the center of the image and the *y* axis represents the ratio between the distances to the image center in the distorted and undistorted image. The central curve is the mean distortion, and the two envelopes are the maximum and minimum distortion at the same distance.



- The CA 2D map tab shows the lateral chromatic aberration on a color scale. A radio button control toggles between a 20×30 cm equivalent scale and the measurement in pixels in the image. The former is expressed in μm, and allows the comparison of cameras with different resolutions. The latter is expressed in pixels and is more suitable for a precise examination of the shape of the color aberration map. When moving the mouse over the map, the value of the lateral chromatic aberration is displayed on the right.



- The CA curves tab shows the shift between the color planes. The G plane is taken as a reference. The shift of the R and B planes is measured in pixels through the image field. The upper and lower envelope is displayed for each channel.



- The CPIQ LCA and CPIQ LGD tabs display results of chromatic aberration and distortion following CPIQ standards. See CPIQ section for a description of these results.

The Summary tab contains the mean value and the maximum value of distortion obtained by the global method, and the value of TV Distortion. It also contains the maximum and mean lateral chromatic aberrations in different units:

- As a proportion of the image, in pixels)
- As an equivalent to a 20×30 cm screen, in µm
- On a website, in arcminutes
- On a HD screen, in arcminutes
- On the equivalent of an 8 Mpix image, in arcminutes

Geometric Distortion

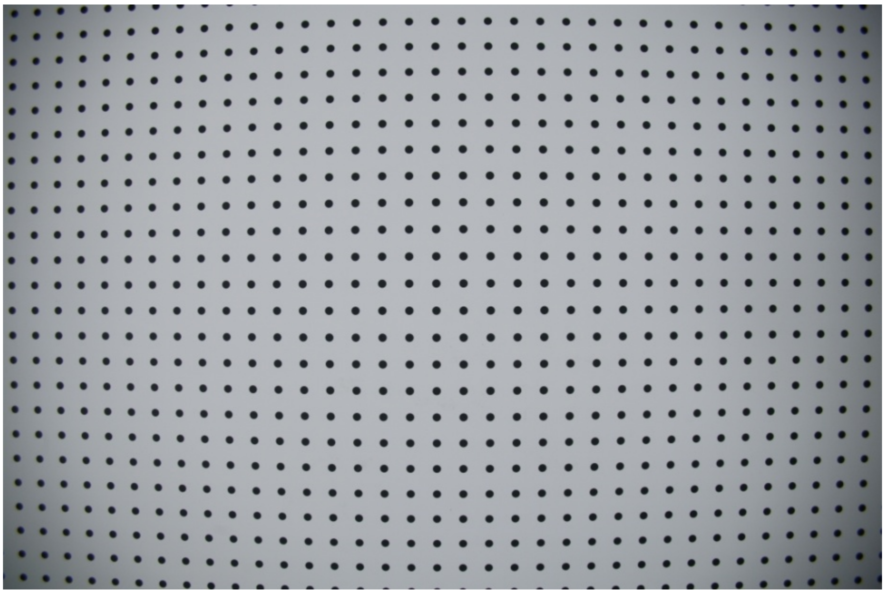
Maximum	1.07 %
Mean	0.49 %
TV distortion	-2.53 %

CA 2D map

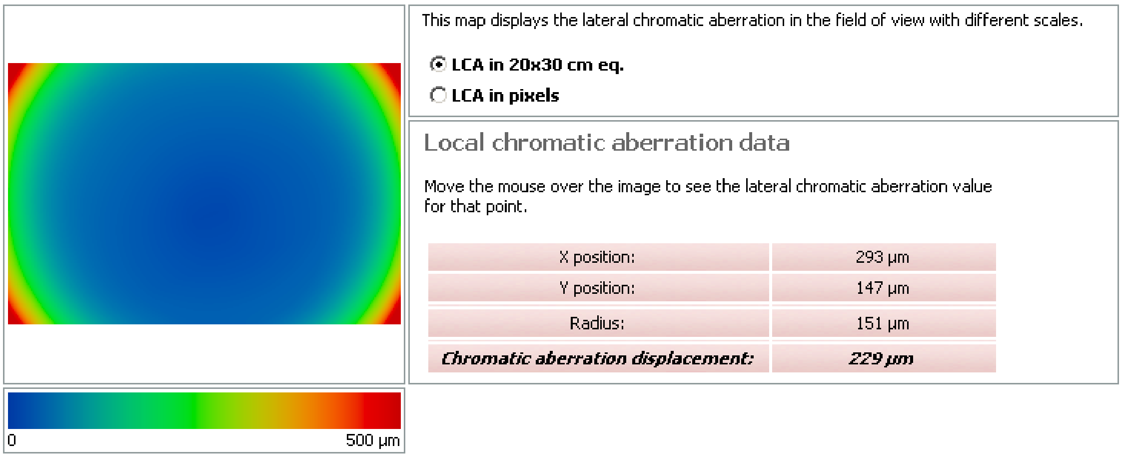
	in pixels	/1000	in µm (20x30 cm eq.)	in arcmin (Web)	in arcmin (HD)	in arcmin (8MPix)
Maximum	1.2	0.6	219.914	0.36	0.71	0.89
Mean	0.8	0.4	143.017	0.23	0.46	0.58

13.7 Examples

The first example comes from a DSLR. The image has been taken with a 16–35 mm lens at 16 mm, on a Canon 1Ds camera, at 0.5 meters from the chart. With that kind of wide angle, distortion is very high.



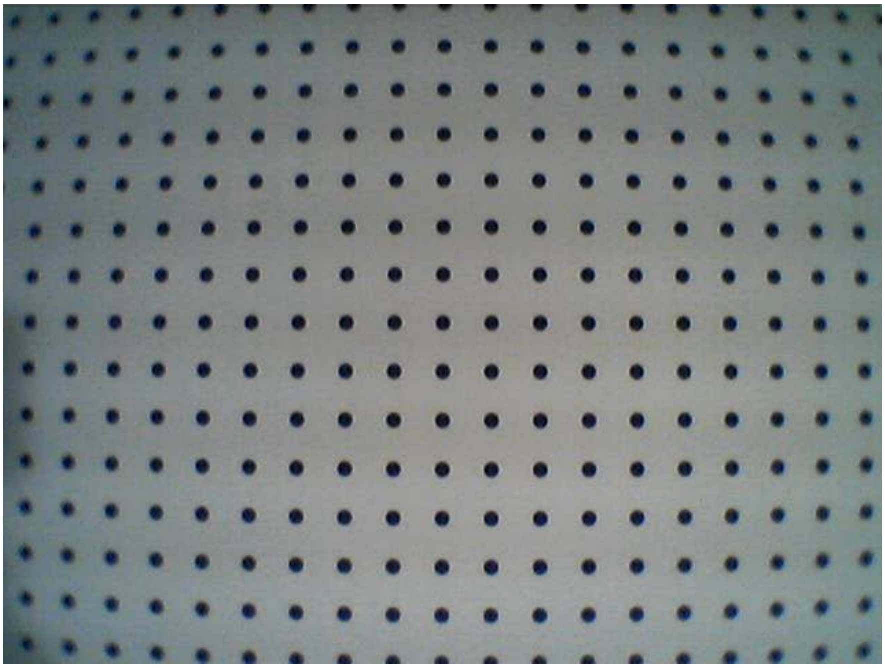
The maximum distortion is 1.52%, with a mean distortion equal to 0.9%. The TV distortion value is -4.35 (barrel distortion, clearly visible on the image). Mean chromatic aberration is 68.24 mm.



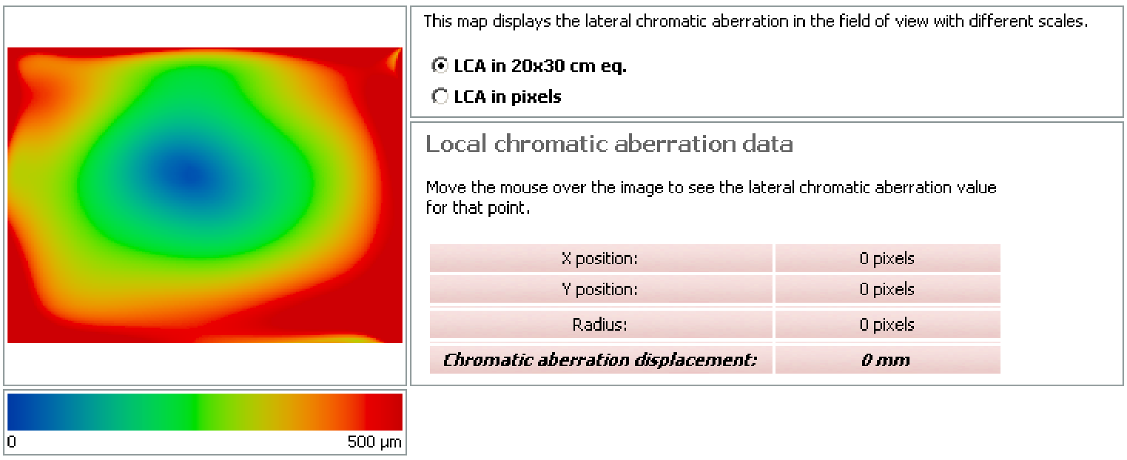
With the 2D LCA map, we can see that the geometric deformation is strong but radial and centered. The lateral chromatic aberration is very high in the corners, but low in most parts of the image field.

The second example comes from a camera phone. The image was taken with a Nokia 7650 phone of a chart at 0.5 m. Focal length is fixed for this kind of camera, and is equivalent to a 35 mm length for a 24×36 mm sensor. But as the sensor is very small, its effective focal length is close to 4 mm (see Focal

Length, Section 16 for more details about effective focal length). This is a very wide-angle length, and thus the image has high barrel distortion.



The maximum distortion is 1.86% with a mean distortion equal to 0.85%. TV distortion value is -4.64. Mean chromatic aberration is 313.39 mm.



We can see on the 2D LCA map that chromatic aberration affects the entire image field except the very center of the image. The phenomenon is also neither clearly radial, nor centered.

13.8 Measurement accuracy

Geometric distortion and chromatic aberration measurements involve distance calculations in the image. These calculations are accurate at about 0.5 pixels which is the usual observed accuracy for the position of the dots' centers. Thus the accuracy of lateral chromatic aberration is ±0.5 pixel.

The accuracy of the geometric Distortion measurement is directly proportional to image resolution according to the formula $\frac{\pm 0.5\,\text{pixel} \times 100}{\text{image height in pixels}}$.

Examples:

- for a 4064×2704 pixels image, the accuracy of the positional error measurement is ±0.02%,
- for a 2272×1704 pixels image, the accuracy of the positional error measurement is ±0.03%,
- for a VGA image (640×480 pixels), the accuracy of the positional error measurement is ±0.1%.

13.9 Measurement scale

Distortion becomes visible once the maximum distortion value exceeds approximately 0.2%.

Maximum distortion value	Maximum TV Distortion	Qualitative distortion level
Between 0.0% and 0.1%	Between 0.0% and 0.3%	Not perceptible
Between 0.1% and 0.3%	Between 0.3% and 0.9%	Visible to an expert
Between 0.3% and 1.0%	Between 0.9% and 3.0%	Visible to a novice
Between 1.0% and 3.0%	Between 3.0% and 9.0%	Very annoying
Over 3%	Over 9%	Unacceptable

As TV distortion is linked to maximum distortion (see the formula in Section 226), it is possible to quantify the distortion level with this value and this tabular. For example, for a camera with a width/height ratio of 3/2, the absolute TV distortion value will be three times the absolute maximum distortion value.

Lateral chromatic aberration can be usefully expressed in units independent of the image resolution. Converting a measurement in pixels into a 200×300 mm equivalent measurement for a sensor with W×H pixels is obtained by the simple formula:

$$\text{measure}_{24\times36} = \text{measure}_{\text{pixels}}\sqrt{\frac{300\times200}{WH}}.$$

(If the aspect ratio is changed, apply the calculation described in Section 6.11). The result is then expressed in mm.

Maximum value of lateral chromatic aberration (in 200×300 equivalent)	Qualitative level
Between 0 and 0.1 mm	Not perceptible
Between 0.1 mm and 0.2 mm	Noticeable
Between 0.2 mm and 0.5 mm	Objectionable
Over 0.5 mm	Not acceptable

Maximum value of lateral chromatic aberration in arcmin	Qualitative level
Between 0 and 0.7 arcmin	Not perceptible
Between 0.7 and 1 arcmin	Visible by an expert
Between 1 and 1.5 arcmin	Visible by a novice
Over 1.5 arcmin	Not acceptable

13.10 Setup parameters influencing the measurement

The following camera settings may influence the measurement

- The use of digital zoom (which should normally be off, unless it is the object of the measurement).
- The image aspect ratio 4:3, 16:9, etc. (normally the shooting should use the sensor field as much as possible, unless it is the object of the measurement).
- The image compression ratio (use the lowest compression ratio).
- The sharpness applied to the image (turn this filter off).
- The ISO setting, the settings for exposure time, aperture, and exposure correction:
  - The lower the ISO setting, the less noise there will be in the image (noise may disturb the measurement).
  - Over-exposure can lead to the appearance of fringing that will alter the chromatic aberration.
  - The aperture has an effect on the depth of field (which may be helpful in framing the test target with certain lenses that do not have the necessary focusing range); a blurry image will give less accurate measurements.
- Color temperature: with a "neutral" image, contrast between the three RGB channels is identical.
- Settings that apply special color processing (sepia, B&W, saturation, color temperature, and so on) should be turned off or set to neutral.
- Resolution, which you should set to the highest available value to gain measurement accuracy, unless this parameter is part of the characterization.

13.11 Measurement validity

An isolated value of distortion is not meaningful. It is always necessary to associate it with the influencing parameters. For example, claiming that the distortion of a camera is 1.2% is meaningless. On the other hand, it is perfectly meaningful to indicate that a camera with a 16 mm lens focused at 5 m has a 1.2% distortion.

Similarly, an isolated value of lateral chromatic aberration is not meaningful. It is always necessary to associate it with the influencing parameters. Claiming, for example, that a camera has a 0.04 mm lateral chromatic aberration is meaningless. On the other hand, it is perfectly meaningful to indicate that the lateral chromatic aberration of a camera at a focal length of 24 mm, with the focus set to 4 m and the digital zoom set to OFF, is 0.04 mm.

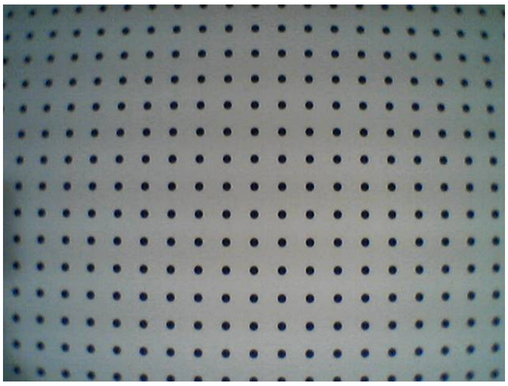
13.12 Comparing two cameras

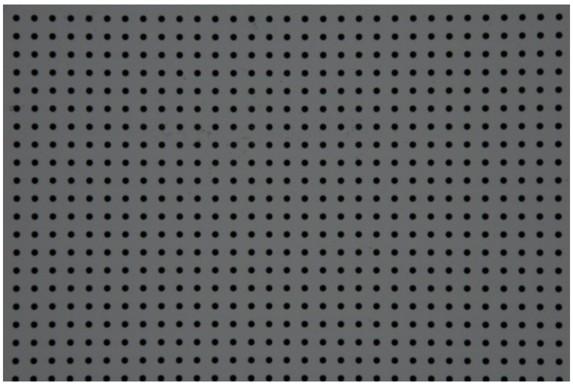
First, the general shape of the geometric distortion figure can be compared (barrel or pincushion).

Besides this qualitative property, you can also compare numerical measurements, since they are independent of the resolution.

You can compare lateral chromatic aberration measurements, provided they are expressed in the same units.

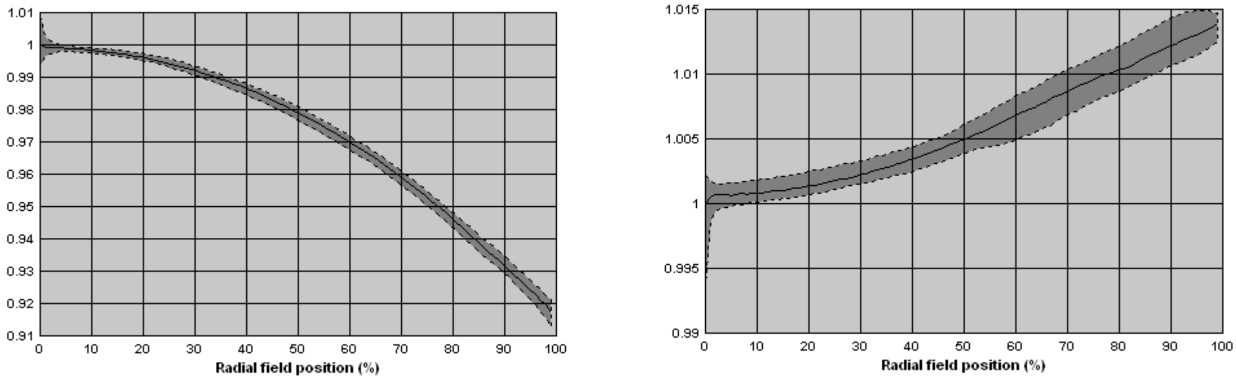
The following examples show the comparison of two cameras. The first is the Nokia camera phone 7650 used as an example above. The second is a Nikon D70s camera with a 135 mm lens at 4.5 m. The Nokia lens is a wide-angle, and the D70s's lens is a telephoto. We can see on the images that the camera phone (left) has barrel distortion, and the DSLR (right) has a pincushion distortion.





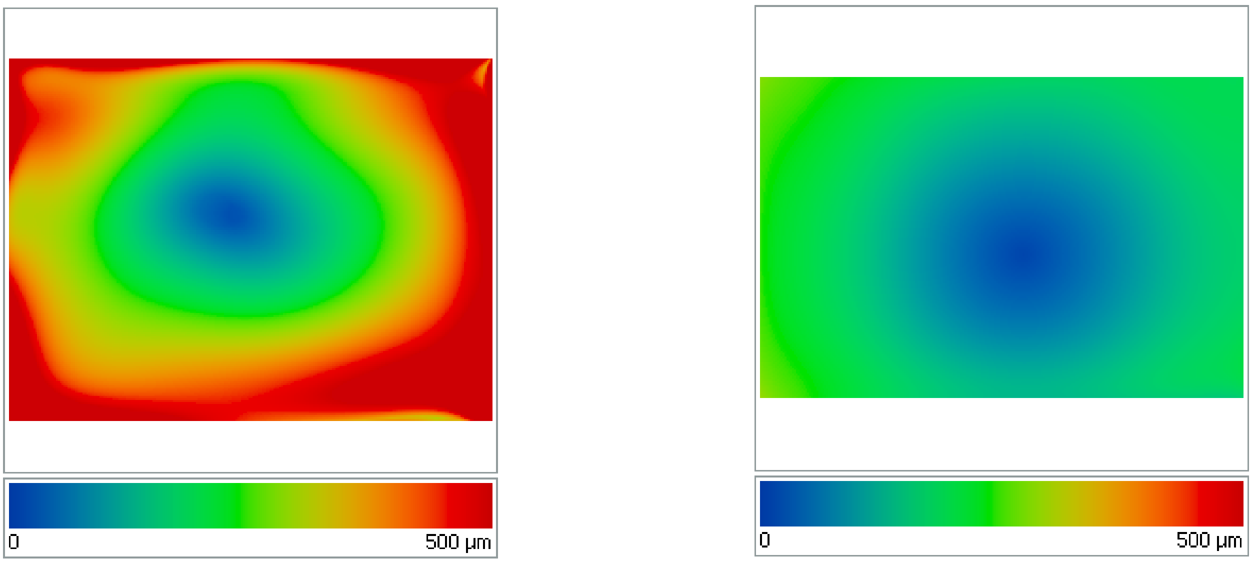
For the DSLR, the maximum distortion is −0.28%, with a mean distortion equal to 0.13%. For the camera phone, the maximum distortion is 1.87%, with a mean distortion equal to 0.85%.

The distortion curves below show the type and the intensity of distortion. The camera phone (left) has a high barrel distortion (decreasing curve). The DSLR (right) has a little pincushion distortion (increasing curve).



Distortion curves for a camera phone with wide angle (left) and a DSLR with telephoto lens (right)

The lateral chromatic aberration shows a quality ranking, as can be seen on the 2D maps using the same color scale. The map of the camera phone's wide-angle lens shows a lot of chromatic aberration. By comparison, the DSLR's telephoto lens displays very little chromatic aberration.



13.13 Shooting

The DC measurement uses a Dots target.

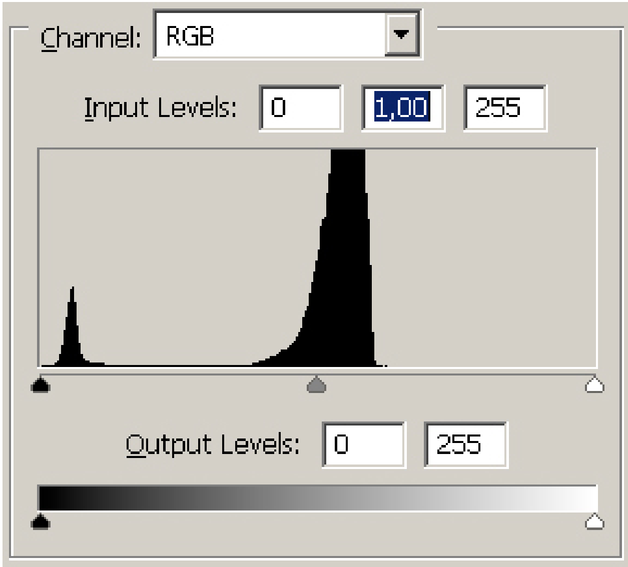
Geometric distortion and chromatic aberration are processed together, as the characterizations are calculated in a single pass.

a) **Determining the influencing parameters** (focal length, focus distance, distance of the subject, digital zoom, aspect ratio). You should check the following parameters:

   - Select the camera's manual mode (if the camera has one).
   - Remember that the measurement depends on the distance between the camera and the scene, which means that a complete qualification of a camera's distortion has to be measured at several distances. Set the focus accordingly to the distance of measurement.
   - Check that the test target is within the depth of field (the smaller the aperture, the higher its f number, f:16 or f:22, for example). Refer to Section **??** to choose the appropriate test target.

b) **Specific shooting conditions** (see also Section 5).

> **Note:** the aperture must be set to the smallest available aperture on the lens (f/22, for example). The framing must be such that:
>
> - The image contains at least 300 spots, or 20 columns of spots for a high-resolution camera (200 spots for a low-resolution camera, typically a camera-phone); they must be sharp (focus should preferably be set according to the chart distance) and have a regular shape; spots and columns must not be cropped.
> - The image contains fewer than 1500 dots.
> - No element external to the test target should appear in the frame.
> - Select the lowest ISO setting, such that the image has a "good" histogram — that is, it should be clearly bimodal and values should not be clipped.



Histogram of a dots chart shot

Take all necessary precautions to avoid shaking the camera when shooting. It might be better to use a cable release or trigger the shot from a computer connected to the camera via a FireWire cable.

Note: It is important to keep a record of all the parameters and settings associated with each shot. Not all camera models record all the EXIF data, and if the measurements are to be used to compare two cameras, the image file recording conditions must be strictly identical.

Note: This measurement allows a full check of the test target flatness. To complete the preliminary check (explained in Section 3.2.1), proceed as follows:

1. Make sure that the framing conditions conform to the conditions described in Section 15.13b. The test target is not considered flat if the difference between the measured positional errors exceeds the tolerance indicated in Section 13.8.
2. Take 2 shots with the camera of your choice: the first shot in landscape format and the second in portrait, without changing the influencing parameters.
3. Measure the distortion for each shot.
4. If the results of the shots differ, contact Technical Support.

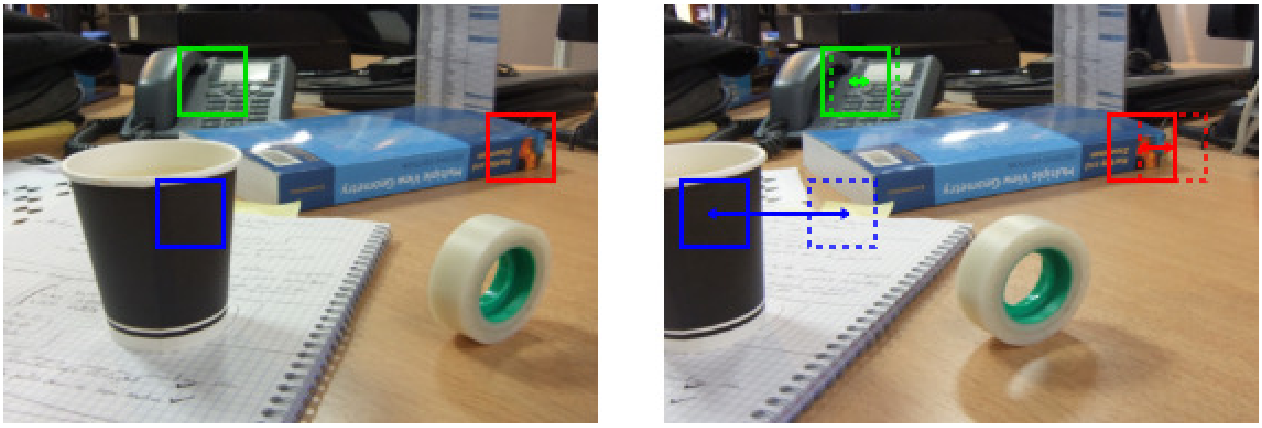
14 – 3D: 3D Geometry

14.1 Introduction

In 1838, Sir Charles Wheatstone created the first “stereoscope,” a device that allowed the separate but simultaneous viewing of two distinct images, one with each eye. Since photography was only in its infancy, Wheatstone used drawings with slightly shifted objects to give an impression of depth when viewed.

We have come a long way since Wheatstone’s invention. Nowadays, we can use binocular cameras or binocular devices coupled with cameras to take two separate photos or movies simultaneously. Viewing is made possible with high frame-rate screens coupled with goggles that block the view for one eye at a time; “anaglyph” images and red-cyan goggles; and auto-stereoscopic display screens that use micro-lenses to direct each pixel to one or the other of our two eyes.

Binocular stereovision aims to simulate human vision by simultaneously capturing a three-dimensional scene from two different points of view. Using these two points of view, our brain can interpret the shifts (or disparities) of objects from one eye to the other and convert this visual information into distance. A close object will cause a large disparity and a far object a smaller one.



Images from a binocular camera. The shift from left to right in the images is larger for the cup in the foreground than for the phone in the background

A necessary step for proper visualization of a three-dimensional scene is the rectification of the stereo system. This rectification is equivalent to forcing the cameras’ optical axes to be parallel and the cameras to be horizontally aligned, which is, in fact, the same configuration of our eyes. The resulting images from these virtual cameras have the following properties:

- The shifting of objects throughout the images is only horizontal.
- Objects at the same distance are identically shifted.

A badly-rectified stereo system can strongly affect the resulting 3D view. A non-uniform disparity for objects at the same distance will give the impression of a distorted 3D scene. On the other hand, non-horizontal shifting is an unnatural movement for our eyes and will therefore be hard for our brains to process. Finally, rectification may be used to limit the intensity of horizontal disparities so as to limit eye convergence or divergence during viewing. Such compensation based on rectification must be adapted to the display device.

14.2 Definitions

Disparity

A disparity is the shift in position of an object from one image to the other.

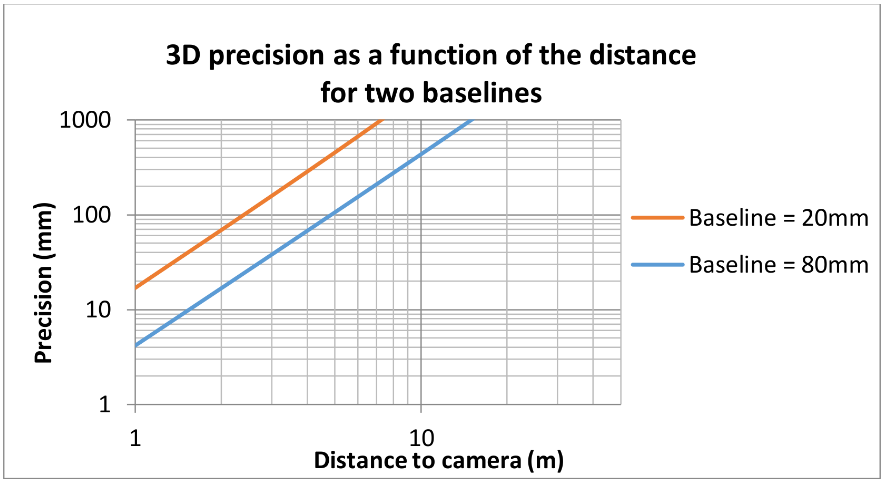
Baseline

The baseline is the distance between the optical centers of the two cameras in a binocular stereo system. The baseline is a very important characteristic of a stereo device since it defines the intensity of the 3D effect.

For a given field of view, a small baseline allows viewing nearer objects with both cameras. A large baseline, however, offers a better visualization of far objects. The latter statement can be explained by the 3D reconstruction formula used for rectified cameras:

$$z = \frac{f \cdot B}{\epsilon} \tag{1}$$

where z is the distance from the object to the camera, ϵ is the corresponding disparity, f is the effective focal length, and B is the baseline of the two cameras. The graph below shows the achievable 3D precision as a function of the distance for two baseline values: 20 mm and 80 mm (the focal length chosen here is the same for both cameras).



Achievable precision for 3D estimation as a function of the distance. Two baseline configurations are tested. The sensor dimensions and resolutions, the focal lengths, and the precision of the disparity are identical for both configurations

From equation (1) and given a focal length, a baseline, and a sensor resolution, we can define the first and last perceptible distance. The first perceptible distance is the minimal distance that both cameras can see, and corresponds to a disparity equivalent to the sensor width. The last perceptible distance is the last distance that can be distinguished from infinity and corresponds to the minimal disparity that can be viewed (1 pixel, for instance). Using the two previous baseline values, we obtain the following ranges for disparity (assuming a 5 Mpix sensor, a FoV of 45°, and a disparity precision of 1 pixel):

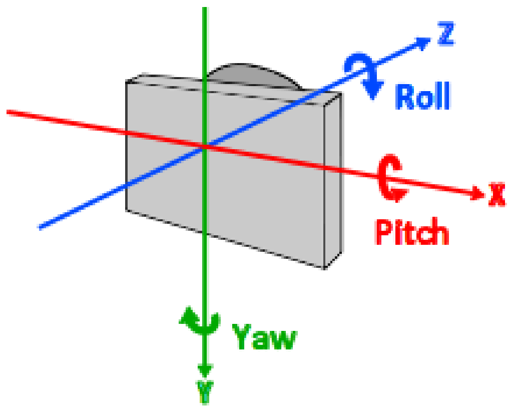
	First perceptible distance (m)	Last perceptible distance (m)
Baseline = 20 mm	0.024	62.56
Baseline = 80 mm	0.096	250.24

The baseline value therefore affects the nearest and furthest object visible by a stereoscopic camera.

Pitch, Yaw, Roll

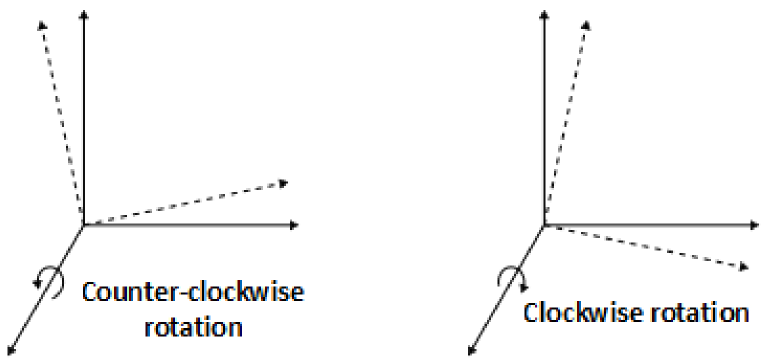
Each camera defines a coordinate system whose three axes are the optical axis of the camera lens and the horizontal and vertical axes of the sensor. The change in orientation of the second camera compared to the first one is defined by a three-dimensional rotation.

Analyzer uses the *ZYX* Euler angle convention to define the rotation of the second camera (right) compared to the first one (left). This means that the orientation of the second camera is obtained by a first rotation φ around the horizontal axis of the first camera (pitch angle), a second rotation θ around the vertical axis of the first camera (yaw angle), and a last rotation ψ around the optical axis of the first camera (roll angle).



Angle convention used in this manual

Finally, we use the counter-clockwise convention for a right-handed coordinate system, which means that when the rotation axis points towards the target, the two other axes are rotated counter-clockwise:

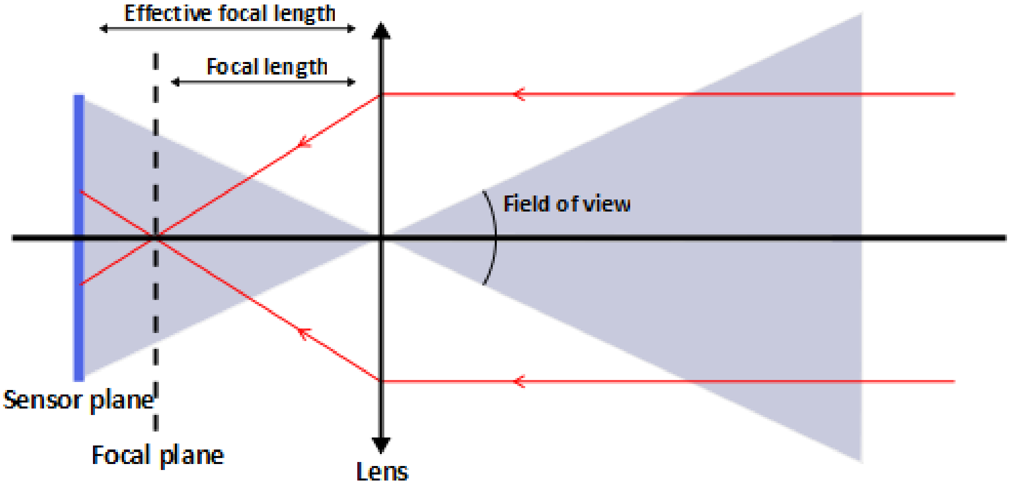


Clockwise vs. counter-clockwise rotation in a right-handed coordinate system

Assuming a rectified stereo system, the three angles should be 0°, since the cameras have the same orientation. The further away from 0°, the lower the quality of the 3D rendering will be.

Field of view, focal length, and effective focal length

These three concepts are illustrated in the following figure:



Field of view, focal length, and effective focal length

The focal length is the distance between the lens principal plane and the focal plane. This value is expressed in mm and will be referred to as f_∞.

In camera calibration literature, the term "focal length" often mistakenly refers to the distance between the sensor plane and the lens principal plane. Since the term is not consistent with the one used in optics, we will use the term "effective focal length" when talking about this distance (see Section 16 on EFL for more details). In camera calibration, the effective focal length is usually expressed in pixels. We will therefore refer to it as f_{pixels} or f.

The field of view is the extent of a given scene that is imaged onto the sensor. It is related to the effective focal length by:

$$f_{\text{pixels}} = \frac{\text{Sensor size}_{\text{pixels}}}{2 \cdot \tan \text{FoV}/2} \tag{2}$$

Moreover, when the focus is at infinity (i.e., sensor plane corresponding to focal plane), the effective focal length is related to the focal length by:

$$f_{\text{pixels}} = \frac{\text{Sensor size}_{\text{pixels}}}{\text{Sensor size}_{\text{mm}}} f_{\infty} \tag{3}$$

Principal point offset

In 3D geometry, the principal point refers to the intersection of the camera optical axis and the sensor plane. Its position is given as two coordinates in the image (in pixels). This point is usually close to the image center.

This term is not to be confused with the one used in optics to characterize optical systems.

Geometric distortion

In the presence of distortion, images are modified in such a way that straight lines are no longer straight. This artifact can then impact the disparities between images and decrease the quality of the 3D rendering.

More details about geometric distortion are given in Section 13 on DC measurement.

External parameters

The external camera parameters define the physical position of a camera in a three-dimensional space. They are divided into:

- A three-dimensional rotation of the camera compared to the three axes of a reference coordinate system. This rotation is characterized by the 3 angles (φ, θ, ψ).
- A three-dimensional translation of the camera compared to a reference point.

Internal parameters

The internal camera parameters refer to the properties of a camera for a given picture. They are divided into:

- The effective focal length.
- The principal point.
- The geometric distortion.

14.3 Influencing factors

Two parameters impact 3D Geometry measurement:

- The selected focal length if the lens is a zoom lens.
- The focus distance.

14.4 Measurement of 3D geometry

3D geometry is measured from two shots of a Dot chart for both cameras in the stereo system. An additional marker needs to be set on the chart to replace one of the dots in order to have a reference point in both images. The shots need to be performed at different distances. The change of position must be a simple translation (no rotation), preferably orthogonal to the chart. Finally, the two cameras must have the same configuration relative to each other for both distances. These conditions can be easily achieved with the Analyzer 3D setup, which is composed of a translation rail orthogonal to a chart (see figure, Photo of Analyzer 3D setup, in Section 14.12).

The 3D geometry is computed separately for each camera, and then the results are merged to obtain the parallax. We therefore consider only one of the two cameras in the following computations.

Any point from the chart in homogeneous coordinate $(x, y, 1)^T$ is projected onto the image plane by the following homography:

$$H = \left[h_1, h_2, h_3\right] = \lambda \begin{bmatrix} f_x & s & p_x \\ & f_y & p_y \\ & & 1 \end{bmatrix} \left[r_1, r_2, t\right] = \lambda \cdot K \cdot \left[r_1, r_2, t\right] \tag{4}$$

The internal parameter matrix K contains the following parameters:

- (f_x, f_y) is the effective focal length of the camera (expressed in pixels along each image axis).
- (p_x, p_y) is the position of the principal point in the image (in pixels)
- s is the skew factor and should be close to 0 for most cameras

The external parameter matrix describes the position of the camera compared to the chart, and is composed of:

- The first two column vectors $[r_1, r_2]$ of the 3D rotation matrix $R = [r_1, r_2, r_3]$ that changes the chart coordinate system into the camera coordinate system
- The rotated position of the camera optical center (C): $t = -R \cdot C$

Finally, the scalar value λ is arbitrary since any homography is defined up to a factor.

If we omit λ, the evaluation would be impossible, as a single homography provides only 8 constraints, insufficient for the required 11 parameters.

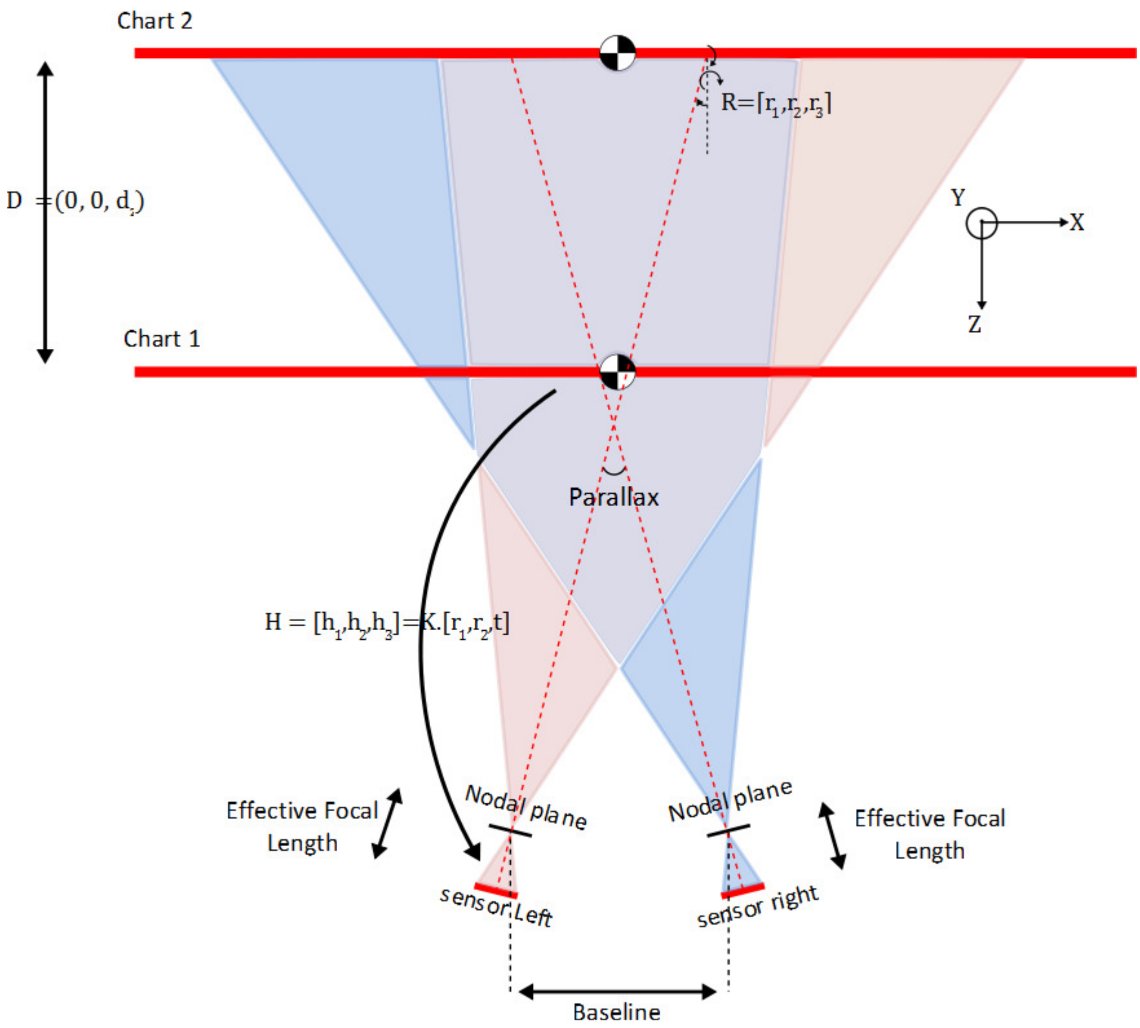
If the camera is translated orthogonally to the chart of a known translation $D = (0, 0, d_z)$, the points from the chart are projected onto the camera with the following homography:

$$H' = \left[h_1, h_2, h'_3\right] = \lambda \cdot K \cdot \left[r_1, r_2, t'\right] \tag{5}$$

Compared to the camera's first position, only the last column of the homography has changed (since the rotation and the internal parameters are the same as before). Moreover, t and t' are related to the third column vector of the 3D rotation matrix by the following equation:

$$t' - t = \lambda^{-1} \cdot K^{-1} \cdot \left(h_3' - h_3\right) = d_z \cdot r_3 \qquad (6)$$

In this second view, there are still 11 parameters to compute (since the translation is measured manually), but the two homographies impose 11 constraints (which is enough for the evaluation).



3D Geometry measurement description

Homography computation

The homographies are estimated together as a pair since their first two columns are identical. The computation is done using two steps:

- A direct estimation from 6 points (3 from the first view and 3 from the second view) and their matches on the chart.
- A refinement of the estimation using the Levenberg-Marquardt algorithm.

Parameter estimation

The camera parameters (internal and external) are computed using two steps as the two homographies:

- A first estimation directly from the homographies.
- A refinement of the estimation using the Levenberg-Marquardt algorithm.

The internal parameters can be estimated from the properties of the 3-column vectors of the rotation matrix:

$$\begin{cases} r_i \cdot r_j = 0 \\ r_i \cdot r_i = r_j \cdot r_j \end{cases} \quad \text{for } i, j \in \{1, 2, 3\} \tag{7}$$

The vectors r_i are related to the homography column vectors by:

$$r_i = \begin{cases} \lambda^{-1} \cdot K^{-1} \cdot h_i & \text{if } i = 1, 2 \\ \lambda^{-1} \cdot K^{-1} \cdot \dfrac{\left(h'_3 - h_3\right)}{d_z} & \text{if } i = 3 \end{cases} \tag{8}$$

By combining the two previous points, we obtain 6 equations which allow estimation of the 6 terms of the symmetric matrix $K^{-T} \cdot K^{-1}$, hence the internal parameters:

$$\begin{cases} h_1^T \cdot K^{-T} \cdot K^{-1} \cdot h_1 = h_2^T \cdot K^{-T} \cdot K^{-1} \cdot h_2 \\ h_1^T \cdot K^{-T} \cdot K^{-1} \cdot h_1 = \dfrac{\left(h'_3 - h_3\right)^T}{d_z} \cdot K^{-T} \cdot K^{-1} \cdot \dfrac{\left(h'_3 - h_3\right)}{d_z} \\ h_2^T \cdot K^{-T} \cdot K^{-1} \cdot h_2 = \dfrac{\left(h'_3 - h_3\right)^T}{d_z} \cdot K^{-T} \cdot K^{-1} \cdot \dfrac{\left(h'_3 - h_3\right)}{d_z} \\ h_1^T \cdot K^{-T} \cdot K^{-1} \cdot h_2 = 0 \\ h_1^T \cdot K^{-T} \cdot K^{-1} \dfrac{\left(h'_3 - h_3\right)}{d_z} = 0 \\ h_2^T \cdot K^{-T} \cdot K^{-1} \dfrac{\left(h'_3 - h_3\right)}{d_z} = 0 \end{cases} \tag{9}$$

Finally, the external parameters are easily deduced from the internal parameters and the homographies:

$$\begin{cases} r_1 = \lambda^{-1} \cdot K^{-1} \cdot h_1 \\ r_2 = \lambda^{-1} \cdot K^{-1} \cdot h_2 \\ r_3 = \lambda^{-1} \cdot K^{-1} \cdot \dfrac{h'_3 - h_3}{d_z} \\ C = -\lambda^{-1} \cdot R^{-1} \cdot K^{-1} \cdot h_3 \\ \lambda = ||K^{-1} h_1|| = ||K^{-1} h_2|| = ||K^{-1} \dfrac{h'_3 - h_3}{d_z}|| \end{cases} \tag{10}$$

Polynomial distortion refinement

To refine the estimation of 3D geometry, we correct the distortion during the computations. A point in the image is affected by distortion in the following way:

$$\begin{pmatrix} x_d - x_c \\ y_d - y_c \end{pmatrix} = L(r) \cdot \begin{pmatrix} x - x_c \\ y - y_c \end{pmatrix} \tag{11}$$

where $\left(x_d, y_d\right)$ is the distorted point, (x, y) is the ideal point, $\left(x_c, y_c\right)$ is the distortion center, $r^2 = \left(x - x_c\right)^2 + \left(y - y_c\right)^2$ and $L(r)$ is a radial polynomial of degree 5:

$$L(r) = 1 + \kappa_1 \cdot r + \kappa_2 \cdot r^2 + \kappa_3 \cdot r^3 + \kappa_4 \cdot r^4 + \kappa_5 \cdot r^5 \quad (12)$$

The distortion parameters (center and polynomial coefficients) are first computed from the homography pair using the Levenberg-Marquardt algorithm. Then all the parameters (internal, external and distortion) are refined together through a final iteration of the Levenberg-Marquardt algorithm.

The distortion parameters are not displayed among the measurement results in the Analyzer interface, but they can be obtained in the spreadsheet-formatted exports, specifically in the spreadsheet labeled "Parameters".

Distortion measurement

The 3D Geometry measurement includes measuring the distortion for each camera lens. All curves and output values are computed using the Analyzer DC measurement (see the Section 13 on DC measurement for more details).

14.5 Measurement in raw format

The parameters for 3D measurement are either optical or physical. Consequently, the effective focal length, the distortion, the position, and the orientation of both cameras should be the same with raw images as with generated images. However, the fact that the field of view may be a bit larger in raw images can have a slight impact on the measurements.

14.6 Analyzer output

Analyzer returns the following data:

- The *Summary* tab contains the external parameters defining the 3D geometry:
  - The baseline of the stereoscopic system expressed in mm. If the images are cropped or if an offset is added to the images, the baseline value is the one that corresponds to the virtual stereo

system.

	mm
Baseline	75.43

– The orientation change of the right camera compared to the left camera, which is given by three angles: pitch angle around the first camera horizontal axis, yaw angle around the first camera vertical axis, and roll angle around the first camera optical axis. For well-rectified cameras, all 3 angles should be close to 0°.

	Parallax (°)
Pitch	-0.10
Yaw	-0.25
Roll	0.25

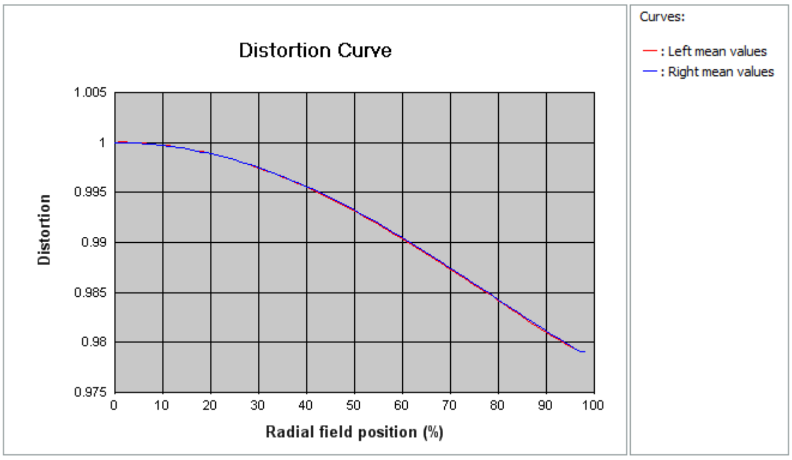
- The *Internal* tab contains the following information characterizing each camera:

  – The internal parameters: effective focal lengths, principal points (a projection of the optical center in the image), and the skew parameter (a shear parameter which should be close to 0). These parameters are given in pixels as well as in 24×36 mm equivalents. The internal parameters of a well-rectified stereo system should be the same for both cameras.

	Left		Right	
	Pixels	24x36 mm equiv.	Pixels	24x36 mm equiv.
Focal X	4271.2	40.5	4271.4	40.5
Focal Y	4339.5	41.2	4339.9	41.2
Principal point X	1734.1	16.5	1884.3	17.9
Principal point Y	1434.7	13.6	1434.4	13.6
Principal point offset X	-89.9	-1.5	60.3	1.6
Principal point offset Y	66.7	1.6	66.4	1.6
Skew	2.7	0.0	2.9	0.0

  – The geometric distortion values for each camera, computed from the furthest point of view. The distortion output values of the 3D measurement are the same as those for the DC measurement: mean distortion, max distortion and TV-distortion. The curve of the mean distortion as a function of the radial field is also given. A well-rectified stereo system should have no distortion or at least a similar distortion map for both cameras.

	Left	Right
Maximum	0.47 %	0.47 %
Mean	0.24 %	0.24 %
TV	-1.11 %	-1.11 %

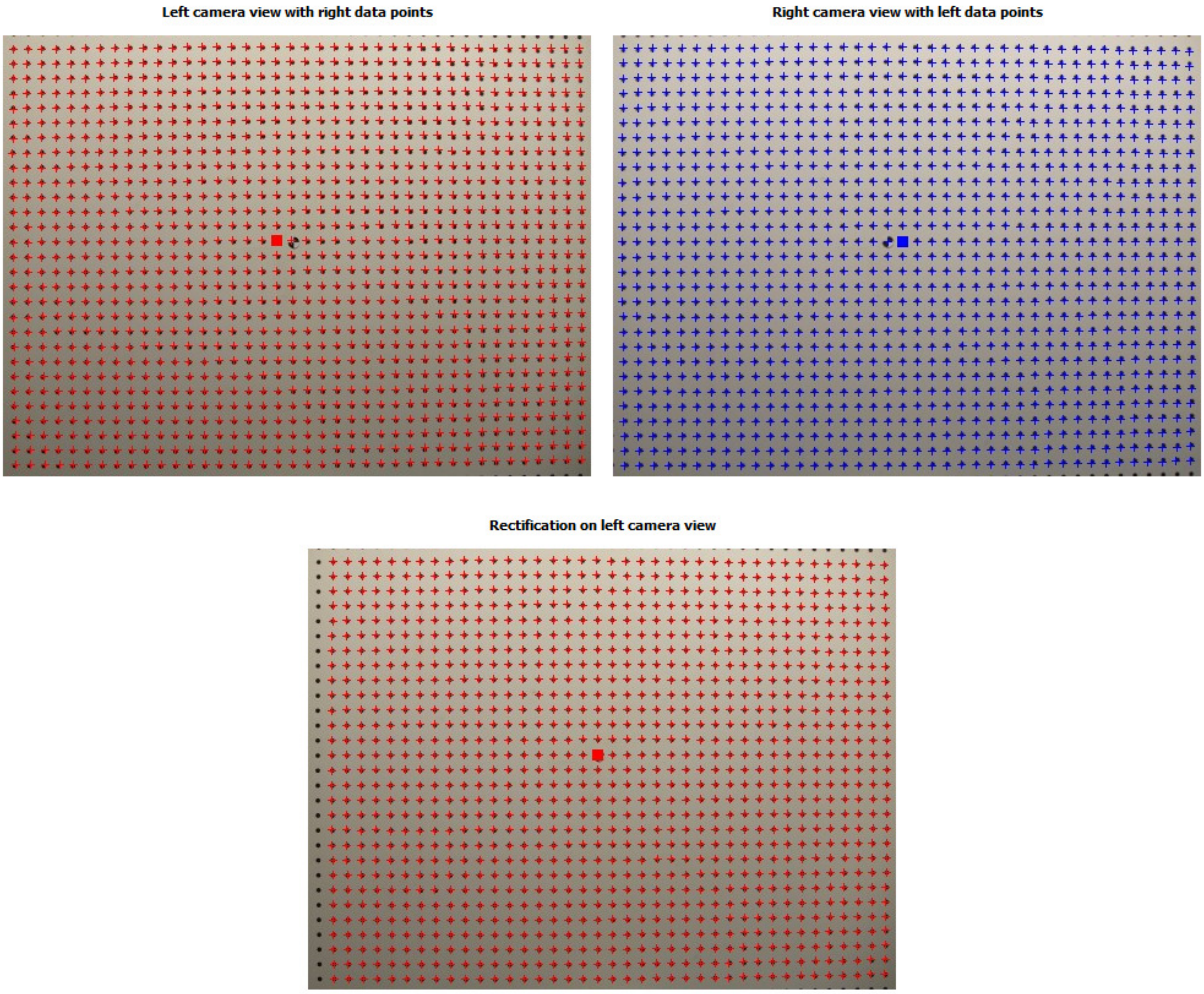


- The *External* tab contains the information about the camera positions relative to each other:
  - The position of the right camera optical center given in the left camera coordinate system (in mm). The baseline is then the norm of this translation vector. For a rectified system, the translation of optical centers should be zero along the *y* and *z* axes.

	Offset (mm)
Center X	75.43
Center Y	-0.47
Center Z	-0.51
Baseline	75.43

  - The difference in camera orientation (per the *Summary* tab).
- The *Views* tab shows the left image with the dot positions from the right image; the right image with the dot positions from the left image; and the left image with the dots from the right image, respectively, after projection onto the left image space using the internal and external parameters previously computed. The last view reveals if the measurement was successful, as erroneous camera parameters will not produce a good projection.

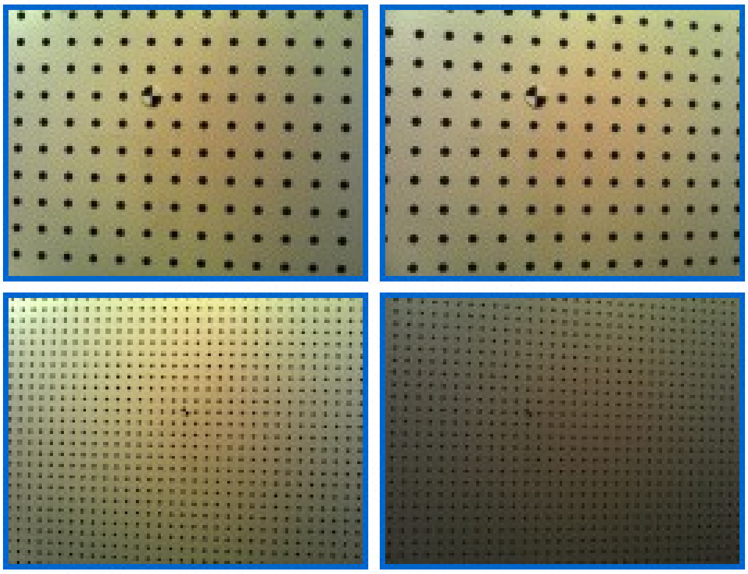
  These images are generated from the furthest view.



14.7 Examples

The following images were taken with two camera modules set on an aluminum plate at 500 mm and 1000 mm from the chart. These distances were measured from the translation rail used for the translation between views.

The images have not been rectified and the focus was the same for each view.



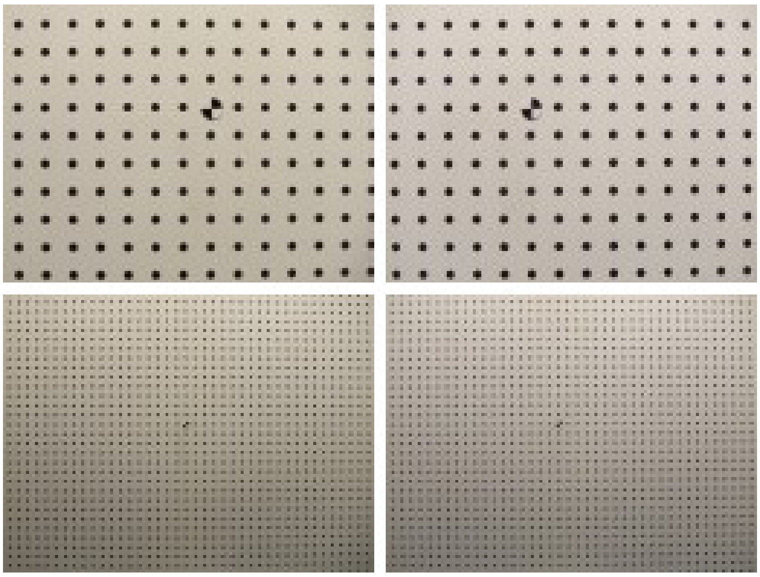
Analyzer measured the following differences in orientation for the two cameras:

	Parallax (°)
Pitch	0.69
Yaw	13.34
Roll	-0.15

As expected from the views, a large yaw (rotation around the vertical axis) was measured. Because of this yaw, 3D objects will be highly distorted when displayed.

Finally, the measured effective focal lengths are approximately the same for left and right cameras and the distortion is less than 1% in the field. Both these characteristics are necessary if these cameras are to be used for 3D visualization (after being rectified).

The next images were taken with a Fujifilm FinePix Real3D W3 at distances of 400 mm and 800 mm from the chart.



Although the pictures were taken in autofocus mode, the change in effective focal length is expected to be low at this distance from the chart and should not affect the results (see the section on measurement accuracy 14.8 for further explanation).

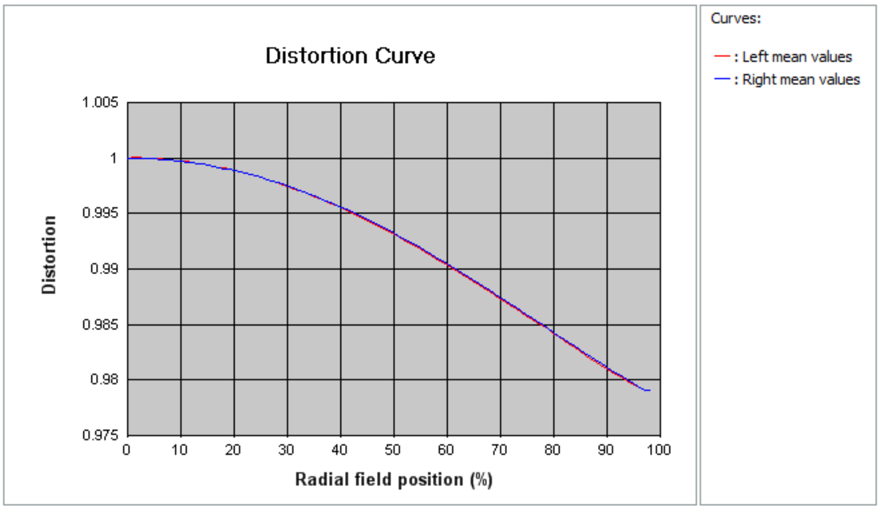
The baseline measured by Analyzer is 75.43 mm, which correspond to the 75 mm given in the specifications. The difference in orientation between the cameras is quite low, as expected from a rectified camera:

	Parallax (°)
Pitch	-0.10
Yaw	-0.25
Roll	0.25

This is confirmed by the difference in position of the optical centers. Indeed, the translation is almost zero along the *y* and *z* axes:

	Offset (mm)
Center X	75.43
Center Y	-0.47
Center Z	-0.51
Baseline	75.43

The distortion measured by Analyzer is around 1%, but more importantly, it is almost the same for both cameras:



14.8 Measurement accuracy

Measurement accuracy depends on the quality of the shooting procedure, especially with respect to the following points:

- The displacement between the two views must be a translation (no rotation of the stereo device).
- The translation between the two views must be orthogonal to the chart.
- The distance between the views should be measured accurately.

The first two points are the most critical ones. Indeed, the maximal change of orientation tolerated by the measurement is 0.5° and the maximal tolerated default of orthogonality for displacement is around 5°. These two conditions can be easily achieved using a translation rail, per the Analyzer shooting protocol.

Another point to consider is the influence of a focus change between the two points of view. Such a change can modify the distance between the sensor and the nodal point (and therefore the effective focal length). This effect is also known as “lens breathing.” Since it is assumed during computation that the effective focal length is the same for both positions, a change of focus can affect the results. Therefore, we advise that you use the manual focus mode when available and keep the focus unchanged for the two views.

The following table shows the measurement accuracy between manual focus (with no focus change) and autofocus modes. The first line shows the accuracy when the same focus is applied for both distances. The second line shows the accuracy when a different focus is applied for each distance. The accuracy table estimation takes into account an orthogonality error up to 5°, a translation rail linearity of less than 2 mm per meter, a distance error of 1 mm, and a baseline between 10 mm and 100 mm:

	Focal length error	Parallax error	Baseline error
No focus change	±0.5%	±0.03°	±0.2 mm
Focus change	±0.8%	±0.03°	±0.8 mm

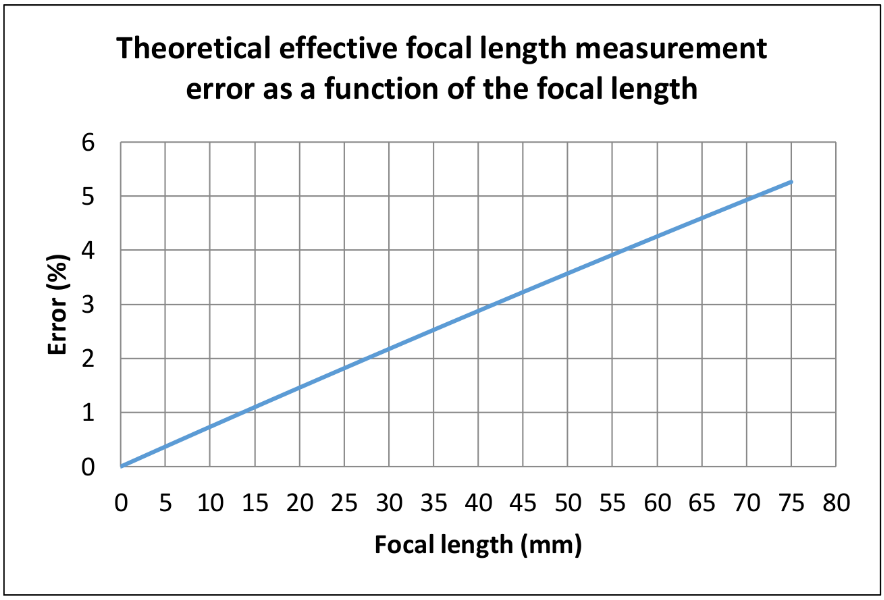
Assuming a refocus obtained by lens breathing, the proportion of effective focal length change implied by this focus change can be estimated using the thin lens equation:

$$\frac{1}{S} + \frac{1}{f} = \frac{1}{f_\infty} \tag{13}$$

where f_∞ is the focal length of the lens at infinity, S is the distance of the object to the camera, and f is the distance between the optical center and the sensor (effective focal length) for an in-focus object at distance. If we assume that the distance is doubled between the two views (per the shooting protocol), the variation of effective focal length is:

$$\frac{\Delta f}{f} = \frac{f}{2S + f} \tag{14}$$

The following graph shows the maximal proportion of effective focal length change due to a focus change during the shooting procedure. The effective focal length change is given as a function of the focal length (distance of the nodal point to the sensor):



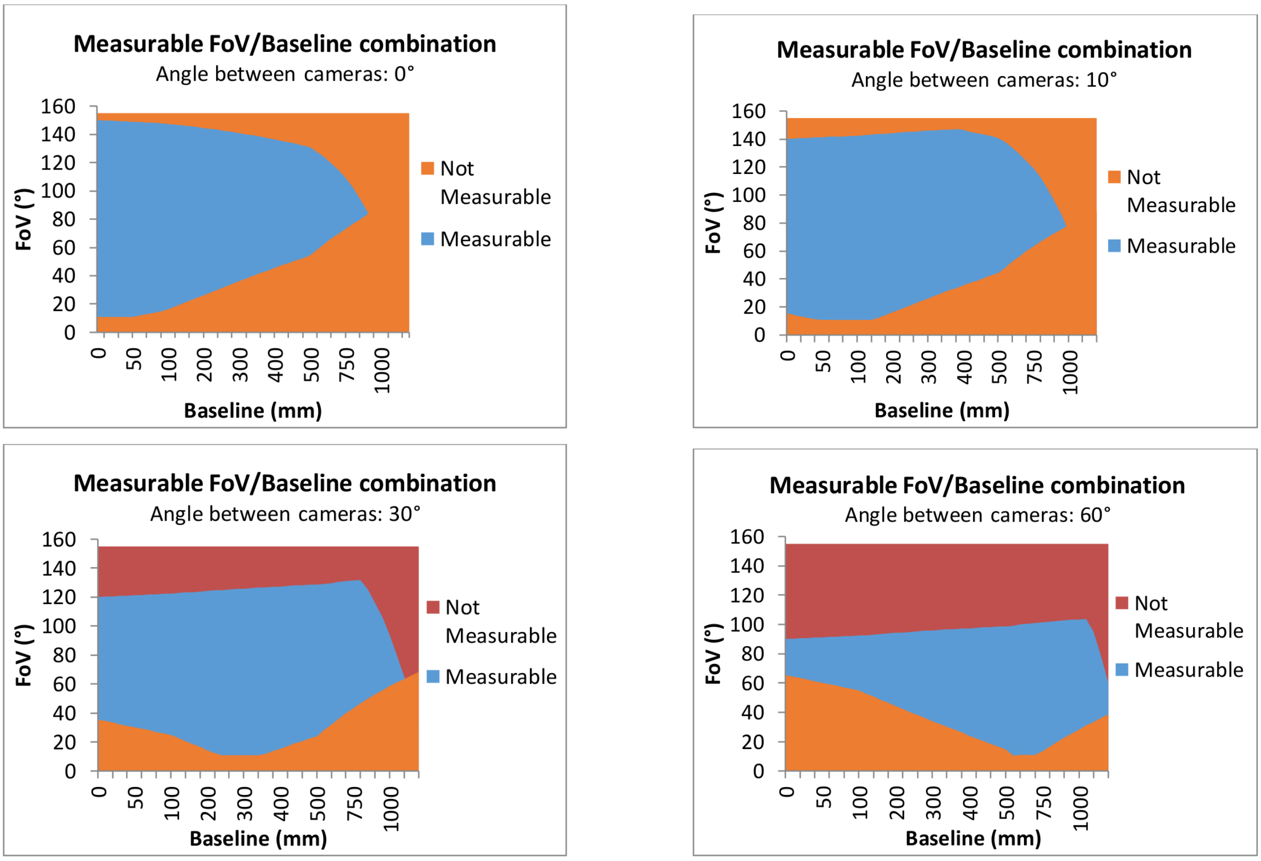
This graph shows the error that occurs if, when following our shooting protocol, the effective focal length is assumed to be fixed when it is not (for instance, when shooting in autofocus mode). For instance, the Fuji Real 3D W3 (which cannot be used in manual focus mode) has a focal length range of 6.3 mm to 18.9 mm. Applying our measurement protocol, an effective focal length of 18.9 mm (when the camera is focused for the first position) changes less than 1.5% when the camera is refocused for the second position.

Limits of the 3D Geometry measurement

The 3D Geometry measurement is limited by the physical conditions of the hardware set up used for shooting:

- Each camera should at least see 50 dots for the nearest view and 300 dots for the furthest view.
- Each camera should see the marker at the center of the chart from both points of view.
- The chart must fill the image field (see the section on shooting conditions below).
- The length of the translation rail (1.56 m).

With the Analyzer 3D setup, the minimal distance to the chart is 10 cm, the maximal distance is 135 cm and the D0002 chart is used. The following graphs show the stereoscopic devices for which the measurement can be achieved (assuming these conditions, and for different parallax values).



Fields of view (diagonal) and baselines for which a 3D measurement is possible. The sensor size ratio used here is 4/3. The maximal field of view is limited by the chart size at the shortest distance. The two observable modes correspond to the two cases in which the size limit is on the left or on the right of the camera. The minimal field of view is mostly limited by the fact that each view (left near, left far, right near, and right far) must contain the marker. The flat portions correspond to the minimal number of dots (50 here) required for processing the measurement

Finally, measurements done on binocular images with different crop values will not be reliable. Indeed, cropping images virtually changes the baseline between the two cameras (since the disparities may be offset), which makes baseline measurement impossible. This special case has been observed with two 3D camera phones for which an automatic (and potentially different) crop is made each time a 3D image is taken.

14.9 Parameter settings that can influence measurement

The following camera settings may influence the 3D measurement for both fixed-focus and autofocus modes:

- The distance between the two views; the second position should be at least twice as far from the chart as the first position. As with the two-shot EFL measurement method, the larger the distance, the more precise the measurement will be.
- The distance from the chart for the first position: at least 50 dots should be visible to each camera. A short distance will give a more accurate estimation of the baseline and a less precise estimate of the focal length. Moreover, with a manual focus, a good focus for each view will be hard to achieve if the first distance is too short.
- The orientation of the cameras relative to the chart must stay the same for the two views. If not, this may affect the quality of the measurement.
- The translation rail orientation should be orthogonal to the chart. This condition is less critical than the previous one: in practice, an orthogonality fault of 5° does not affect the quality of the measurement.
- The stereo system should be as orthofrontal to the chart as possible for greater accuracy of the parallax estimate.
- Set the resolution to the highest available value, unless this parameter is part of the characterization, in order to increase measurement accuracy.
- Cropping. The same crop applied to both left and right camera does not change the cameras' orientation estimate nor the baseline estimate. It will, however, change the focal length value. If a different crop is applied to left and right cameras, the baseline value will change.

14.10 Measurement validity

The relative orientation and the baseline of the two cameras are absolute values, as they depend only on the physical configuration of the stereoscopic system. However, since an image crop or an offset in the disparities virtually modify the camera configuration, the relative orientation and the baseline are truly meaningful only when associated with a crop value and an offset value. For instance, it is perfectly meaningful to say that a stereoscopic system has a pitch of 0.7°, a yaw of 1.2°, a roll of −0.3° and a baseline of 75 mm with no crop and an offset disparity of 150 pixels.

The distortion value is truly meaningful given a distance and a focal length (see the Section 13 on DC measurement for more details).

14.11 Comparing two cameras

The quality of a 3D reconstruction depends on several points of comparison:

- The quality of rectification, which is defined by 3 points:
  - The difference in orientation.
  - The translation of the optical centers of the two cameras.
  - The effective focal lengths of both cameras.

  The camera rectification is the main point of comparison, since it defines whether or not the output images of the stereo device are viewable as they are. A perfectly rectified stereo device will have a yaw, pitch, and roll of 0°, a translation of optical centers that is zero along the *y* and *z* axes, and the same effective focal length for both cameras.
- The baseline, the field of view, and the camera resolution together define the first and last distance that can be viewed. For the same field of view and sensor resolution, a small baseline is better for seeing nearer objects and a larger one will have better depth resolution.
- The following example shows the comparison of two stereoscopic devices. The first device is a pair of unrectified 5 Mpix camera modules set on an aluminum plate. The second is the Fujifilm Finepix Real3D W3 using a 6.3 mm focal length.

The camera modules are not rectified, whereas the Fuji W3 is. This can be easily observed from the difference in camera orientation:

	Parallax (°)
Pitch	0.69
Yaw	13.34
Roll	-0.15

	Parallax (°)
Pitch	-0.10
Yaw	-0.25
Roll	0.25

Differences in camera orientations. Left: non-rectified camera modules. Right: rectified camera Fuji W3

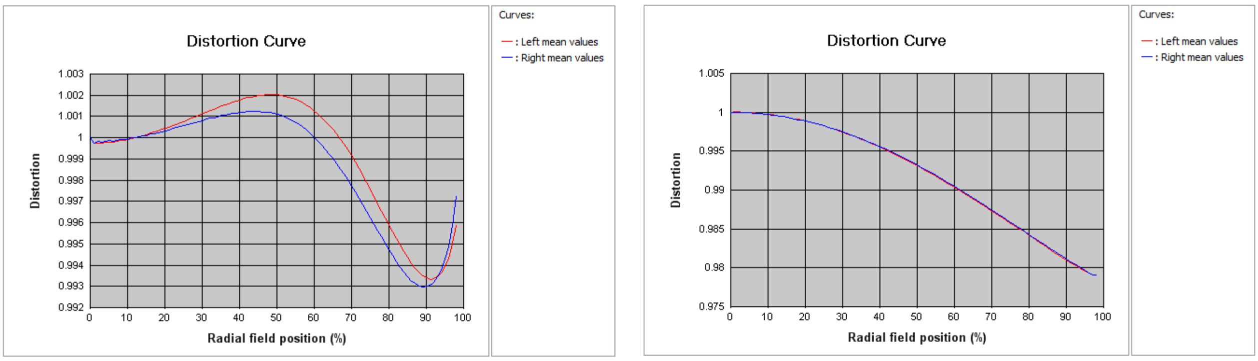
This is confirmed by the difference in position of the optical centers of the cameras in both systems, which is null along the *y* and *z* axes for the Fuji W3:

	Offset (mm)		Offset (mm)
Center X	-66.66	Center X	75.43
Center Y	-0.42	Center Y	-0.47
Center Z	7.16	Center Z	-0.51
Baseline	67.04	Baseline	75.43

Differences in camera positions. Left: non-rectified camera modules. Right: rectified camera Fuji W3

For the camera module pair, the strong yaw will significantly distort the 3D field. Moreover, the pitch will cause small vertical disparities which are hard to see. For the Fuji W3, the angles are close to 0°, and so 3D distortion will hardly be seen.

If we now take a look at the distortion curves, we see that the Fuji W3 is a bit more distorted than the two camera modules. This means that the 3D rendering will be more slightly distorted with the Fuji W3 than with the camera module stereo system. However, the level of distortion remains acceptable for the Fuji W3 and will not greatly impact the 3D rendering.

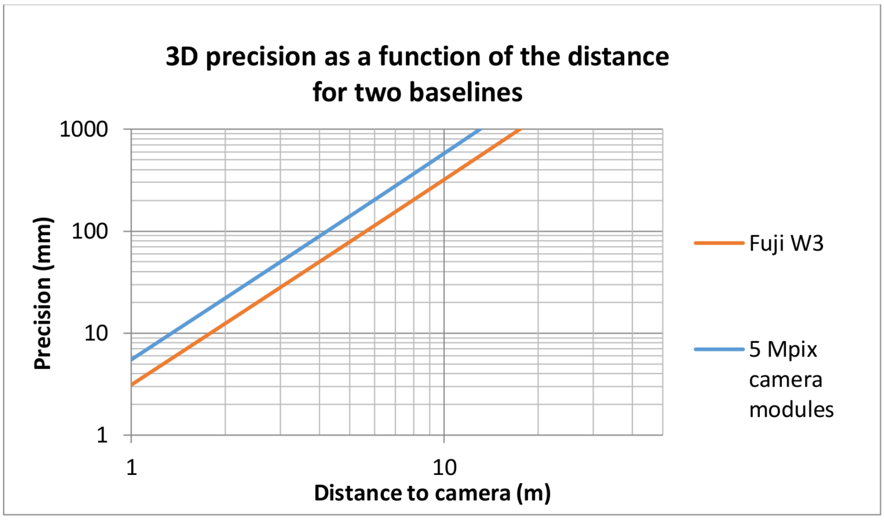


Mean distortion as a function of the radial field. Left: non-rectified camera modules. Right: rectified camera Fuji W3

We can compare the 3D resolution achievable by the two stereo systems assuming a perfect rectification. This can be by accomplished combining the information given by the focal length, the baseline, and the sensor resolution. If the two cameras are rectified, their 3D ranges are then:

	Camera modules	Fuji W3
Minimal distance	70.6 mm	88.5 mm
Maximal distance	183.1 m	322.9 m

Finally, the achievable 3D precision as function of the distance is:



Achievable precision of 3D estimation as a function of the distance for the two tested stereo devices

14.12 Shooting

Measurement equipment

The 3D Geometry measurement procedure requires a geometric translation of the stereoscopic device under test conditions. We therefore advise using the following equipment:

- A 3D geometry chart (a dot chart with a marker replacing one of the dots in the center).
- A translation rail (1.56 m long) supporting a 3-axis head (to achieve a perfect translation with no

rotation).

- A distance meter (if the translation rail has no graduation markings).
- A mirror.
- A laser pointer (and laser protection goggles, if necessary).
- A filter holder to hold the laser pointer still on the 3-axis head.

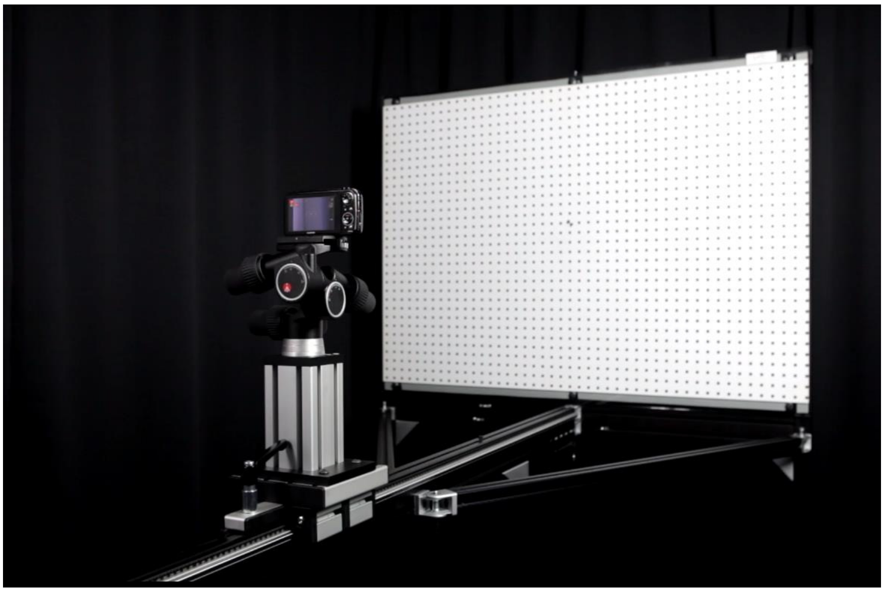


Photo of Analyzer 3D setup

Measurement settings

Since 3D Geometry measurement requires translating the stereo system orthogonally to the chart, you must first measure whether or not the translation rail is orthogonal to the chart. You can also use this procedure to set the rail orthogonally to the chart if it is not attached in the same way as in the 3D setup we propose.

The orthogonality measurement can be achieved with a laser pointer set on a 3-axis head and a mirror, following these two steps:

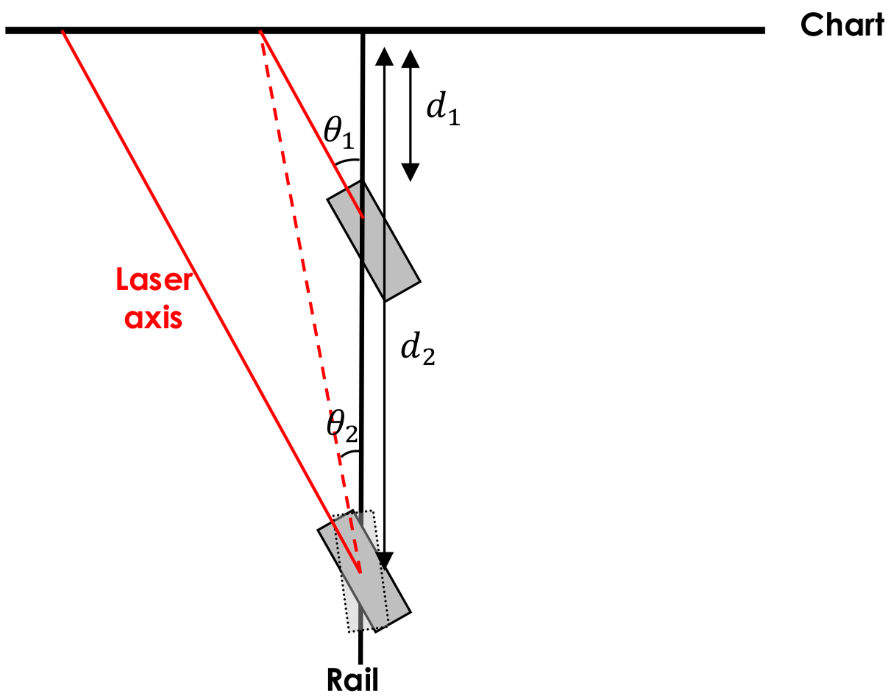
- Set the laser beam parallel to the rail.

- Measure the orthogonality using the mirror.

You can easily align the laser beam with the rail using the following steps:

- Put the laser pointer into the filter holder and set it onto a 3-axis head itself attached to the rail (use laser protection goggles if necessary).
- Put the 3-axis head at the end of the rail which is the closest to the chart.
- Note the position of the laser on the chart using a post-it marked with a cross.
- Put the 3-axis head at the other end of the rail.
- Change the orientation of the laser beam with the 3-axis head until the laser beam is superimposed on the cross on the post-it.
- Go back to step 2 and start again until the laser beam intersects the same point on the chart at both ends of the rail.

This procedure is illustrated by the following figure:



The angles between the laser and the translation rail axes at each iteration of the procedure are linked by:

$$\sin\theta_{n+1} = \frac{d_1}{d_2}\sin\theta_n \tag{15}$$

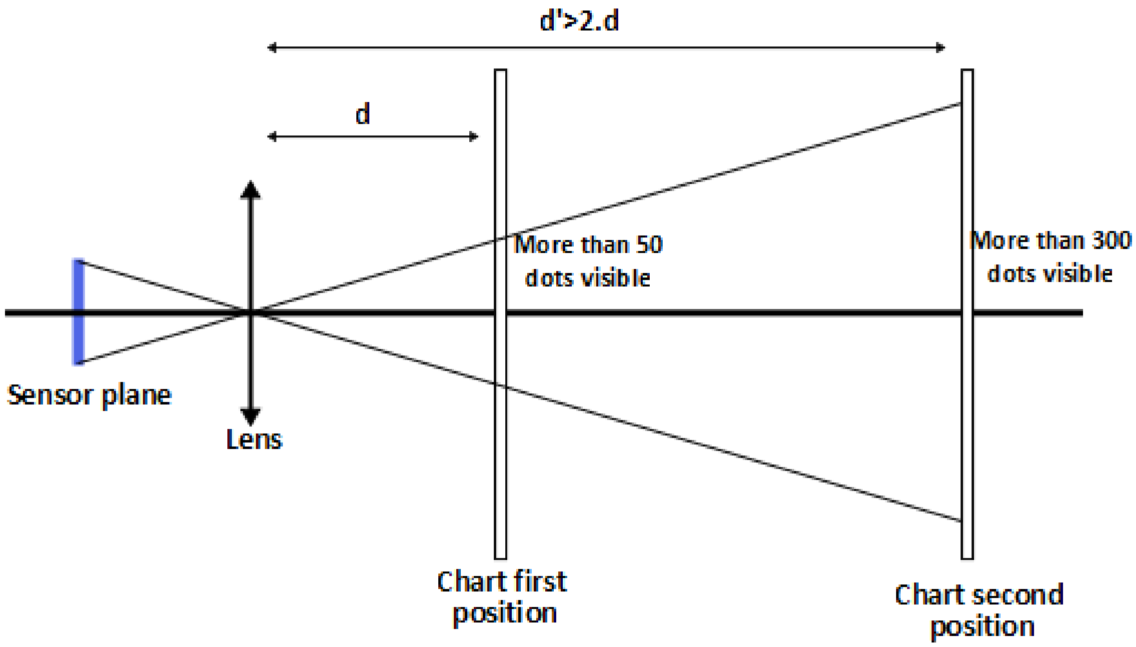
Since $d_2 > d_1$, the angle values converge to 0°.

Once the laser axis and the translation rail axis are parallel, you can check the orthogonality of the rail using a mirror that you put on the chart: if the laser beam reflects on itself, the rail is orthogonal to the chart.

3D geometry shooting protocol

1. Align the rail orthogonally to the chart if necessary (the procedure is described above).
2. Put the stereo device on the 3-axis head and use a mirror to try to align the camera frontally to the chart. Full frontality of the camera is not necessary but preferable.
3. Set the stereo camera in manual focus mode if possible. (If manual mode is not possible, refer to the section on measurement accuracy for an explanation about the error caused by a change of focus.)
4. Put the stereo device at a first position on the translation rail such that both cameras see at least 50 dots (the more the better), then take a picture.
5. Note the position of the camera either by using the graduations on the rail (when available) or by using a distance meter (the procedure is described below)
6. Put the stereo device at another position on the translation rail. **The distance to the chart must be at least twice as far as that of the first position**. It is very important that the orientation of the stereo device stays exactly the same for the two views (which is why the translation rail is needed). Finally, since the Distortion measurement is made using the furthest view, at least 300 dots should be visible by both cameras.
7. Take a picture and note the second position using the graduations or a distance meter.

The necessary shooting conditions are shown in the following figure:



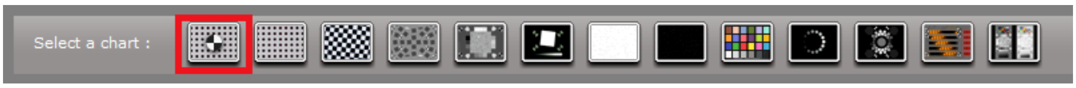
Shooting conditions

Measuring the distance to the target

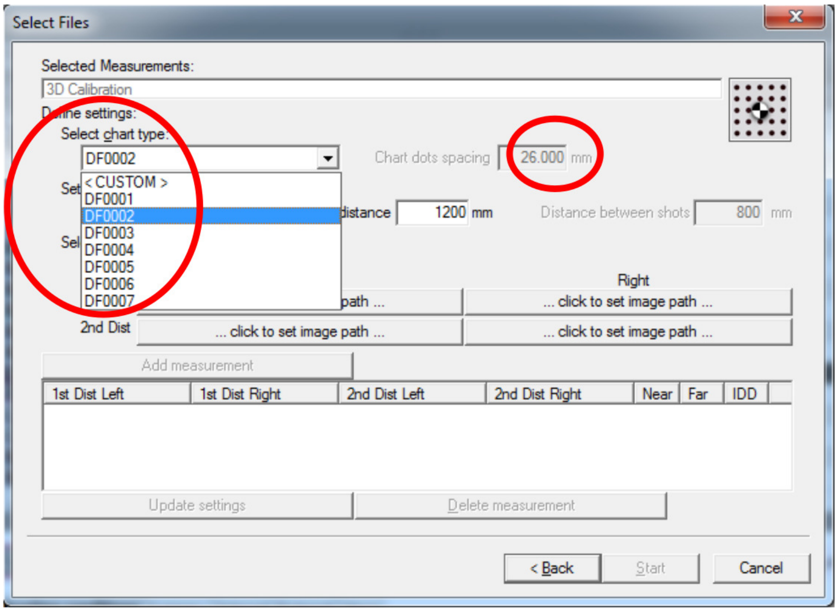
You can measure the distance to the target either from the graduations on the translation rail or by using a distance meter. In the 3D Geometry measurement, the actual distance of each camera center at each position is not relevant. Only the distance between the two views (i.e., the value of the geometric translation) matters. This means that you must measure the two distances against a fixed point relative to the stereo device for both positions.

Launching Analyzer 3D Geometry measurement

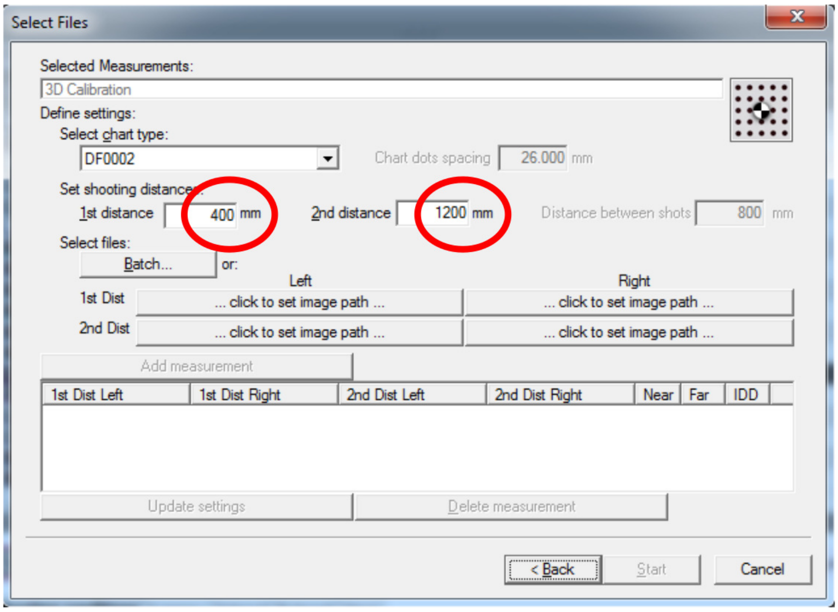
- Select the 3D geometry chart in the Analyzer chart menu bar:



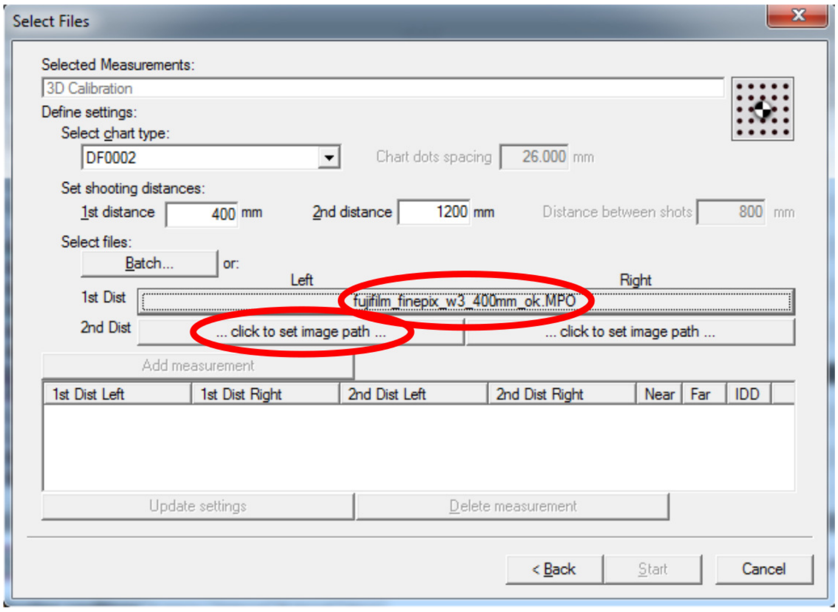
- Set your operator name, then click *Next*.
- Select the chart that you used during shooting (the default is DF0002). If you do not use a Chart, select “Custom”, and enter the spacing between two consecutive dots (in mm):



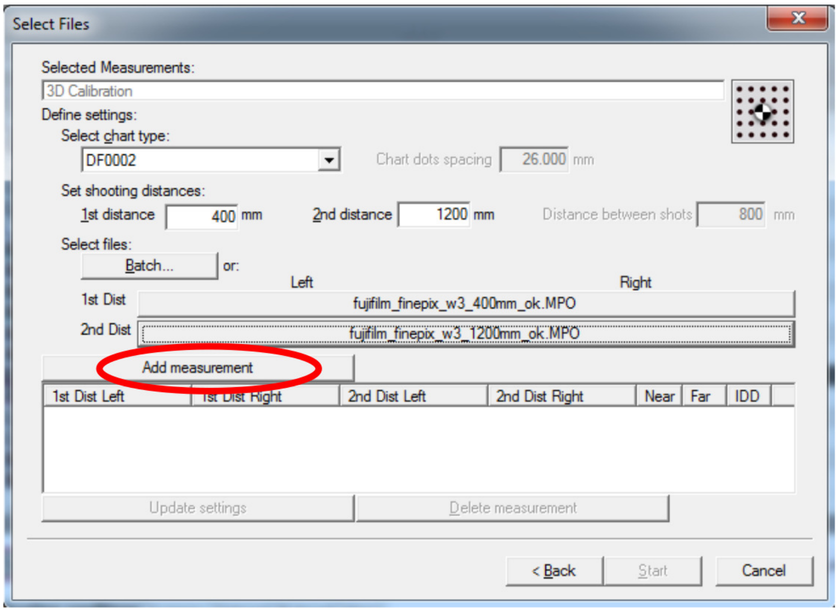
- Enter the two distances to the chart measured during the shooting.



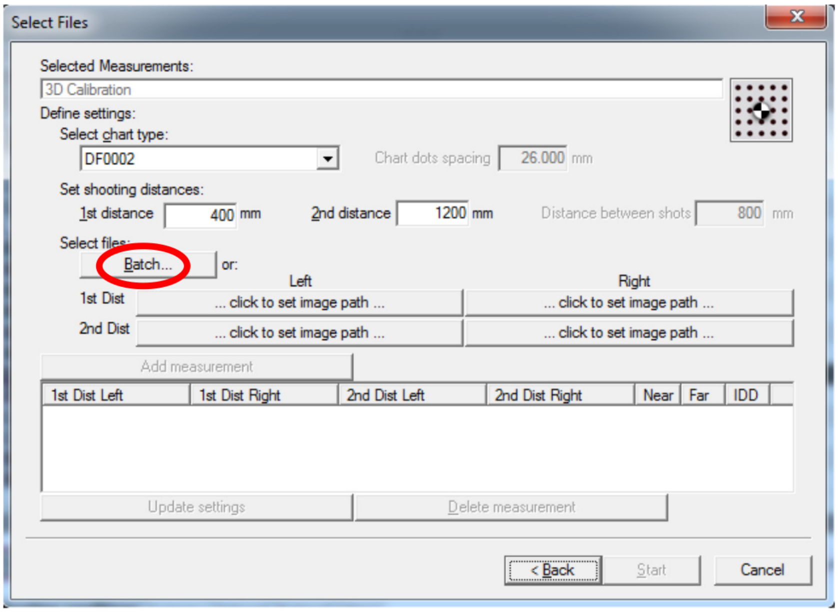
- Select the images to process using the *... click to set image path...* button. Each measurement requires 4 images (2 cameras and 2 distances). In the case of 3D file format (MPO, PNS or JPS), Analyzer automatically fills the *Left* and *Right* corresponding fields. Finally, you can select the 4 files (or just 2 files for 3D file formats) at the same time. However, it is preferable to check if the order is actually the one you desire, otherwise the results might not be as expected.



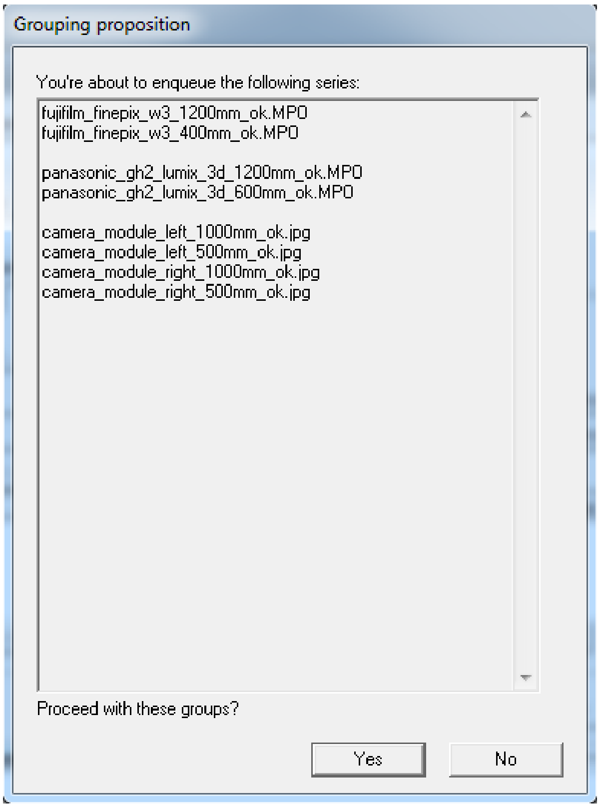
- Once you have filled every field, you must add the measurement to the measurement list by clicking on the *Add measurement* button.



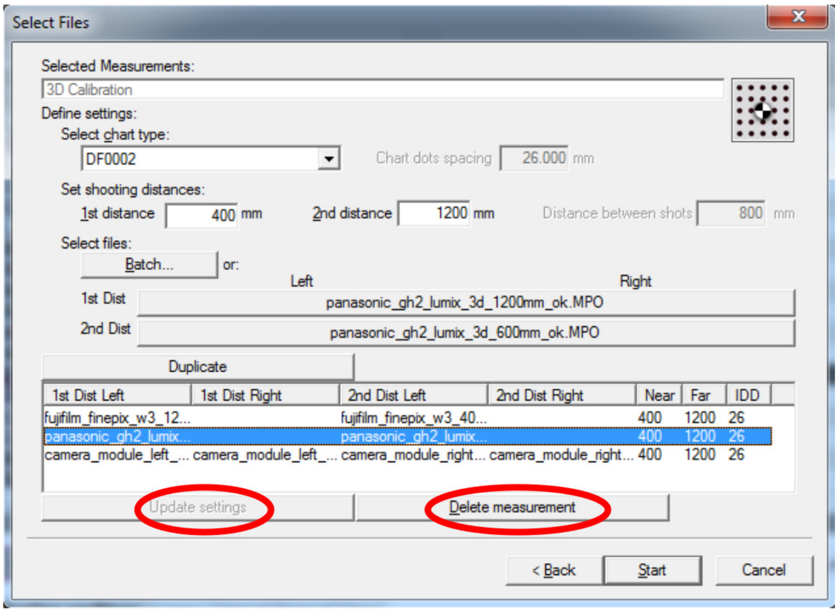
• Another possibility is adding several measurements at once, assuming that they share the same chart and distance parameters. This can be done by clicking on the *Batch...* button instead of the *... click to set image path...* button, and by selecting groups of images. If coherent, measurement groups are created from the entire selected image list (arranged in alphanumeric order):



Analyzer proposes to add the measurements for each group to the measurement list.



- Finally, Analyzer offers the possibility of editing a measurement in the measurement list by clicking on it. Save the modifications by clicking the *Update settings* button. You can remove the measurement from the list by clicking the *Delete measurement* button.



- The measurements from the list all start together when you click the *Start* button.

15 – V: Vignetting

15.1 Introduction

Vignetting is a darkening of the image near the corners. The vignetting that Analyzer takes into account is produced by the body-lens combination. Its origins lie in:

- The attenuation of illumination when the angle of incidence increases, also known as the “$\cos^4$ law of illumination”.
- The physical length of the lens, and/or the use of unsuitable accessories such as a lens hood that is too narrow.
- An inadequate degree of coverage of the sensor by the lens.
- An angle of incidence of light rays that is too strong to hit the bottom of photon wells on CCD and CMOS sensors. The origin of this kind of vignetting is specific to digital cameras, and is also known as “pixel vignetting”.

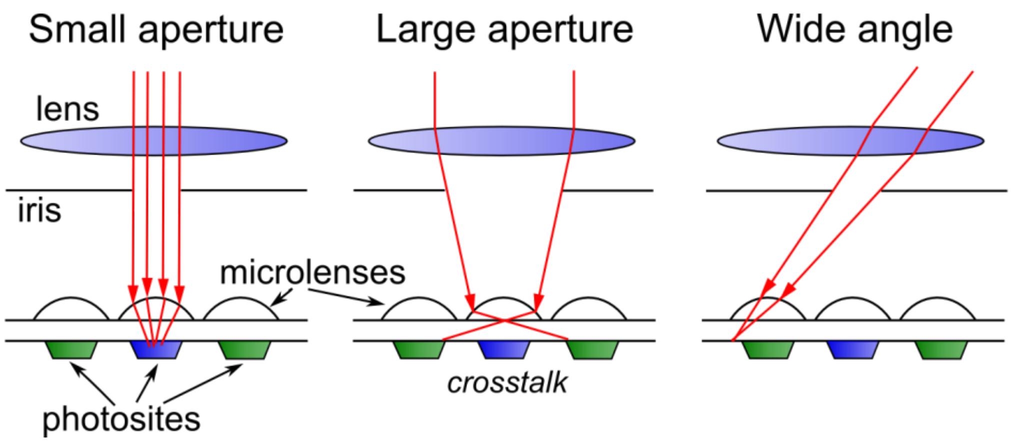
Vignetting can be reduced by using small apertures. On DSLRs, it usually disappears at apertures of f/5.6 or f/8.

The vignetting phenomenon is also known as shading or light fall-off.

Example of image with vignetting. Vignetting is visible in the sky, in the corners

Vignetting also depends on the wavelength. This phenomenon has appeared with new pixel technologies that have reduced pixel sizes on the sensor to 2.2 μm, 1.75 μm, 1.4 μm, or even smaller. The main origins of this phenomenon (called color vignetting) are:

- An infrared (IR) filter in front of the sensor. Such a filter is necessary since CCD or CMOS sensors are sensitive to infrared radiation. However, the position of the bandwidth of the infrared filter depends on the angle of incidence. Hence, some wavelengths that should freely cross the filter are progressively attenuated when the angle of incidence increases.
- Crosstalk between pixels, mostly at the borders of the sensor. This means that the photosites are no longer independent, and colors spill over. The micro-lenses used to redirect light rays to photosites may be the origin of the crosstalk, depending on their position in the sensor (at the center or on the border); depending on the incident angle of the light rays, they may redirect rays to the wrong photosites.



Origin of crosstalk

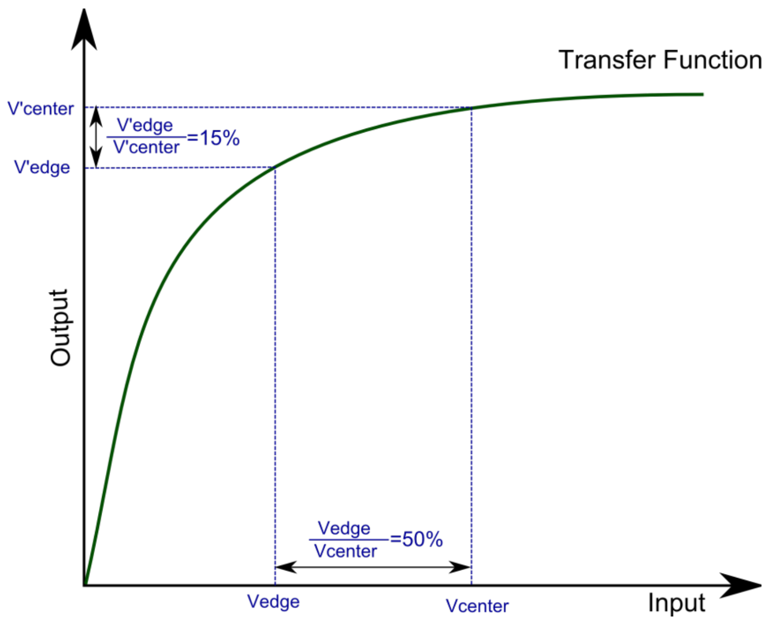
15.2 Definitions

Analyzer characterizes the fall-off of grey levels in the image corners.

This is characterized by a particular point called the vignetting center and a function of the distance to this point. The vignetting center is usually close to the image center but does not need to coincide exactly with it. For example, if the lens is decentered, the two centers will not coincide.

The vignetting function is the ratio of the observed grey level at a point with the grey level at the vignetting center. It is usually a decreasing function of the distance to the vignetting center. However, the vignetting center may not be the brightest point in the image, especially if the camera ISP corrects or even overcorrects vignetting.

It is worth noticing that for RGB images, the computations are performed with the data in the image file, so the measurement does not correspond to the "photonic" vignetting referred to by opticians. Analyzer takes into account all the phenomena that cause vignetting. Besides the vignetting introduced by the incidence angle of the light on photosites along the sensor edges, the Tone Curve (or transfer function) also plays an important part. (Analyzer's Tone Curve measurement is presented in Section 25.) By applying a non-linear function to the raw values, the pixel values are no longer proportional to the illumination.



Impact of the transfer function on vignetting: application of a transfer function can reduce vignetting value

Note also that for cameras with a fixed lens, some vignetting correction may be applied during raw conversion. See Section 15.5 for more details about the differences between raw and RGB Vignetting measurements.

15.3 Influencing factors

Three physical parameters have an influence on vignetting:

- The focal length setting of a zoom lens.
- The aperture.
- The focusing distance for some optics, and for values less than 25 cm (10").

Note: It is important that the mid-grey measured at the center of the image file be constant from one shot to another in order to make valid comparisons.

15.4 Measuring vignetting

Vignetting measurements are performed using a Dots chart, and consist of measuring the attenuation of the white background in the field. The presence of black spots is used only to help the camera choose good exposure settings.

Analyzer can measure vignetting as long as the black dots are the darker part of the image. It can be slightly less in practice, since noise has to be taken into account. However, a fall-off of up to 90% can be measured with no problem, and covers almost all existing cameras.

Luminance vignetting

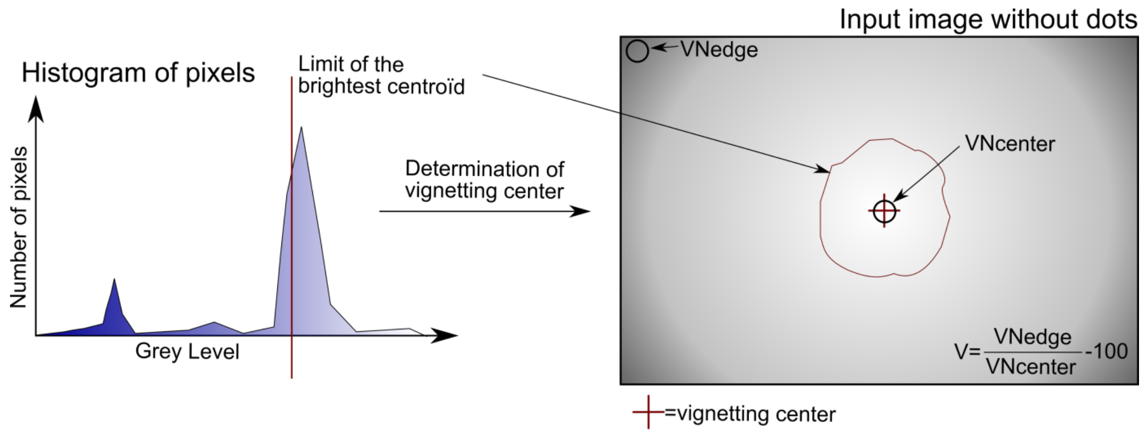
The measurement gives a maximum attenuation value that is expressed as a percentage or as an exposure value (EV).

For example, by applying the following formula:

$$Y = -\log_2(1 - X),$$

where Y is the value in EV, and X the attenuation.

An attenuation of 25% corresponds to −0.42 EV. This attenuation is expressed with respect to the weighted center of the Vignetting. This center is the geometric center of the pixels with a grey level higher than 85% of the distribution in the image, weighted with their grey level, as shown below.



Computation of vignetting center and vignetting

In the case of isotropic vignetting, the attenuation curves are sufficient to describe vignetting. They give attenuation against distance from the vignetting center for each channel.

If vignetting is not isotropic, these curves are meaningless, and you must use a description of vignetting in the field instead. This description is given by 2D maps that represent attenuation in the field and contour lines of attenuation.

Analyzer also returns the mean grey level value for the whole image. Since vignetting depends on the Tone Curve, the measurement is more meaningful when this mean value is close to the target exposure value (usually about 50% of the grey level dynamic range).

Color vignetting

Analyzer characterizes the ratio of attenuation between the observed channel and the luminance channel, or between the observed channel and the average of green attenuations for raw images.

This means that vignetting is measured for all channels with respect to the center of the image and then compared to a “mean attenuation,” which is the luminance attenuation in RGB images and the mean of green attenuations for raw images.

For a channel C, the vignetting at a position (i, j) in the field is computed from the grey levels I of the image, with the following formula:

$$V_{i,j}^{C} = \frac{I_{i,j}^{C}}{I_{\text{center}}^{C}}$$

For a channel C, the color vignetting at a position (i, j) in the field is then:

$$VC_{i,j}^{C} = \frac{V_{i,j}^{C}}{V_{i,j}^{\text{ref}}}$$

with $V_{i,j}^{\text{ref}} = V_{i,j}^{\text{Luminance}}$ for a RGB image and $V_{i,j}^{\text{ref}} = \frac{V_{i,j}^{\text{Green1}} + V_{i,j}^{\text{Green2}}}{2}$ for a raw image.

As they are ratios between attenuations, values of color vignetting by channel have no unit.

The standard deviation of color vignetting is obtained as follow, from the color vignetting values of channels red and blue, in the field:

$$\text{standard deviation} = \sqrt{\frac{\text{variance}(VC^{\text{Red}}) + \text{variance}(VC^{\text{Blue}})}{2}}$$

Since one of the main causes of color vignetting is the shift of the infrared filter towards visible wavelengths, Vignetting is generally more important on the red channel than on the green channel, while the blue channel is the least affected. Since luminance is usually very close to the green value, the color Vignetting on the green channel is usually close to 1 for every position in the field.

Analyzer also computes the imbalance between the green channels, for raw images. At each position i in the field, imbalance is defined as:

$$\text{Gimb}_i = 2 \times \frac{\text{Gr}_i - \text{Gb}_i}{\text{Gr}_i + \text{Gb}_i}$$

with Gr (green red) and Gb (green blue) the two green channels in the Bayer filter array.

The maximum green imbalance is then:

$$Gimb_{max} = \max_i(abs(Gimb_i))$$

15.5 Measurement in raw format

In raw images, digital values increase linearly with the number of photons detected by the sensor and converted into charges. In this case, Analyzer measures the photonic vignetting along with the vignetting from the sensor, if any (e.g., color vignetting). However, you may have to deal with a dark signal value.

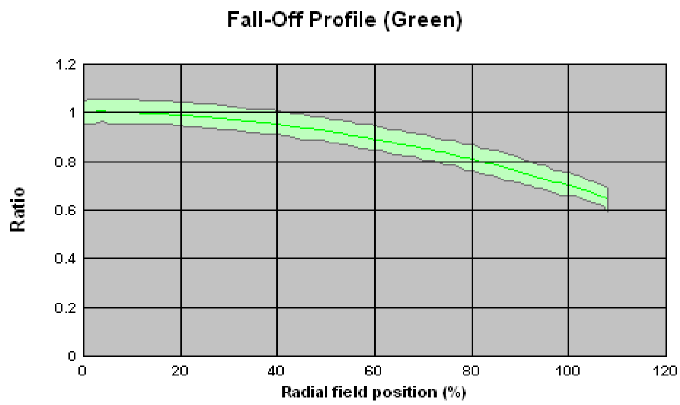
More precisely, transfer functions for raw images sometimes have a non-null y-coordinate at the origin, due to an electronic constraint, called dark signal (see Section 24). Some cameras correct this in their raw images, but some do not. In order to perform an accurate Vignetting measurement, you will need to provide Analyzer with these dark signal values (one per channel) by using sidecar files containing this kind of information about the image (see Section 4.6 for information about sidecar files).

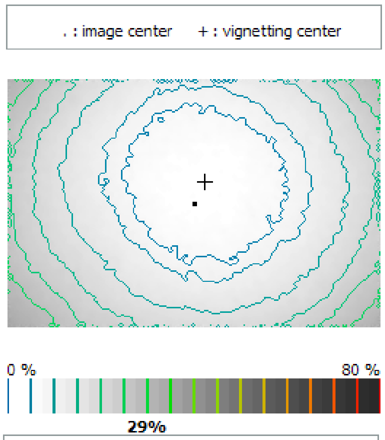
Depending on the camera, the results of the Vignetting measurement may dramatically differ for raw and RGB images. The raw conversion of some cameras may have algorithms to correct vignetting, which is why vignetting may be much more significant in raw than in RGB images. On the contrary, vignetting may be over-corrected and then the raw attenuation ratio appears higher than that shown in the attenuation curve of an RGB image.

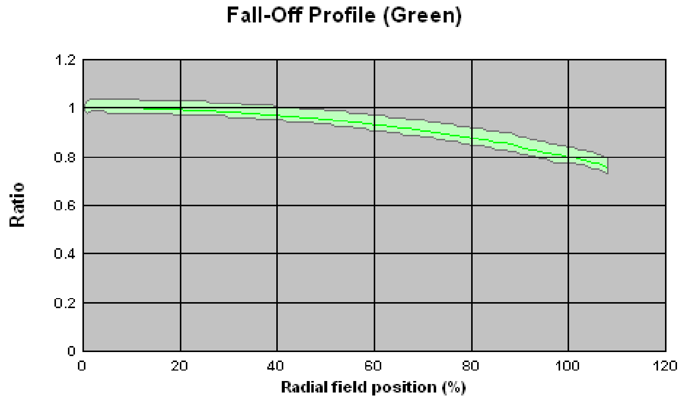
The application of a Tone Curve on the image (see Section 25) also modifies the vignetting in RGB compared to the vignetting in raw.

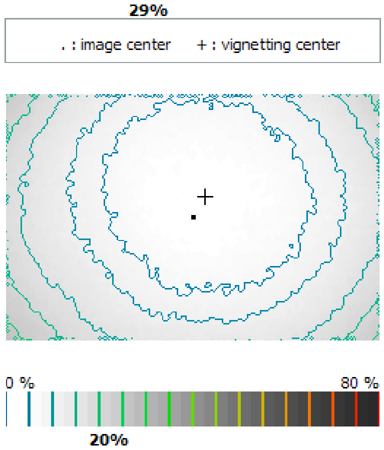
The figure below gives an example of green vignetting from a Canon DSLR with a 24–70 lens. The upper map is measured from the raw image, and the lower map is measured from the RGB image. As can be seen, the raw conversion has modified the vignetting caused by the lens, which drops from 29% to 20%, mainly due to the application of a Tone Curve.

Note that the center of vignetting (the cross) does not correspond to the center of the image (the point), which explains why there are vignetting values for position above the half-diagonal of the image (> 100% of the half-diagonal).

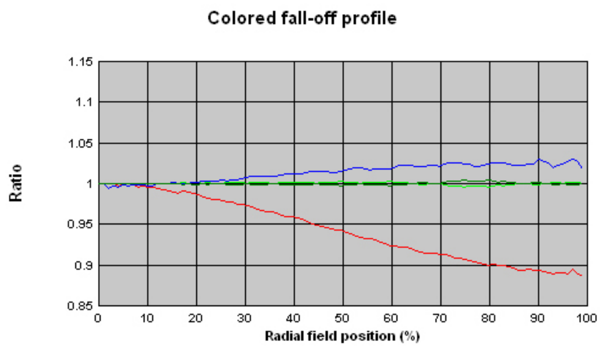


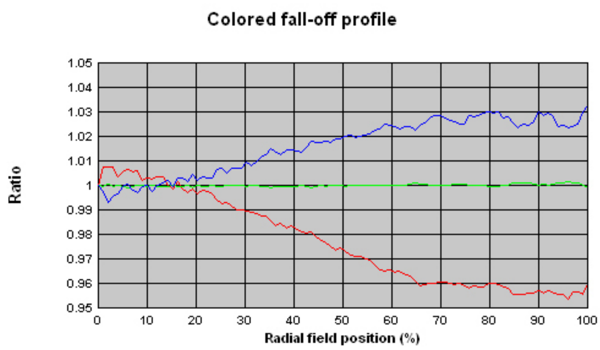






In the same way, color vignetting can be modified or corrected by the raw converter. The two following graphs display measurement results from a camera phone. The first measurement is performed on the raw image, the second one on the RGB image. Notice that color vignetting has been modified by the raw conversion; in particular, the red ratio has changed from 90% to 95%.





Color vignetting of a single shot, with raw image data on the left and RGB image data on the right

Note that raw conversion in camera phones usually corrects vignetting. This is possible because the lens is fixed. When the lens can be changed by the user, as with a DSLR, no vignetting correction is applied. Then the difference between raw and RGB images is not due to a correction, but is mainly a side effect of the application of the Tone Curve.

15.6 Analyzer output

Analyzer returns the following data:

- The summary tab contains two sections, "Geometry" and "Variations in the field".

  The first section gives information about the vignetting center of each channel:

  – The distance of the vignetting center from the image center, given as a percentage of the half-diagonal of the image.

  – The grey level at this position for each channel (RGB images only).

  – The maximum distance between centers as a percentage of the half-diagonal of the image.

Geometry

	R	G	B	Y
Off-Centering (%)	41.6	48.5	25.7	45.2
Grey level at vignetting center	149	147	148	148

Max. distance between centers	50.4%

  The second section gives information about attenuation, amplification and color vignetting:

  – The maximum vignetting values for each channel of the image, expressed in different units.

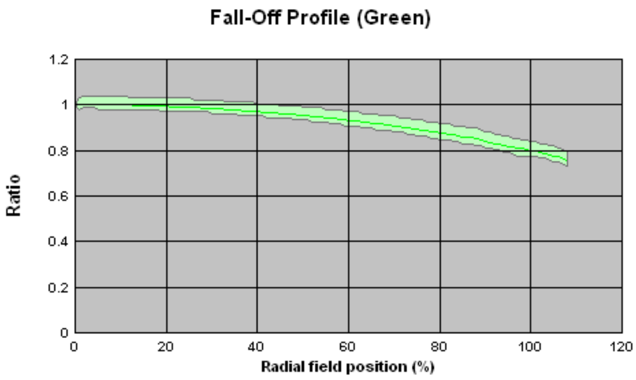
  – The maximum amplification.

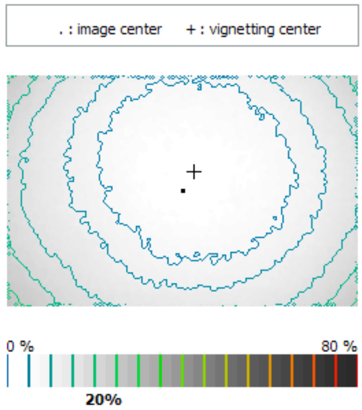
  – The color vignetting in percentages, for red and blue channels. A 0.95 value of color vignetting in the color vignetting profile is represented by a value of 5%. These values are computed on vignetting profiles.

  – The maximum of green imbalance.

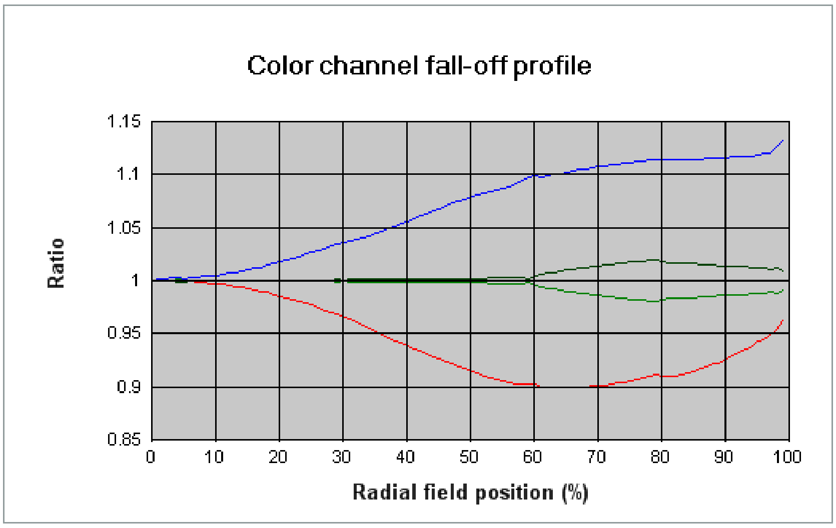
- The vignetting by channel tab displays the vignetting for R, G, B and Y (for a RGB image) or Gb (for a raw image) as a function of the position in the image field. Attenuation is computed from the vignetting center of each channel. A 2D map shows the attenuation in the field.

  If vignetting in not centered in the image, the values for radial field positions may be higher than 100%, because 100% represents the length of the half-diagonal of the image.



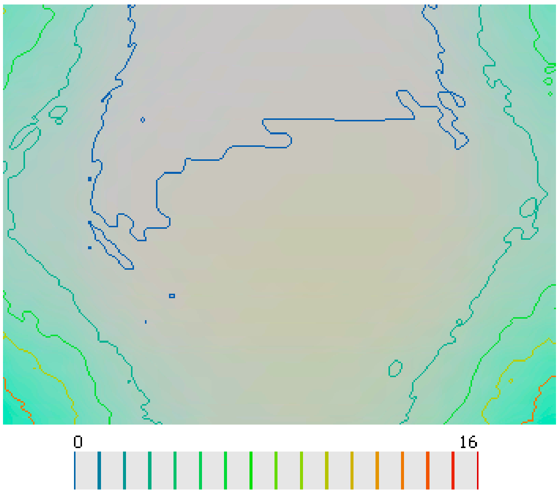


- The color vignetting tab displays the ratio between the vignetting in R, G or B and the vignetting in Y (for RGB images) or the vignetting mean of the two green channels (for raw images).



A 2D map of color vignetting is also displayed:

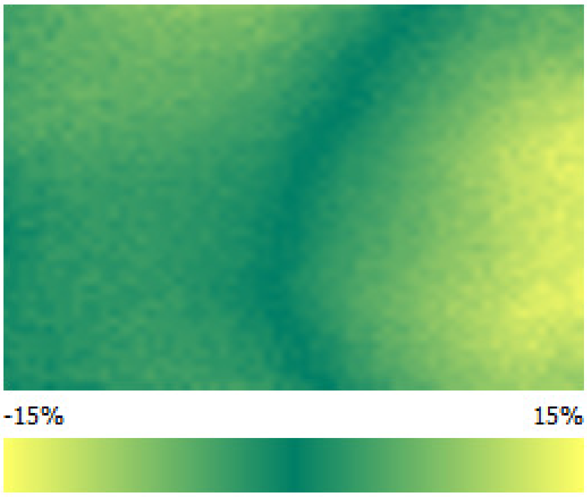
- For RGB images, the map is a subsampled version of the original image in which chromatism has been amplified four times. Edges show the limits of the areas of the field having the same chromatism ($\sqrt{a2 + b2}$) in the CieLab color space). Use this map to see coloration due to vignetting.



- For raw images, a map for all channels, similar to the one in RGB is displayed, but is has a few differences:
  - White balance is corrected for a neutral center,
  - Amplification is done on differences [blue-mean green] and [red-mean green].

- The color vignetting by channel tab displays maps of color vignetting for red and blue channels, and a map of the green imbalance for raw images.

  Each map displays color vignetting in false colors. The scale is given under each map. Here is for example a map of green Imbalance:



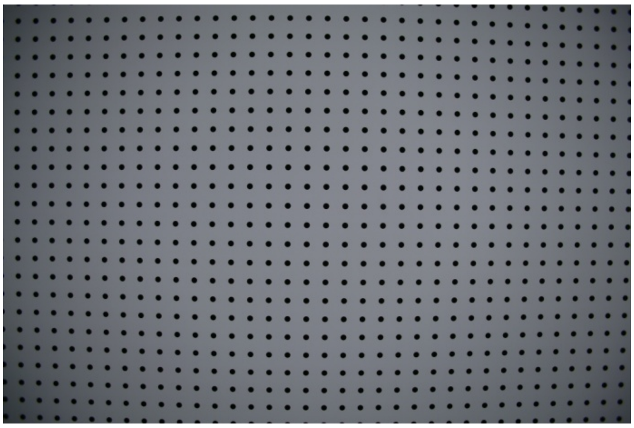
Several values are also given:

- The maximum attenuation and amplification in the field. A 0.95 value of color vignetting (attenuation) is represented by a value of –5%, a 1.1 value amplification of 10%.
- The standard deviation of color vignetting.
- The maximum of green imbalance (raw only).

- The CPIQ CU tab displays results of color uniformity following CPIQ standards. See CPIQ section for a description of these results.

15.7 Examples

The following figures show the results for a Canon EOS 1DS with a Canon EF24-70 f/2.8L USM lens. The focal length is 17 mm, ISO 100, f-number 2.8, focus distance 0.4 m. The measurement is done on the following RGB image:

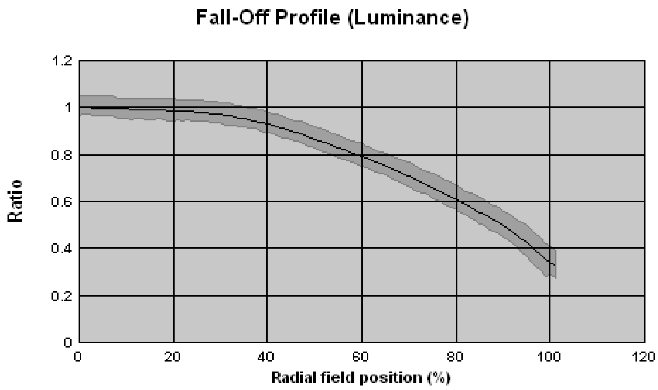


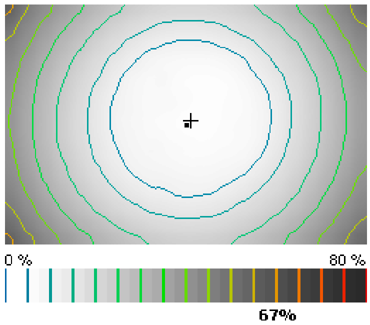
Short focal length lenses are known to suffer from vignetting, especially with wide apertures on zoom lenses.

On luminance channel, the maximum measured fall-off is 1.62eV (68%), and the mean grey value is 131, which is suitable for a 8-bit image.

The fall-off profiles represent the attenuation as a function of radial field position (percentage with respect to the image size).

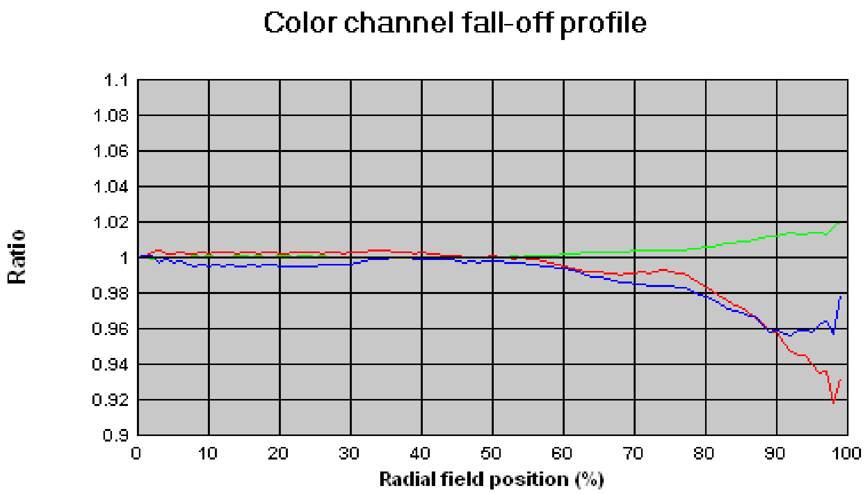
The 2D map of attenuation displays the attenuation in the field. The center of vignetting is represented by a cross and the image center by a dot. Vignetting is centered and isotropic.



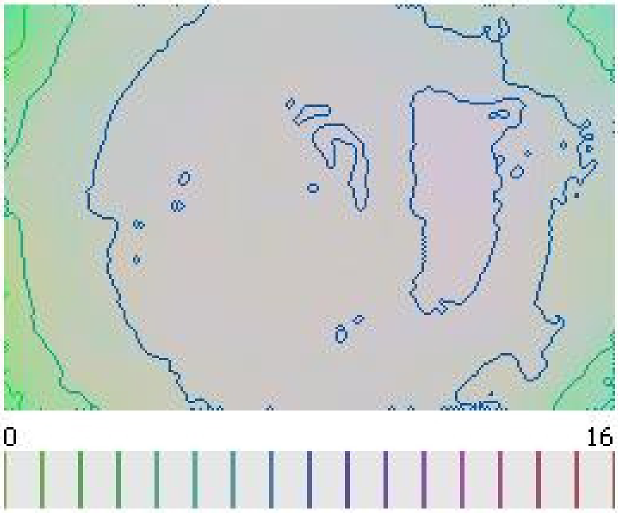


With 68% of attenuation in the corners, vignetting is very strong and objectionable. This example is quite extreme, but it is a real case. For such a camera, a solution for decreasing vignetting (apart from digital correction) is decreasing the aperture.

The Color channel fall-off profile shows low color vignetting in most parts of the field, except in the corners. Red and blue channels are more attenuated than the green channel, which means that corners will appear green.



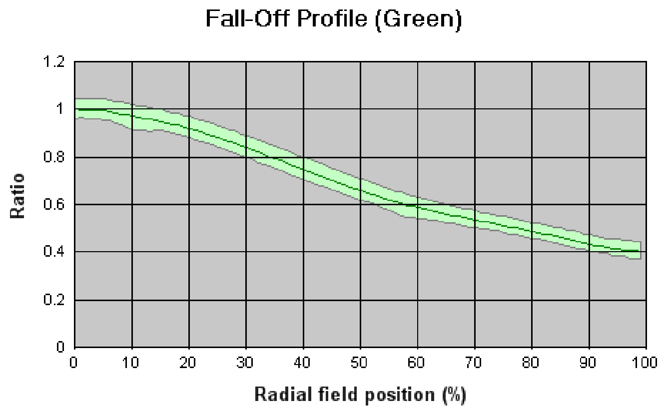
If we look at the 2D map of amplified chromatism, we can see that edges of the image appear green. Of course, the colors have been amplified, and the real image is not that green.

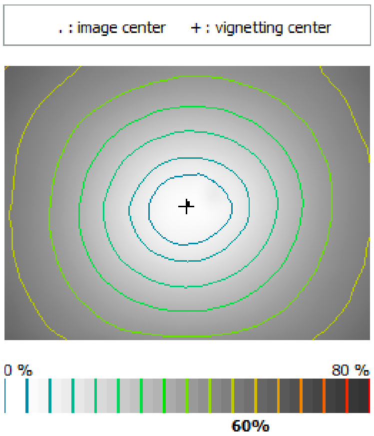


2D map of color vignetting for Canon EF24-70 f/2.8L USM lens

The following example of a white raw image shows the Vignetting measurements for a 5 Mpixel camera phone (ISO speed 100, aperture f/2.8, focus distance 1 m).

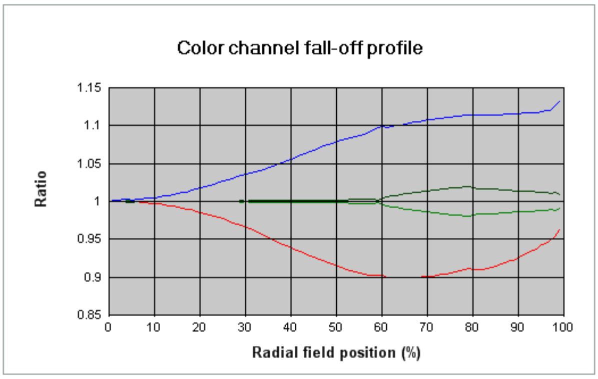
Maximum fall-off is 1.3 eV (60%) for green channels.

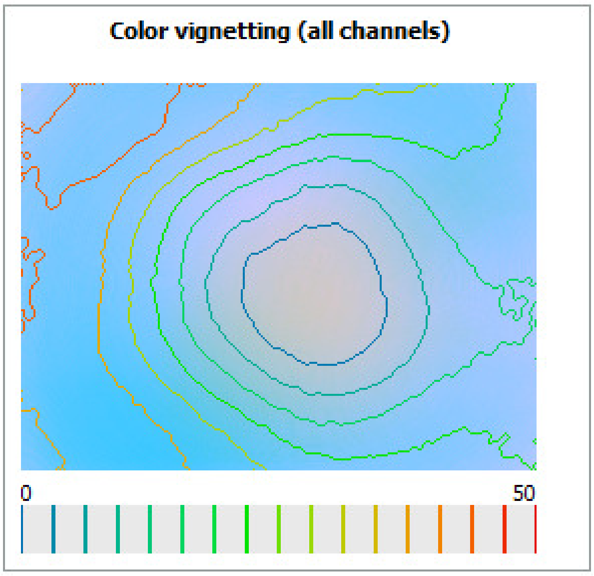




Vignetting for 5 Mpixels Sensor, (ISO speed 100, aperture f2.8, focusing distance 1 m)

With a maximum of attenuation of 60%, vignetting is strong. But this is a raw image, and vignetting may be corrected during image processing. It is worth noting that if vignetting is isotropic, it is not the cause of the color vignetting:

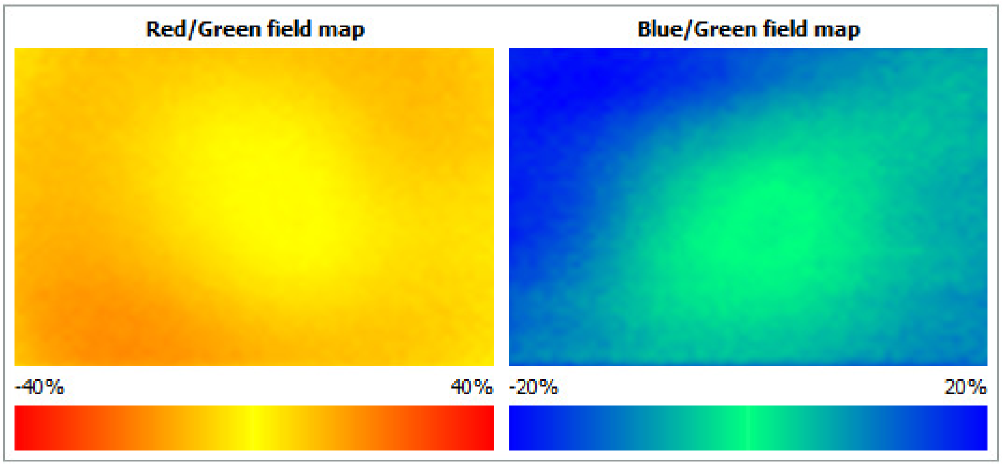




Color vignetting for 5 Mpixels Sensor

The color vignetting here is roughly isotropic. Looking at the graph and at the map, we see that if the color vignetting is not corrected, the corners and left side will appear blue, because the red channel is more attenuated than the green, while blue is less attenuated.

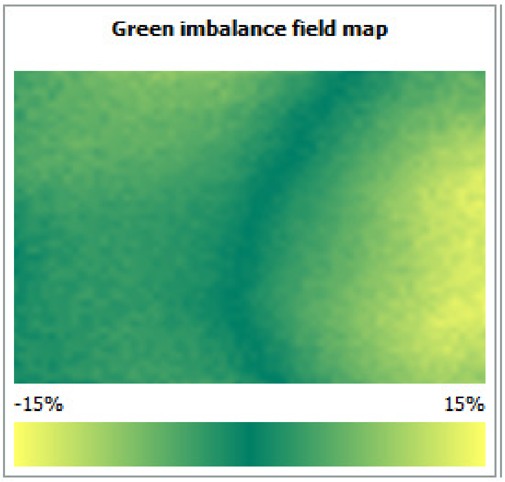
It is also visible in the field map images for the red and blue channels:



Red and blue maps of color vignetting for 5 Mpixels Sensor

The maximum attenuation for the red channel is –18.5%, while the maximum amplification for the blue channel is 20.5%.

Looking at the green imbalance field map, it appears that the two green channels are significantly different:



Green imbalance map for 5 Mpixels Sensor

The maximum green imbalance in the field is 14%. This imbalance, which usually comes from pixel crosstalk, is anisotropic.

15.8 Measurement accuracy

If the lighting is not completely uniform, and the sensitivity of the sensors in the CCD or CMOS matrix vary, measurements may fluctuate. A variation of ±2.5% is tolerated on measured values for vignetting.

For raw images, if the dark signal is not known, the error will be as follows:

$$\Delta V = \frac{(1 - V) \cdot DS}{N_{\mathrm{center}} - DS}$$

where *DS* is the dark signal value.

The error will be approximately equal to the proportion of dark signal in the sensor dynamic. This means if the dark signal represents 3% of the dynamic (for example, if the dark signal is 1024 on a 16-bit sensor), there will be an error of approximately 3% in the attenuation value.

The accuracy of the color vignetting ratio is 0.5%.

15.9 Measurement scale

Tables below characterizes the quality of an image depending on the values for luminance and color vignetting.

For raw images, the results are given before color rendering. As color vignetting may be amplified or reduced depending on white balance and gamut extension, same raw results can lead to different perceptions of vignetting on the final RGB images, so you should use these results carefully. On the other hand, the results provide useful information about the spectral response of the sensor, as well as the efficiency of the infrared filter.

Luminance vignetting

Maximum vignetting value (Ev)	Maximum vignetting attenuation value (%)	Qualitative level
Between 0 and 0.1 Ev	Between 0 and 7%	Excellent
Between 0.1 and 0.3 Ev	Between 7% and 19%	Very good
Between 0.3 and 0.4 Ev	Between 19% and 24%	Good
Between 0.4 and 0.7 Ev	Between 24% and 38%	Fair
Between 0.7 and 0.9 Ev	Between 38% and 46%	Bad
Over 0.9 Ev	Over 46%	Very bad

Color Vignetting measurement scale

These scales are given for values in the *Color Vignetting by channel* tab. Values in the summary, computed from vignetting profiles, are less precise and thus should not be used.

Maximum color vignetting ratio value (%)	Qualitative level
Between 0 and 3%	Excellent
Between 3% and 5%	Good
Between 5% and 10%	Fair
Over 10%	Bad

Green imbalance measurement scale (for raw images only)

Maximum green imbalance (%)	Qualitative level
Between 0 and 3%	No visible imbalance
Between 3% and 5%	Slightly visible imbalance
Between 5% and 10%	Visible imbalance
Over 10%	Very visible imbalance

15.10 Set up parameters influencing the measurement

Parameters that influence the Vignetting measurement are:

- The part of the transfer curve that is involved, which depends on:
  - The ISO sensitivity (set the exposure for a grey level roughly equal to 120–180).
  - The exposure correction, which should be OFF (EV = 0).
- Use of a digital zoom, which should normally be OFF, unless it is the object of the measurement.
- Image aspect ratio 4:3, 16:9, etc.: normally the shot should use as much of the sensor field as possible, unless it is the object of the measurement.
- Compression ratio, which should be as low as possible (TIFF format is preferable to JPEG, and if JPEG is used, choose a compression ratio that is less than 10).
- Dark signal for raw images.
- Specific modes of the camera such as saturation, contrast, color modes and so on, which should be turned OFF.

15.11 Measurement validity

An isolated value of vignetting is not meaningful. It is always necessary to associate it with the influencing parameters. Claiming, for example, that a camera produces a vignetting of 10% is meaningless. On the other hand, it is perfectly meaningful to indicate that a camera with a 16 mm focal length lens, at an aperture of f/2.8 and a mid-grey level at center equal to 160, produces a vignetting of 10%. For color vignetting, the measurement also depends on the illuminant. To compare two cameras, you must use shots obtained with the same illuminant (tungsten or daylight, for example).

> **Note:** There may be other influencing factors for certain cameras, such as (for example) use of a digital zoom lens, the aspect ratio 4:3 or 16:9, etc. In such cases, you should mention these factors along with the vignetting values.

15.12 Comparing two cameras

The measurements of vignetting are independent of the resolution. Two cameras may be compared as is, in identical image locations.

When comparing two cameras with measurements from RGB images, make sure the mid-grey value is the same.

15.13 Shooting

The V measurement uses a Dots chart.

a) **Determine the influencing parameters** (focal length, aperture, focus distance, ISO setting, Ev, digital zoom, aspect ratio).

b) **Specific shooting conditions** (see also Section 5); the framing should be such that:

   - There is no set requirement on the number and the size of black spots. The image should be sharp. Simply avoid having spots that are too big in the corner of the image.
   - No element that is external to the test target should appear in the shot.
   - The target lighting should be as uniform as possible (the variation should be ≤ 0.1 EV over the whole frame).

Take all necessary precautions to avoid shaking the camera when shooting. You might want to use a cable release or trigger the shot from a computer connected to the camera via a FireWire cable.

Note: It is important to keep a record of all the parameters and settings associated with each shot. Depending on the model, not all cameras record all the EXIF data, and if the measurement is to be used to compare two cameras, the image file recording conditions must be strictly identical.

Note: This measurement allows you to check the uniformity of the test target illumination. A first visual check is described in Section 3.2.2. For this purpose, use any camera with a small aperture (f/22, for example) so that vignetting is minimized. Perform two measurements in a row, one with an image in landscape format, and the other one with an image in portrait format, without changing the influencing parameters. For each measurement, make sure that the framing conditions are correct. The lighting is uniform if the vignetting centers are identical for the two shots. If they are not, the lighting system needs to be adjusted and/or its position modified. Once the lighting is uniform, you can measure the camera vignetting.

15.14 Sidecar parameters

See also Sections 4.5 and 4.6.

While performing raw measurements, be aware that some cameras acquire raw images with some rows or columns that are not lit when shutter is open. In this case, use crop parameters recorded in sidecar files so that Analyzer will ignore those pixels.

The following sidecar parameters can be used for the Vignetting measurement:

```
[Crop]          // analysis area section
Left= ...       // left position
Right= ...      // right position
Top= ...        // top position
Bottom= ...     // bottom position

[Black]         // Black value section
BlackValue= ... // value to subtract to have 0 black (must be in 15b for raw images)
```

16 – EFL: Effective Focal Length and Field Of View

16.1 Introduction

Among the parameters that describe a lens, focal length and aperture are perhaps the most important. A lens may have a fixed focal length, the most common being 50 mm. It may also have a range of focal lengths, making it a zoom lens. For example, a 17–70 mm lens is a lens that can be set to a focal length between 17 mm and 70 mm.

The focal length determines the angle of view (or field of view), which is the extent of the scene that appears in the photo.

The focal length permits to separate lenses in three categories:

- Normal or medium lenses have an angle of view of about 50°, with a focal length of about 50 mm.
- Wide-angle lenses: their angle of view is wider than normal lenses, their focal length shorter (for example, a 14 mm lens with a diagonal field of view of 114°). They are used, for example, for landscape photography.
- Long-focus or telephoto lenses: their angle of view is narrower than normal lenses, their focal length longer (for example, a 200 mm lens with a diagonal field of view of 12°). They can be used to photograph subjects such as wild animals from a long distance.

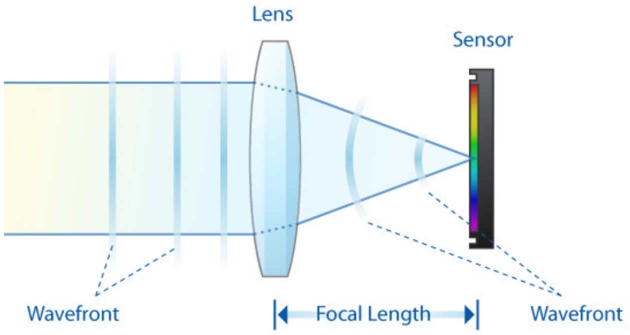
Despite its apparent simplicity, determining the focal length is not straightforward, particularly for large complex optical systems.

Examples of the same scene photographed with focal lengths of 18 mm, 59 mm and 200 mm

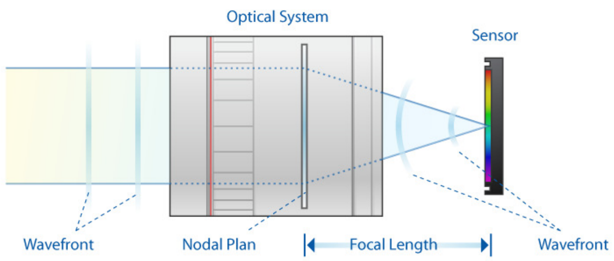
16.2 Definitions

16.2.1 Focal Length

In the case of a thin lens, the definition of focal length is quite simple: it is the length between the lens plane and the plane on which collimated light rays are focused on a spot, the focal point. Collimated light is light whose rays are parallel (sometimes described as light focused at infinity), and thus has a plane wavefront.

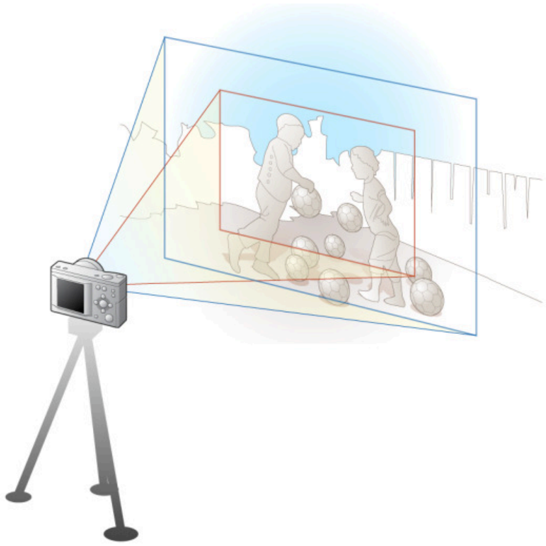


Thick optical systems are different. They are composed of several lenses, and it is not possible to easily determine the plane where collimated beams start to converge to the focal point. This plane is called the nodal plane. In these systems, the focal length is the distance between the focal point and the nodal plan.



16.2.2 Field of View

The field of view, also called the angle of view, is the extent of a given scene that is received by the image sensor. It can be measured vertically, horizontally, and diagonally.



The field of view (FoV) depends on the focal length, the sensor size, and the distortion length. It also depends on the focus. Complex optical systems (known as zoom lenses) may vary the focal length, hence the field of view.

16.3 Influencing factors

Several parameters impact the Effective Focal Length and the field of view:

- The chosen focal length if the lens is a zoom lens.
- The focus distance.

The following parameters may also impact the Effective Focal Length for some lenses:

- The illuminant, for lenses with wide lateral chromatic aberration.
- The distance to the object, for very-wide-angle lenses such as fish-eye lenses, and when the distance to the subject is very short.

16.4 Measurement of Focal length and Field of view

The measurement can be performed with one shot or two shots of a Dot Chart, depending on whether or not you know the position of the nodal plane. If the nodal plane is known when using the shooting procedure described below, only one shot is needed. If not, you will need two images shot at different distances from the chart.

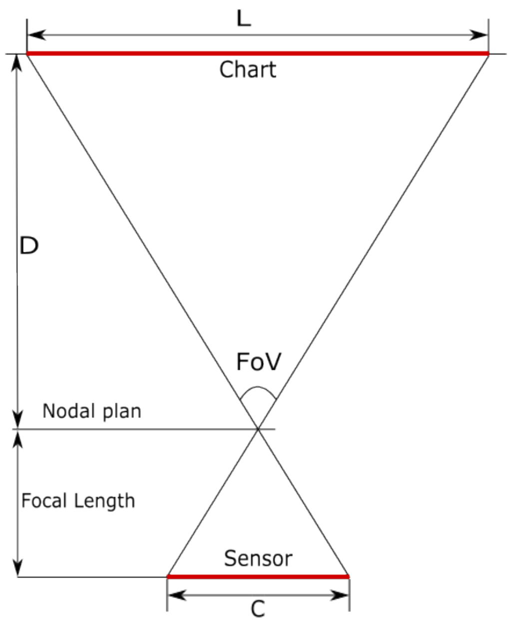
The measurement uses the distance between dots to estimate the length of the chart that is visible in the image. From that length, the sensor size and the distance between the nodal plane and the chart, the Effective Focal Length and the field of view are computed.

If you do not know the distance between the nodal plane and the chart, then you can obtain the measurement from two shots of two charts (you must know the distance between the two charts)

The following table summarizes the pros and cons of both methods:

	Two shots method (TSM)	**One shot method (OSM)**
Domain of use	Camera lenses with a manual focus position. Nodal point is not needed.	Camera lenses with auto focus/no-manual focus. Nodal point is needed.
Pros	Easy, no need to find nodal point.	Accurate: fewer measurements.
Cons	Less accurate: need more measurements. Does not work with auto focus lenses.	Needs to find the nodal point.

16.4.1 One Shot Method (OSM):



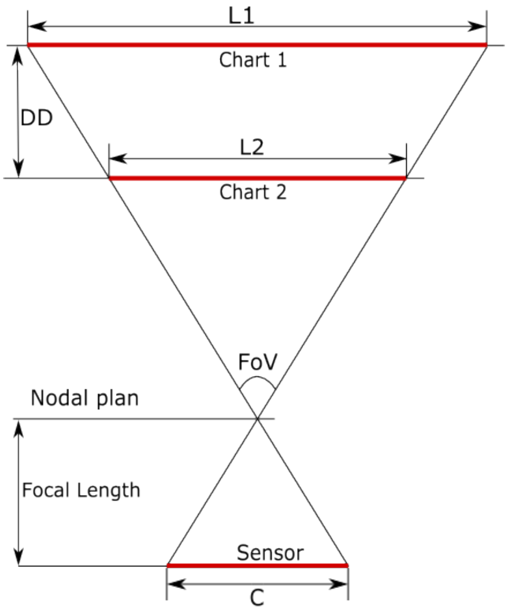
The focal length and the FoV are computed as follows:

$$\mathrm{FoV} = 2 \cdot \arctan\left(\frac{L}{2 \cdot D}\right),$$

$$\mathrm{F} = \frac{C \cdot D}{L},$$

with D being the distance between the nodal plane and the chart plane, L the length of the chart in the image, and C the size of the sensor.

16.4.2 Two Shots Method:



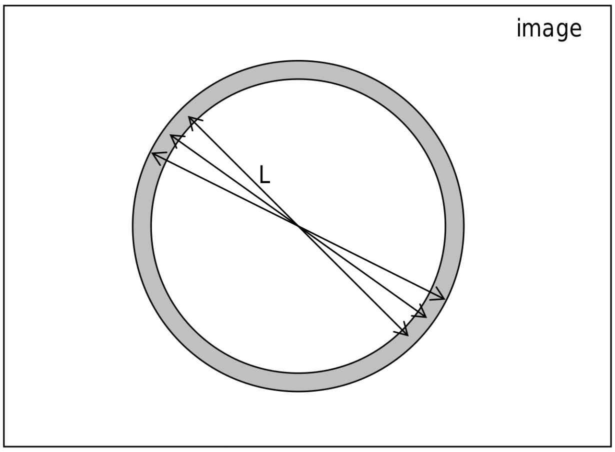
$$\mathrm{FoV} = 2 \cdot \arctan\left(\frac{L_1 - L_2}{2 \cdot DD}\right)$$

$$F = \frac{C \cdot DD}{L_1 - L_2},$$

L_1 and L_2 being the length of charts number 1 and 2 in the images and DD the distance between the two charts.

Be aware that this measurement depends on the focus distance. If the lens cannot be set to manual focus, the two shots method cannot be used, because the focus will vary from one shot to the other.

Analyzer provides the measurement vertically, horizontally, diagonally. A curve of the focal length as a function of the distance to the image center is given. A similar graph is given for the FoV.



These curves are computed using circular crops of the shots. The mean, minimum and maximum *L* length are computed for each ring, and used to compute the focal length and the field of view.

16.4.3 Orthofrontality

To obtain correct results, the normal of the chart plane must be parallel to the optical axis. That is why the measurement also outputs the angle between these two axes, known as the angle of orthofrontality. Pan and tilt angles are also given to correct the orthofrontality for the next shot.

16.5 Measurement in raw format

Focal lengths and fields of view should be the same for raw images and for RGB images. They may actually differ slightly, and the field of view may be wider in raw images than in RGB images for the same body/lens system.

It is difficult to claim that the measurement for raw images is always more accurate than for RGB images. The measurement difference comes from the fact that the raw image is larger than the RGB image, the latter being generated after cropping.

Manufacturers usually give the sensor size. However, it is not known whether this size corresponds to the raw image, or if it already takes cropping into account and corresponds to the RGB image. This factor determines whether the raw or the RGB measure is more accurate.

16.6 Analyzer output

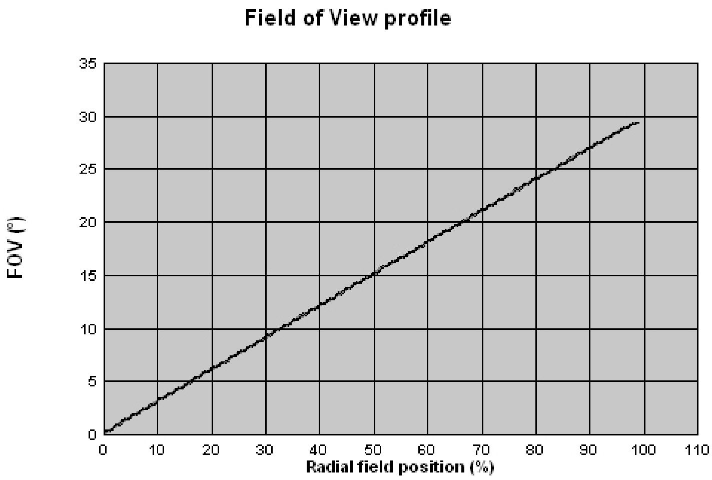
Analyzer returns the following data:

- The *Summary tab* contains two tables. The first one contains results directly related to the measurement: the horizontal, vertical, and diagonal field of view (usually the FoV indicated by manufacturers); the Effective Focal Length; and the 24×36 mm equivalent focal length, which can be used to compare sensors with different sizes. Analyzer provides the orthofrontality angles in the second table. It also shows in which direction you must rotate the camera. In the example below, the camera must be slightly turned downward and leftward, but the errors are very small.

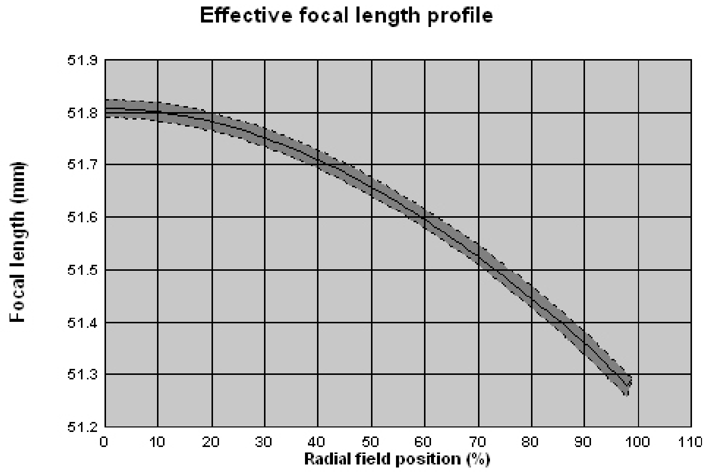
	Height	Width	Diagonal	Center
Field Of View in degrees	16.49	24.62	29.46	-
Effective focal length in mm	51.64	51.42	51.29	51.81
Effective focal length (24x36 mm equiv.) in mm	82.62	82.28	82.07	82.90

Orthofrontality in degrees	0.50 °
Tilt in degrees	0.40 ° ↓
Pan in degrees	-0.30 ° ←

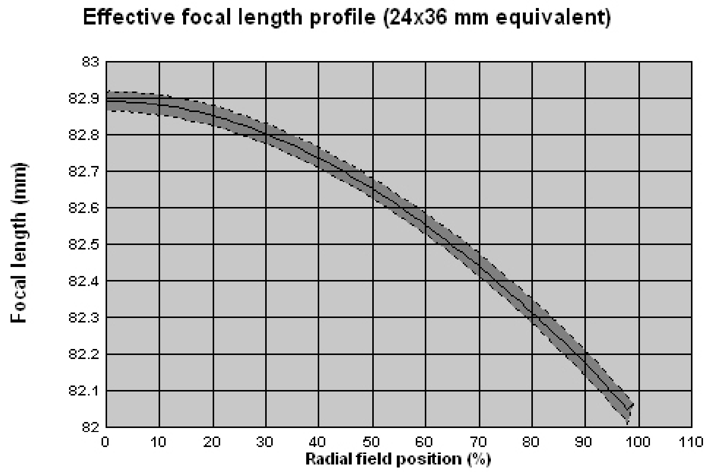
- The *Field of View* tab shows the value of the field of view occupied by a disk centered on the image center and whose radius is a varying proportion of the image size.



- The *Effective Focal Length* tab shows the focal length corresponding to the field of view above. A non-constant curve shows geometric distortion. The central curve is the mean computed on a circular ring, and the two envelopes are the minimum and maximum values for this ring.

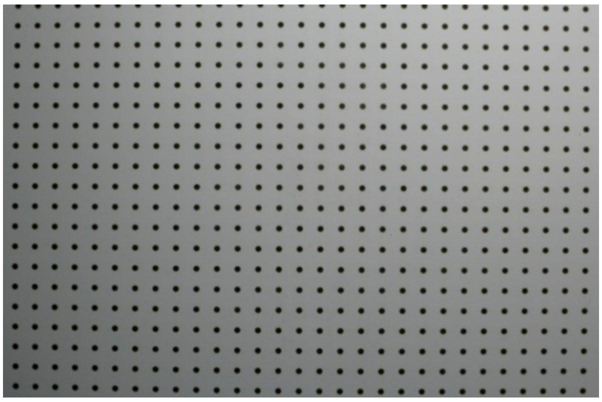
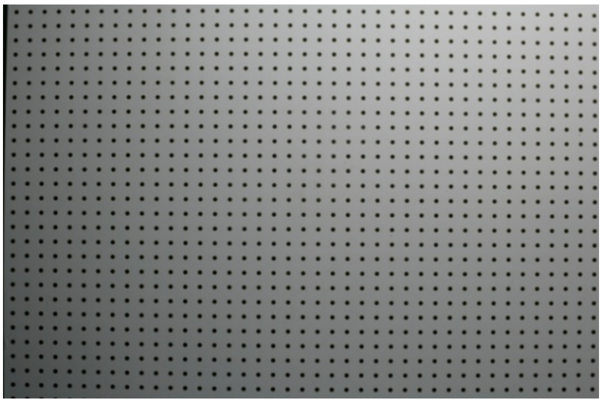


- The *24×36 mm equivalent* tab shows what the focal length would be if the sensor were a 24×36 mm sensor or film. You can use these results to compare the focal lengths of two different cameras.



16.7 Examples

The following two images were shot using a Canon EOS 5D with a Canon 50 mm/1:1.4 lens.

The distance between the chart and a fixed point near the camera is 1063 mm for the first image, and 1492 mm for the second, thus the distance between the two charts is 429 mm. The distance between the dot centers is 26 mm on both charts.

The ambient illuminant is fluorescent.

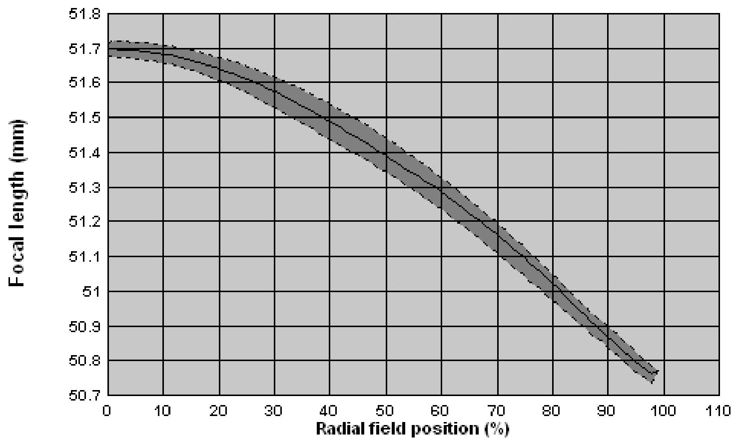
Analyzer measures orthofrontality angles of 0.34° and 0.45°, respectively. The sensor size for this camera is 36×24 mm. The focus has been set to infinity. Analyzer gives the following results for this measurement:

	Height	Width	Diagonal	Center
Field Of View in degrees	26.26	38.78	46.05	-
Effective focal length in mm	51.31	51.00	50.77	51.69
Effective focal length (24x36 mm equiv.) in mm	51.31	51.00	50.77	51.69

Given the distance between charts, the error is 1.2%, thus the diagonal field of view is between 45.5° and 46.6°.

The manufacturer specifies a diagonal angle of view of 46° for this lens. The main measurements used to describe a lens are the diagonal angle of view and the vertical focal length. In this example, the vertical Effective Focal Length is 51.31 mm.

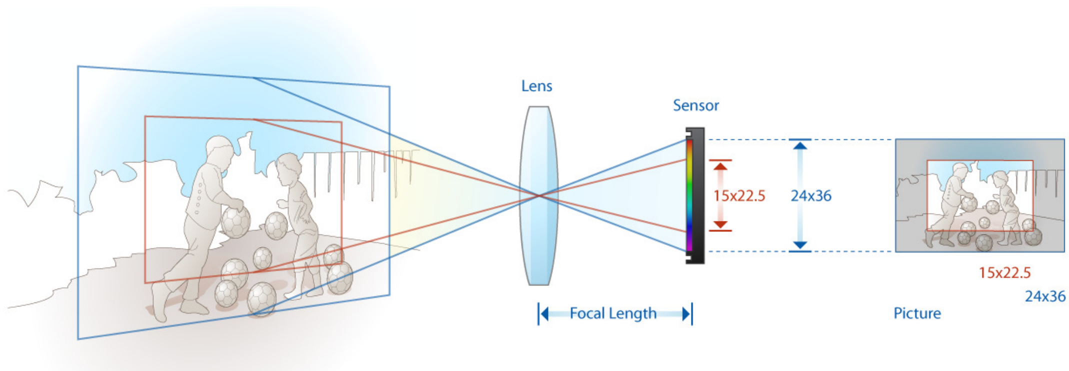
The Effective Focal Length as a function to the image center is as follows:



As can be seen, this focal length is not completely constant, which means that the lens has a slight distortion.

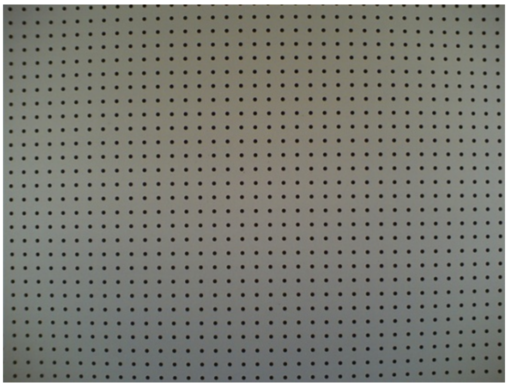
The sensor size of this camera is 24×36 mm. Therefore the Effective Focal Length and the focal length equivalent to 24×36 mm are equal. For cameras with different sensor sizes, such as 15×22.5 mm, the focal length equivalent to 24×36 mm will differ from the effective focal length.

To understand the concept of focal length equivalent to 24×36 mm, it is useful to consider that reducing the sensor size while keeping the same optical system can be seen as cropping the image. Thus some elements present on images with a 24×36 sensor will disappear on a 15×22.5 sensor. In term of elements present in the scene, this is roughly equivalent to using a lens with a higher focal length.



If a 50 mm lens is used on a camera with a 15×22.5 mm sensor, the Effective Focal Length remains the same, but the focal length equivalent to 24×36 mm is multiplied by the reduction factor. This means that this focal length will be $\frac{50 \times 36}{22.5} = 80\,\text{mm}$.

The following picture has been taken using a Nokia N90:



The Nokia N90 has an autofocus lens and has no manual-focus position. Thus only the one-shot method (OSM) is possible.

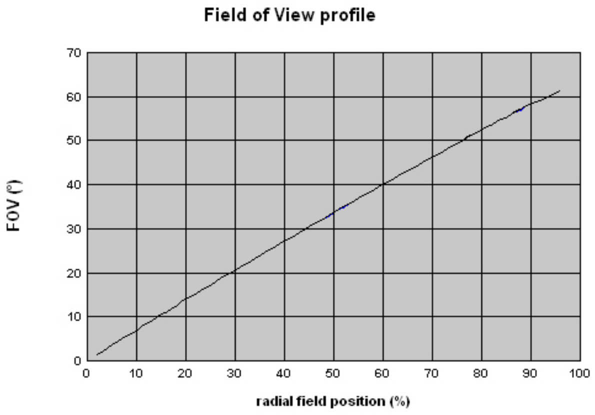
The illuminant is fluorescent, the distance to the chart is 1.583 m, and the focal length is set to an unknown length.

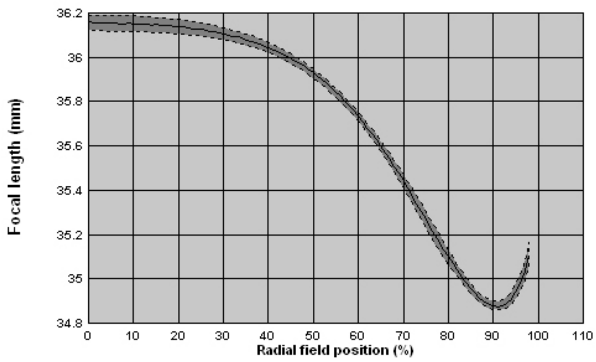
As the sensor size of this camera is not known, Analyzer returns 24×36 mm equivalent measures.

Analyzer gives the following result for this measure:

	Height	Width	Diagonal	Center
Field Of View in degrees	39.80	52.34	63.05	-
Effective focal length in mm	35.76	35.12	35.16	36.19
Effective focal length (24x36 mm equiv.) in mm	35.76	35.12	35.16	36.19

The diagonal field of view is 63.05°; the vertical focal length equivalent to 24×36 mm is 35.76 mm. The manufacturer specifies a focal length of 5.50 mm (which is more coherent for a camera phone). However, the sensor size is smaller than 24×36 mm, so the focal length 24×36 mm equivalent is longer. We can also deduce from the focal length that the sensor size is about 5.62×3.68 mm. Again, distortion can be read from the non-constancy of the Effective Focal Length in the image field.



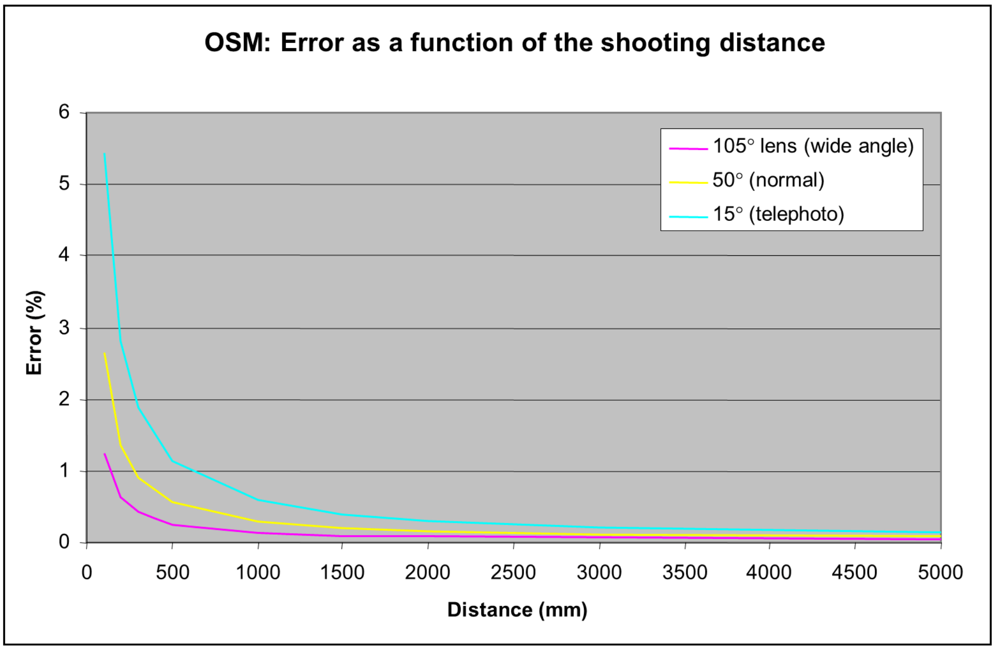


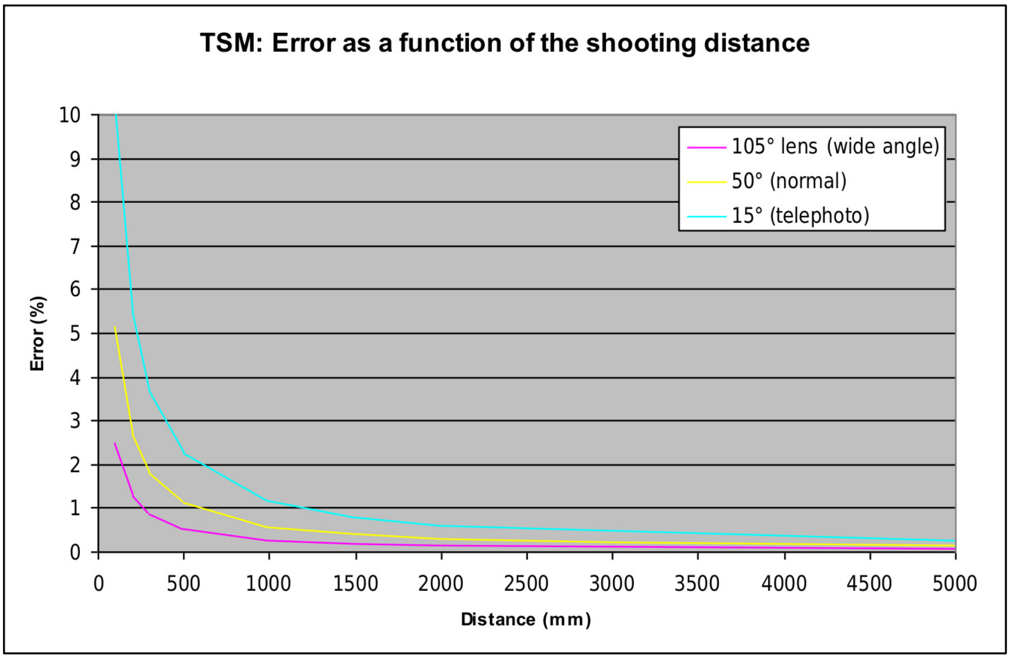
16.8 Measurement accuracy

The measurement accuracy depends on the accuracy of the measured distances and on the orthofrontality of the chart during shooting. You must follow the shooting procedures as closely as possible.

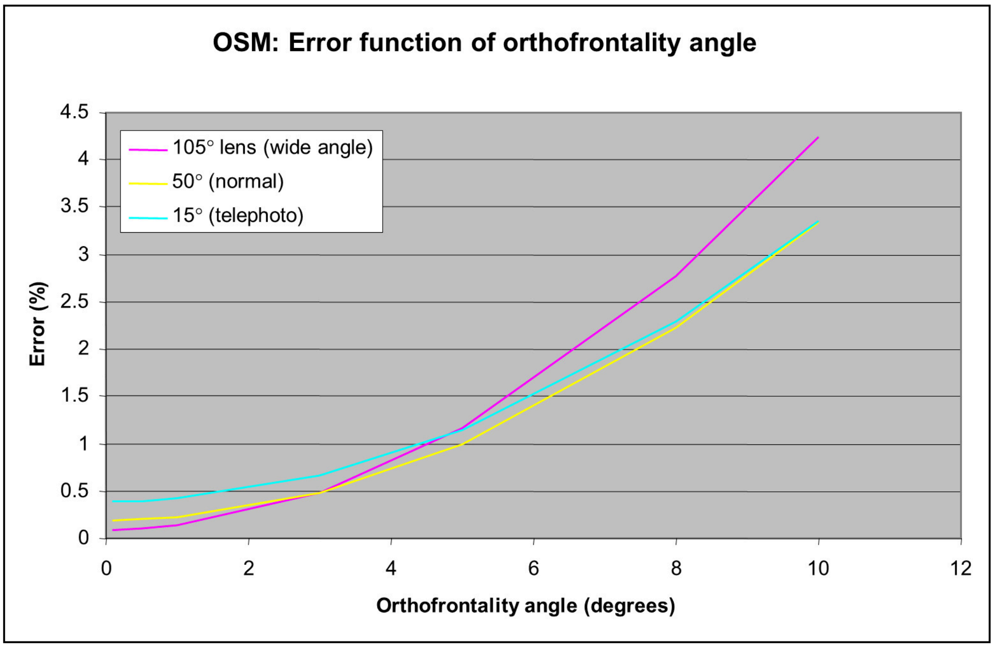
With an orthofrontality angle of less than 0.5 degree, and a distance error of less than 1% on the measured distance, measurement accuracy is 1%.

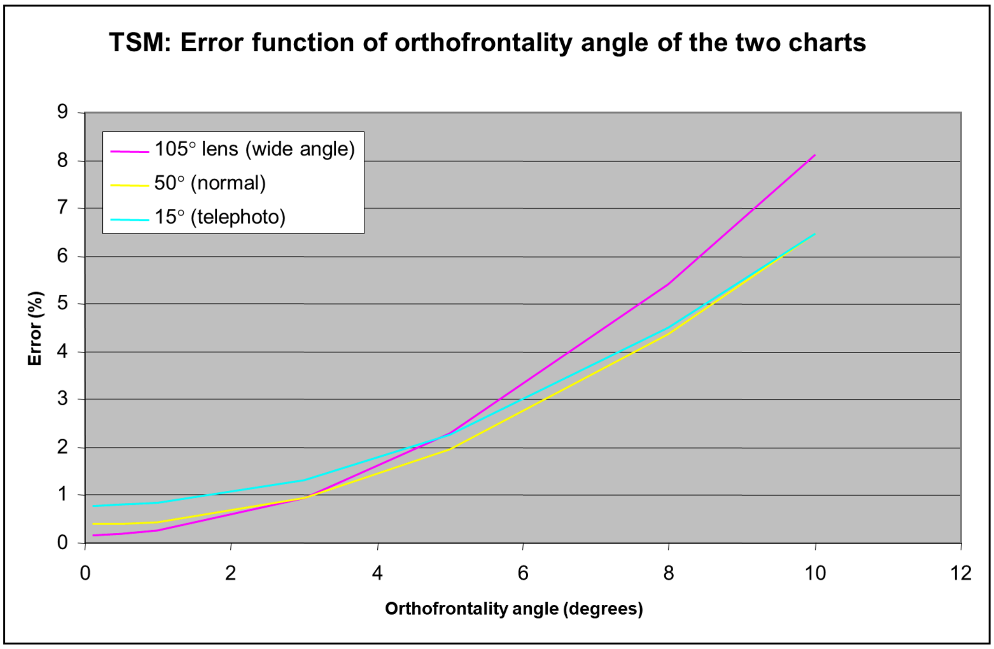
The following graph describes the influence of the shooting distance on the accuracy for three focal lengths, using the two methods. With the OSM (one-shot method), the relevant distance is the distance between the camera and the chart. With the TSM (two-shot method), the distance between the two charts is more important. It is worth noticing that the greater the distance, the more accurate the measurement. Also, the TSM requires greater shooting distances to achieve the same precision as the OSM.





Influence of distance on measurement (orthofrontality angle is 0.5°, accuracy of distance measurement 2 mm)





Influence of orthofrontality angle on measurement (distance is 1.5 m, accuracy of distance measurement 2 mm)

These graphs are obtained from the following expressions of the relative errors on the focal length and the field of view. For the OSM, the relative errors are:

$$\frac{\partial F}{F} = \frac{\beta^2}{2} + \frac{\alpha^2}{\cos^2\frac{\theta}{2}} + \frac{\partial D}{D} + \frac{\partial L}{L}$$

$$\frac{\partial\theta}{\theta} = \frac{\sin\theta}{\theta}\left(\frac{\beta^2}{2} + \frac{\alpha^2}{\cos^2\frac{\theta}{2}} + \frac{\partial D}{D} + \frac{\partial L}{L}\right)$$

where θ is the FoV, θ the orthofrontality angle of the telemeter, α the orthofrontality angle of the chart, ∂D the accuracy of the telemeter and ∂L the precision of the length measured in the image. ∂L is actually negligible.

For the TSM, the relative errors are

$$\frac{\partial F}{F} = \frac{\beta_1^2 + \beta_2^2}{2} + \frac{\alpha_1^2 + \alpha_2^2}{\cos^2\frac{\theta}{2}} + \frac{2\partial D}{D_2 - D_1} + \frac{2\partial L}{L_2 - L_1}$$

$$\frac{\partial\theta}{\theta} = \frac{\sin\theta}{\theta}\left(\frac{\beta_1^2 + \beta_2^2}{2} + \frac{\alpha_1^2 + \alpha_2^2}{\cos^2\frac{\theta}{2}} + \frac{2\partial D}{D_2 - D_1} + \frac{2\partial L}{L_2 - L_1}\right).$$

Errors of orthofrontality and telemeter naturally add, while the difference of the distance between the two targets becomes the main factor.

16.9 Set up parameters influencing the measurement

The parameters influencing the measurement of the Effective Focal Length and the field of view are:

- The orthofrontality of the chart.
- The accuracy of the measured distances.
- The digital zoom.
- Possible image cropping.

16.10 Measurement validity

An isolated value of focal length, or field of view, is not meaningful. You must always indicate whether the field of view has been measured vertically, horizontally or diagonally. Because of distortion, the same is true of the focal length, which may be slightly different on the horizontal and on the diagonal.

You also need to always associate a measurement with the influencing parameters. For example, it is meaningless to claim that a 28–80 mm lens has a diagonal field of view of 65°. You must note that this lens, with its focal length set to 28 mm and its focus set to infinity, has a diagonal field of view of 65°. To be totally accurate, as the illuminant and the distance to the subject also impact the measurement to a lesser extent, it is also better to state precisely that you obtained the measurement under, for example, a daylight illuminant at a distance to the subject of 5 meters.

16.11 Comparing two cameras

To compare two cameras (or two lenses), you must use the same focus and the same focal length (for zoom lenses).

When possible, set the focus to “manual” and adjust both lenses to infinity.

16.11.1 Example 1: Comparing two camera phones

We compared two camera phones, the Nokia 6650 and the Sony-Ericsson K800i. The Nokia was released in 2003, and the Sony-Ericsson in 2006, which means that they differ by several generations. Measurements were made at 1.250 m, under fluorescent illuminant.

Note that the Sony-Ericsson K800i has an autofocus lens, whereas the Nokia 6650 has a fixed-focus lens set between 60 and 85 mm, in order to be sharp from 60 cm to infinity. Both have a fixed focal length.

The OSM is the best method to use, because one camera has an autofocus lens. As their focal length is short (less than 5 mm), we did not try to find their nodal point with a panoramic head, but instead we considered that their nodal point is in the center of the lens. Thus the accuracy of the measured distance will be reduced, and we estimate that there is an error of about 5 mm.

As the sensor size is not known for these cameras, Analyzer uses the 24×36 mm default value and the results are obtained in equivalent to 24×36 mm.

The measurement of interest to us is the diagonal field of view for these cameras. For the Nokia 6650, we find a diagonal field of view of 62.43°. As the error in distance measurement is 5 mm, we have a global error of 0.4%, which means that the FoV is between 62.2° and 62.7°.

	Height	Width	Diagonal	Center
Field Of View in degrees	40.32	52.34	61.63	-
Effective focal length in mm	35.26	35.12	36.16	35.35
Effective focal length (24x36 mm equiv.) in mm	35.26	35.12	36.16	35.35

Orthofrontality in degrees	0.07 °
Tilt in degrees	-0.04 ° ↑
Pan in degrees	0.05 ° →

Analyzer Focal Length summary for SE K800i

	Height	Width	Diagonal	Center
Field Of View in degrees	39.64	51.37	62.43	-
Effective focal length in mm	35.92	35.89	35.59	36.12
Effective focal length (24x36 mm equiv.) in mm	35.92	35.89	35.59	36.12

Orthofrontality in degrees	0.48 °
Tilt in degrees	0.40 ° ↓
Pan in degrees	-0.26 ° ←

Analyzer Focal Length summary for Nokia 6650

For the SE K800i, we find a diagonal field of view of 61.63°. We still have a global error of 0.4%, which means that the FoV is between 61.4° and 61.9°. These two optical systems thus have equivalent FoVs.

16.11.2 Example 2: The same lens on different bodies

The same lens, a Canon EF 85 mm f/1.8 USM, is used on two different bodies: the Canon EOS 30D and the Canon EOS1DS Mark II. They differ in their sensor size: the 30D has a 22.5×15.0 mm CMOS sensor, whereas the 1DS Mark II has a 36×24 mm CMOS sensor (full-frame 35 mm).

Here are the summary results for these two bodies:

	Height	Width	Diagonal	Center
Field Of View in degrees	26.49	39.24	46.61	-
Effective focal length in mm	50.85	50.36	50.08	51.25
Effective focal length (24x36 mm equiv.) in mm	50.85	50.36	50.08	51.25

Orthofrontality in degrees	0.45 °
Tilt in degrees	0.35 ° ↓
Pan in degrees	0.28 ° →

Canon EOS1DS Mark II (sensor size 24×36 mm)

	Height	Width	Diagonal	Center
Field Of View in degrees	16.49	24.62	29.46	-
Effective focal length in mm	51.64	51.42	51.29	51.81
Effective focal length (24x36 mm equiv.) in mm	82.62	82.28	82.07	82.90

Orthofrontality in degrees	0.50 °
Tilt in degrees	0.40 ° ↓
Pan in degrees	-0.30 ° ←

Canon EOS30D (sensor size 15×22.5 mm)

The Effective Focal Length is about the same for the two bodies, but their field of view is very different. The diagonal FoV is 46.61° for the 1Ds Mark II, and 29.44° for the 30D because of its reduced sensor size. The equivalent to 24×36 mm horizontal focal length of the 30D is 82.72 mm.

16.12 Shooting

16.12.1 Finding the nodal point

This protocol describes how to find the nodal plane of a lens using a panoramic head.

Briefly, this operation consists in finding the camera's axis of rotation that is free of parallax. If the panoramic head axis and the nodal point coincide, two aligned targets at different distances remain aligned whenever the panoramic head axis is rotated.

Most panoramic heads usually have their own documentation. The protocol below is a general explanation working for all panoramic heads. For additional explanations, please refer to the manufacturer's guide.

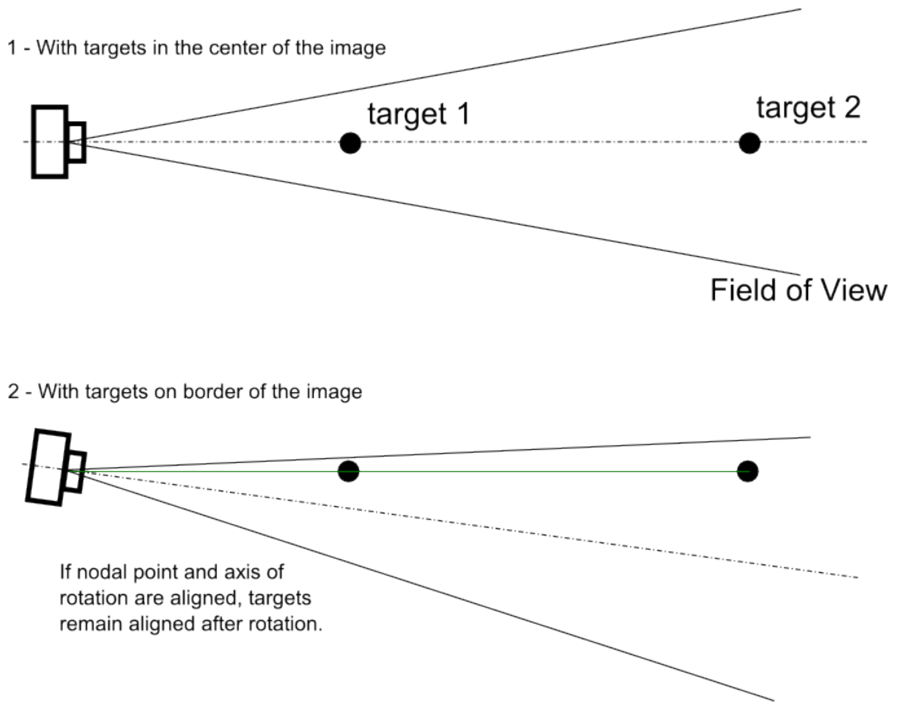
Apart from the combination of camera body and lens you are measuring, you will need the following hardware:

- A photographic tripod with a panoramic head and a kneecap head.
- A spirit level (use the tripod's spirit level if it has one).
- Two sharp targets, such as pencils or nails.

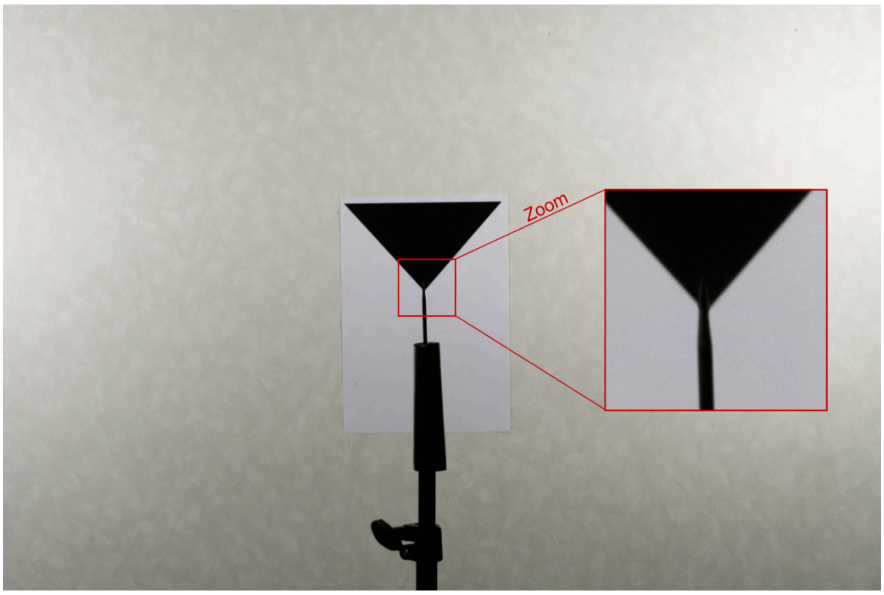
- A computer for digitally zooming in on images if it is not possible to do so with the camera.

Follow these steps to carry out the test:

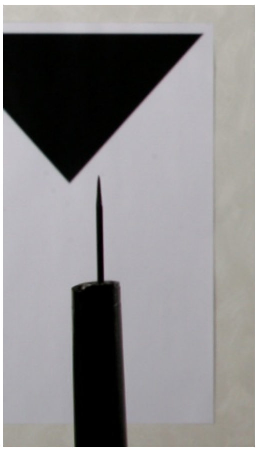
1. On the camera, set the values of the focal length and the focus to be tested.
2. Set the camera on the tripod, and use the spirit level to make sure that the panoramic head is level and stable.
3. Set the two sharp targets roughly aligned along the camera optical axis and about 2–3 meters apart (see the illustration further below); their end points must be at the same height and should face each other. Both targets should be visible within the image field. Set a low aperture on the lens to increase depth of field.
4. On the panoramic head, set the lateral position of the camera. When looking at the camera from the front, the center of the lens diameter must be directly over the axis of rotation of the panoramic head. Use the micro-adjusting thumbscrews to adjust the lateral position accurately.
5. Without changing the parameters on the panoramic head, move the combined camera and panoramic head until you see the two sharp targets precisely aligned in the image center. Use the digital zoom function of camera, or a computer, to be accurate. This does not change the focal length or focus settings.
6. Rotate the panoramic head to move the image of the targets toward the border of the image field. If the rotation axis does not coincide with the nodal point, the targets are no longer aligned after the rotation of the panoramic head.
7. Set the longitudinal position of the camera on the panoramic head so that the targets are aligned again. Use the digital zoom to be accurate. If the settings are now correct, the panoramic head can be rotated while the targets remain aligned. Focal length can now be measured. If it is cannot be measured, the lateral adjustment was wrong, so you must repeat step 4.



Determination of nodal point, position of the targets in field of view – top: step 5; bottom: step 7



Determination of nodal point: move the tripod so that remote sharp objects are aligned



If the sharp objects are no longer aligned after rotating the panoramic head, then the nodal point is not on the rotation axis

16.12.2 Measuring the focal length and the field of view

- You must use a Dots chart for the focal length measurement. To give an accurate measurement, Analyzer requires that you accurately measure the distance between the nodal plane and the chart, or between the charts for the two-shot method. The chart(s) must be orthofrontal to the camera.
- The lens focus must be set to manual, and the focus value must not change between both shots. To compare with the manufacturer's values, set the focus to infinity.
- To check the orthofrontality, a first approximation makes use of a mirror. Attach a mirror to the chart so that the reflection of the camera on the mirror can be seen in the viewfinder. The center of the lens must appear in the center of the image. For better accuracy, use the digital zoom function of the camera, or a computer.

For some focal lengths, this method is not suitable because the camera appears too blurry in the mirror. Even in those cases, the following protocol still applies.

16.12.3 Estimating and correcting orthofrontality

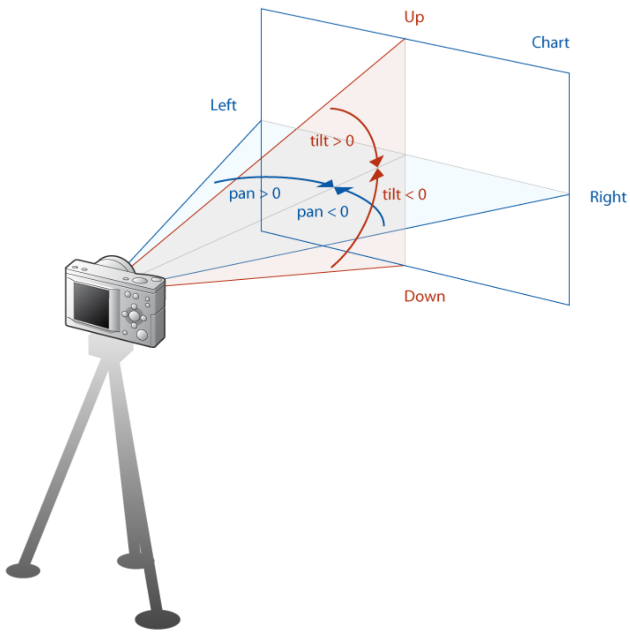
Analyzer can estimate the orthofrontality angle of the chart. It returns three values: the angle of orthofrontality, and the pan and tilt angles required to improve the orthofrontality. If the angle of orthofrontality is less than 0.5°, orthofrontality is considered as correct.

To estimate the orthofrontality with Analyzer, create a sidecar file for the image (see Section 16.13), and perform an Effective Focal Length measurement. The Summary tab contains the pan and tilt angles for correcting the camera orientation and the direction in which the camera should be rotated.

Orthofrontality in degrees	0.45 °
Tilt in degrees	0.35 ° ↓
Pan in degrees	0.28 ° →

Pan and tilt angles are oriented as follows:

- If the tilt angle is > 0, the camera must be rotated downwards, and if the tilt angle is < 0, the camera must be rotated upwards.



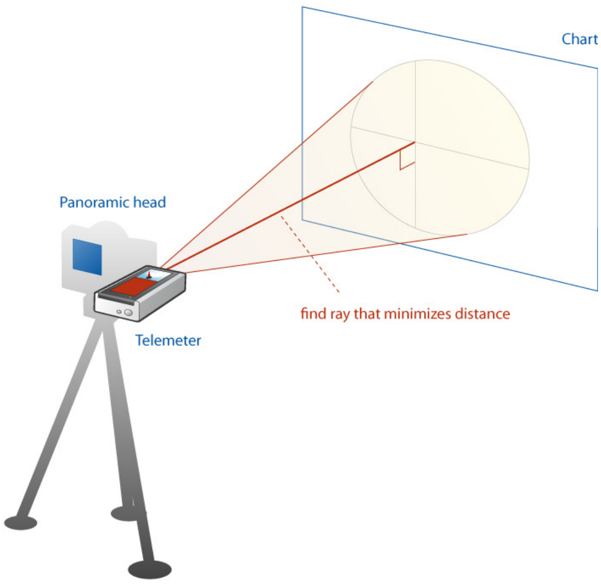
- If the pan angle is > 0, the camera should be rotated to the right, and if pan the pan angle is < 0, the camera should be rotated to the left.

Turn the micrometric screws of the kneecap head to adjust the orthofrontality.

16.12.4 Measuring the distance to the target

Use a laser telemeter (or any equivalent device) to measure distances. For example the Leica A4 has an accuracy of 1.5 mm.

Be sure to measure the distance between the nodal plane (or a fixed mark near the camera when using the two-shot measurement) and the point of the chart appearing in the image center. Use the camera viewfinder to check that the laser beam spot appears in the center of the image. The telemeter should be set up against the panoramic head. Modify its parameters to take the measurement from its bottom.



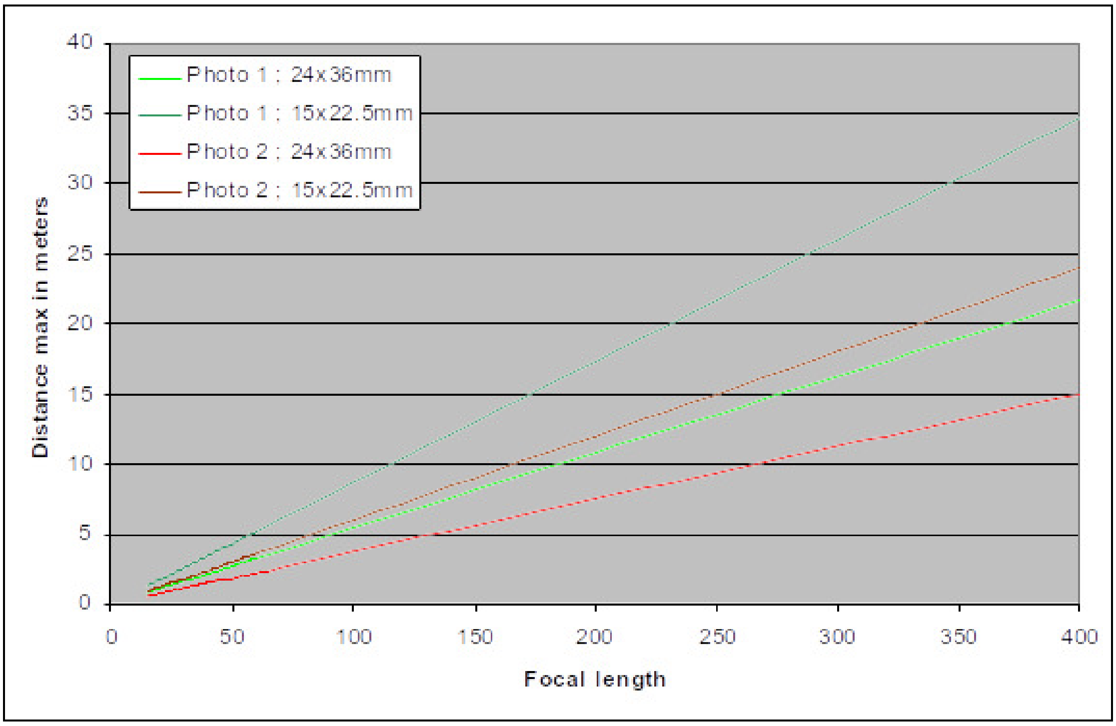
Set the telemeter to "continuous mode." Change the orientation of the telemeter and read its measure continuously to find the shortest length. The shortest length corresponds to the distance measured with a laser beam perpendicular to the chart.

The radius of the Manfrotto® panoramic head is 32 mm, and should be added to the length measured by the telemeter to obtain the distance between the chart plane and the nodal point. If another panoramic head is used, refer to the documentation or the manufacturer to determine its radius.

You must always set the laser telemeter in the same place, and the laser spot must appear in the viewfinder. To estimate the distance measurement precision, measure the same distance several times. Switch the telemeter off before shooting.

> **Note:** A correct measurement using the two-shot method (TSM) requires that the focus does not change between the two shots, so it may be necessary to increase the depth of field (by decreasing the aperture — that is, by increasing the f-number). Be aware that reduced apertures need more light for correct exposures.
>
> Increasing the f-number also sharpens the dots, and consequently helps Analyzer to detect dots and therefore complete the measurement. For this reason, it might prove useful to reduce the aperture even with the one shot method.
>
> The two-shot measurement is all the more accurate when the distance between the two charts is large. You can use two different charts for the two shots, but always use charts adapted to the distance and the field of view of the camera.

The targets D0001 and D0002 are the more useful charts for the focal length measurement. As the accuracy of the measurement increases with the distance to the chart (OSM), or the distance between the charts (TSM), try to be as far as possible from the charts. The graph below gives the maximum possible distance-to-object for both charts. As the camera sensor size will modify the equivalent to 24×36 mm focal length, distances will be different depending on whether or not the sensor is full-frame (24×36).



Maximum possible distance usable depending on the focal length, for different charts and sensor sizes

16.13 Sidecar parameters

A sidecar file must be attached to every image and stored in the same directory (see Section 4.5 for information on sidecar files). This file contains information about the shooting conditions. For the Effective Focal Length measurement, the fields are as follows:

```
[EFL]                  // Section for Effective Focal Length measurement
ReciprocalFile=...     // Name of the second image, without its path (optional, for TSM)
DotSpacingMM= ...      // Distance between two dots of the dots chart (in mm)
NodalDistanceMM= ...   // Distance between chart and nodal point (in mm)
SensorWidthMM=...      // Width of the sensor (in mm)
SensorHeightMM=...     // Height of the sensor (in mm)
```

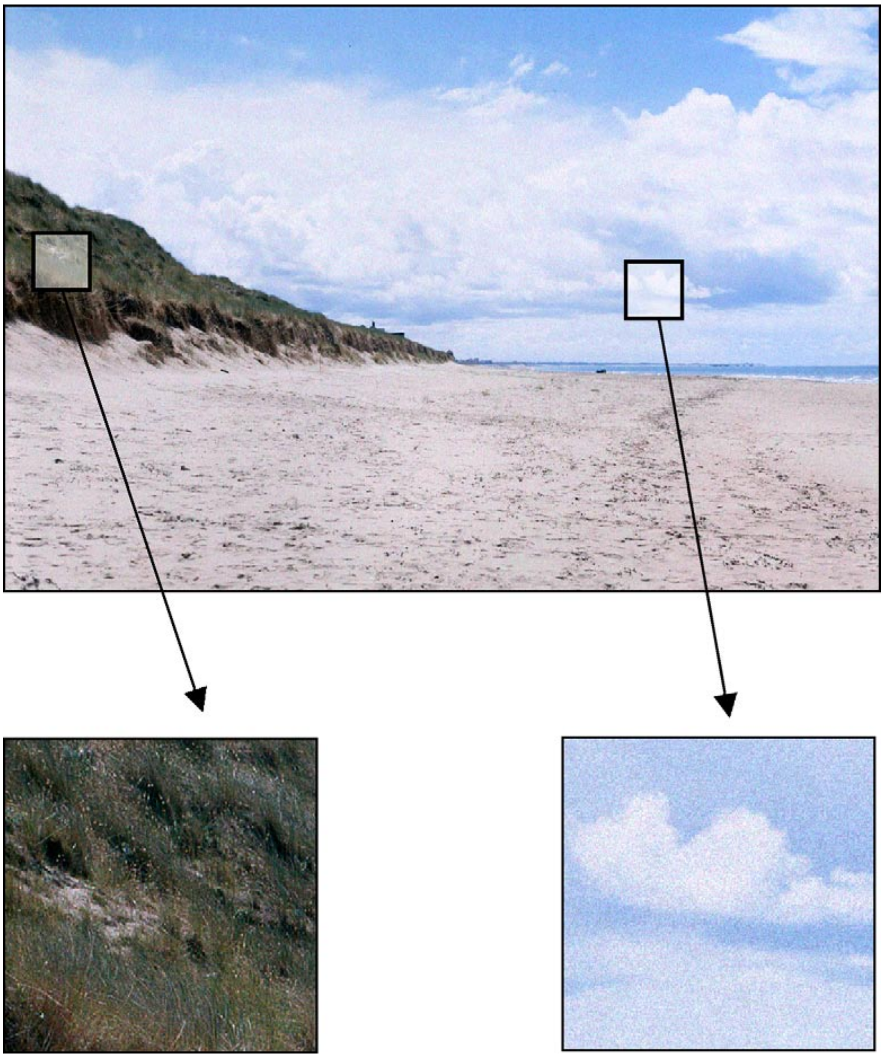
For an OSM measurement, all the fields of the sidecar file must be provided except the “ReciprocalFile” field. Analyzer ignores this field for the OSM.

For a TSM measurement, each image must have its own sidecar file. You need to fill the “ReciprocalFile” field only for the first image. The two images and their sidecar files must be in the same directory.

17 – N: Noise

17.1 Introduction

The noise in an image is described as a random granulation that is particularly visible in uniform areas. Unlike geometrical distortion or vignetting, it is not exactly reproducible from one image to another, but only statistically reproducible.



Noise is more noticeable in the uniform areas of the image and is almost invisible in highly textured areas

The noise in an image is caused by many different factors, such as:

- Photonic noise: classical light sources produce random variations in luminous flux which, after deflection in the optical system, produce the most common form of noise in photographic images.
- Thermal noise: due to the effect of the ambient temperature, a sensor can generate random signals; this type of noise is directly proportional to the exposure time and inversely proportional to the size of the photosites.
- Imperfections in the photosites: the sensors consist of common elements (anti-reflection filters, for example), which affect all the sensor photosites in the same way, and individual elements (microlenses; the photosites themselves, for example) which are all different. These variations involve a variable response of each photosite to an identical exposure; the generated noise has a constant value from one image to another, and is proportional to the exposure level.
- The noise created by the charge transfer process: the transfer may be incomplete or interfere with adjacent photosites.
- The shape of the transfer function, and rounding errors which appear during conversion of analog to digital data (ADC, analog-to-digital converter): these two factors are the main sources of noise in the image. Their effects are directly associated with the depth of the image (8 bits, 12 bits, etc.). The ISO setting, which defines the level of amplification to be applied to the sensor, directly affects the amplitude of this type of noise.
- Demosaicing and compression processing (DSP, digital signal processing).

The camera's embedded software may automatically modify the DSP noise output:

- A sharpening filter that operates only on the gain (the most simple method) uniformly boosts the noise over the whole surface of the image.

- A sharpening filter with a threshold parameter does not greatly enhance the noise in uniform areas.

- A sharpening filter with a blur mask produces the most effective result by reducing the noise in the areas where it is most visible.

17.2 Definitions

Noise is characterized by several values:

- The standard deviation of noise represents the dispersion of the digital grey levels around the current grey level; it is expressed in grey levels (GL).

$$\sigma_{GL} = \sqrt{\frac{1}{n}\sum_{i=0}^{n}\left(GL(x_i, y_i) - \overline{GL}\right)^2}$$

  where $\overline{GL}$ is the mean grey level measured in the patch.

- The signal-to-noise ratio (SNR) defines the purity of the output signal and gives direct information about the ability of the camera to reproduce a signal. It is expressed in a logarithmic scale, in decibels (dB), and is obtained from the following formula:

$$\text{S/N ratio} = 20\log_{10} \times \frac{\text{mean}}{\text{standard deviation}}$$

Noisy images with increasing standard deviation of noise
(left image SD = 2, center image SD = 4, and right image SD = 9)

- The grain description characterizes the noise spot. Noise grain is particularly well described by the autocorrelation function that measures how a pixel is similar to its neighbors. Below is an example. The autocorrelation function is normalized such that the peak value is the noise standard deviation.

  The structure of the noise is described by the following values, extracted from the autocorrelation functions:

  – **Grain size** is the effective radius of the noise spot, expressed as a number of pixels. It is to be related to the image resolution. The equivalent grain size (EGS) for a 24×36 mm format, expressed in mm, is:

$$\text{EGS} = \left(\frac{24\times 36}{\text{Width}\times\text{Height}}\right)^{\frac{1}{2}}\cdot \text{GS}$$

Where Width is the image width, in pixels, Height is the image height, in pixels, GS is the grain size in pixels.

- **Asymmetry** is the ratio GS_x/GS_y between the size of the noise spot along the X axis (GS_x), and the size of the noise spot along the Y axis (GS_y). This ratio evaluates the spatial homogeneity of the noise spot (or isotropy). It is close to 0 if the noise is more spread out along the Y axis; it is close to 1 if the noise is the same in every direction; it is greater than 1 if the noise is more spread out along the X axis.

• The noise coloration is described by two values computed for a chosen grey level GL_0:

- **Noise coloration index** defines the coloration level of the noise; it is expressed as a percentage. 0% corresponds to a pure luminance noise that does not create any color modification; 100% corresponds to pure colored noise with uniform luminance; only the color varies. The coloration index does not depend on the global noise level in the image. The key idea for defining the coloration of noise is that given a color (R, G, B), any color of the type $(\lambda R, \lambda G, \lambda B)$ has the same hue and differs only in luminance.

  Let us now call (R, G, B) the mean color in an image area. Given an observed color (R_i, G_i, B_i), the noise $\Delta = (R_i, G_i, B_i) - (R, G, B)$ can be decomposed into two parts. The luminance part is in the direction of (R, G, B) and the color part is orthogonal to (R, G, B). Elementary geometry shows that the color error in the red channel is

$$CR_i = R_i - R\frac{RR_i + GG_i + BB_i}{R^2 + G^2 + B^2}.$$

  The color noise CG_i and CB_i in the G and B channels are obtained in the same way. The noise color index is defined as

$$\text{noise coloration index} = \frac{\frac{1}{N}\sum_{i=1}^{N} CR_i^2 + CG_i^2 + CB_i^2}{V_R + V_G + V_B}$$

  V_R, V_G, V_B are respectively the variances on the R, G, and B channels. This value always belongs to the interval $[0, 1]$. Notice that on a grey patch (with a correct white balance), the color error simplifies into $CR_i = R_i - L_i$, where $L_i = \frac{1}{3}(R_i + G_i + B_i)$.

- **Coloration index in pixel value** is expressed as a number of grey levels; it corresponds to the strength of perceived noise coloration. This measurement accumulates the differences between each color component and the arithmetical mean of color components. It is consistent with human perception of color noise. Indeed, for a given absolute noise coloration index, the higher the noise level, the more easily perceived the coloration strength.

The real coloration index is deducted from the absolute noise coloration index formula:

$$\text{coloration index in pixel value} = \sqrt{(V_R + V_G + V_B) \cdot \text{noise coloration index}}$$

Noise intensity and noise size are equal on all images, but coloration index is increasing from left to right

In addition to these values directly related to the uncertainty of the measured grey level, Analyzer provides three additional measures:

- **Dynamic range** is defined as the ratio between the largest luminance and the lowest luminance that a camera can capture. The lowest luminance that can be captured is the first luminance that is distinguishable from noise, so this lower boundary is defined as the luminance for which the SNR is greater than 1. The dynamic range is a luminance ratio and has no unit, but can also be expressed in EV.
- **Contrast dynamic range** is also a ratio between luminances, with no unit, that can also be expressed in EV. It is computed only on RGB images. The difference between it and the other dynamic range is that the differences in grey levels are used to determine if two luminances are distinguishable from one another, rather than from noise. Two highlight filters are considered distinguishable if the difference in their grey levels is above 2, and if the difference between two low-light filters is above 10. This range is more consistent than the dynamic range based on the perception of dynamic in images, particularly images displayed on a screen. The measurement is computed on the green channel.
- **Tonal range** is the effective number of grey levels in the system. This measurement has to take noise into account. Indeed, a very thin grey level quantization is irrelevant if it is much smaller than noise. The standard deviation of noise can be viewed as the smallest difference between two distinguishable grey levels. The expression of the tonal range is

$$\mathrm{TR} = \int_{x_{\min}}^{x_{\max}} \frac{\mathrm{d}x}{\max(\sigma(x), 1)}.$$

The tonal range is a number with no unit. Another interesting number is $\log_2(\mathrm{TR})$, which represents the number of bits necessary for encoding all the distinguishable grey levels. raw conversion sometimes creates a lot of colored noise because the spectral response of the color filters is very close, and color rendering needs to stretch the different channels very differently from one to another. So for RGB images, this number can be much smaller than the theoretical 8 bits. Very noisy sensors, or shots taken with a high ISO sensitivity, increase this phenomenon further.

17.3 Influencing factors

Three parameters influence the Noise measurement:

- The sensor exposure.
- The exposure time.
- The ISO setting (or gain).

The dependence of noise on these exposure parameters can be reduced to two: the ISO and the average grey level, or target exposure (which results from the above parameters). Indeed we note that, whatever the values of the exposure parameters, the measures of noise are identical for a given combination of ISO and grey level, within the measurement accuracy.

17.4 Measurement of noise

Analyzer can use either a X-Rite ColorChecker® Classic or the HDR Noise chart. The test target is automatically detected in the image.

Measurement of noise is performed for each color channel R, G, B and for the luminance Y for RGB images and R, Gr, Gb, B for raw images.

The mean grey level and the standard deviation are computed on each patch. Grain size, asymmetry and noise coloration index are computed, and if necessary interpolated, for one grey level selected by the user.

Noise measurement is performed by a standard deviation calculation on a uniformly lit area on the sensor. While the area on the target is very uniform, vignetting may lead to non-uniform area, basically a low frequency gradient from one side of the area to the other, which would bias the standard deviation measurement. On system with a fixed aperture, it is not possible to reduce vignetting by using a small aperture (high f#). This is the reason why Analyzer actually subtracts the low frequencies from the measurement area with a second order polynomial function.

Hence, the standard deviation is computed on a corrected area as follows:

$$\mathrm{GL2}(x_i, y_i) = \mathrm{GL}(x_i, y_i) - P(x_i, y_i) + \overline{P}$$

Where GL is the grey level at (x, y) position and GL2 is the corrected value at (x, y), is a second order polynomial function that fits the GL function on the measurement area with a mean square error approximation.

Analyzer also computes the dynamic range and the tonal range of the system.

17.5 Measurement in raw format

Analyzer is able to measure noise on both raw and RGB images. The presentation and the meaning of the results are the same. However, Noise measurements on raw and RGB are complementary and quantify different aspects of the camera. The noise on raw measures the noise of the sensor, but since raw conversion changes the distribution of the noise, the Noise measurement on RGB images leads to different results.

In particular, depending on the spectral responses of the color filters, it may be necessary to apply a strongly-amplified white balance on one or several channels (up to 3 or 4 times). It is very common for sensors not to be very sensitive to blue wavelengths, though the blue channel is strongly amplified. It is also common that the spectral responses of the red, green, and blue channels have an important overlap, which leads to a color rendering with a strong chrominance amplification. The combination of both white balance and color rendering may lead to a strong amplification of the noise (up to 8 to 10 times). For more information, see Section 30, Color Sensitivity Measurement.

The demosaicing algorithm has to mix information from different color channels, which leads to a combination of noises as well. Sharpening filters may also increase noise. Compression also creates quantization noise that may be structured by the compression itself (as per the 8×8 JPEG blocking effect).

On the other hand, it is normal for an ISP to include a noise filter. And a very strong compression may use a quantization larger than the noise standard deviation. In this case, noise may be completely absorbed by the quantization.

The dynamic range has also a different meaning depending on if it is measured on raw or RGB images. Because of the tone curve, which will flatten the bright grey levels and stretch out the dark ones, measuring on raw gives a potential dynamic range for the camera, which can be lost for the final RGB image if the tone curve flattens most grey levels. Measurements on raw and RGB are thus complementary. The measurement of contrast dynamic range is done only on RGB images, because it is a measurement related to the perception of dynamic.

17.6 Analyzer output

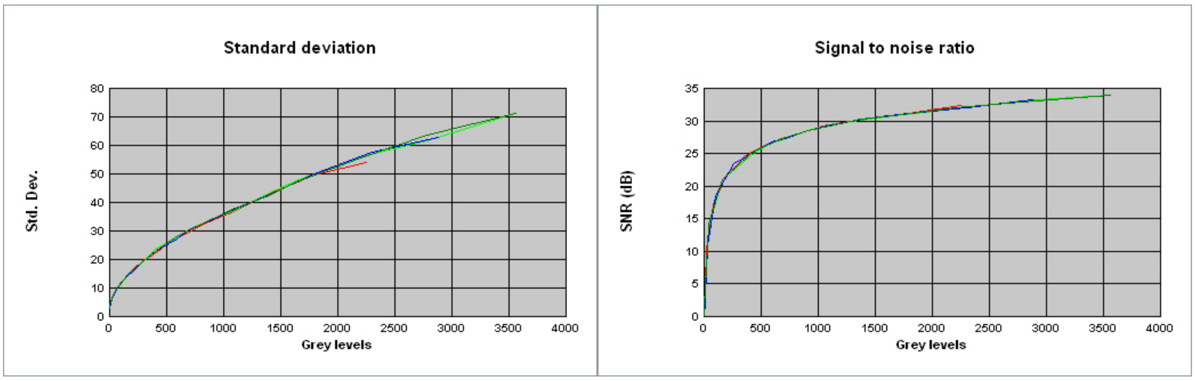
The output of the Noise measurement consists of the following items:

- A Summary table containing, for each color channel and for the luminance, the SNR in dB, the standard deviation, the grain size and its asymmetry. The coloration index (relative and in pixel value) is also indicated. These values are computed at a reference grey level. By default, this value is 50% of the theoretical dynamic. The standard deviation is expressed in grey levels, in 8 bits for RGB images. For raw images, the results are given with the dynamic of the sensor, which is indicated in the image file itself. Raw images with DSLR are usually encoded on 12 bits; low-end Digital Still Cameras and camera phones usually encode images on 10 bits. The noise value is given at a value about half of the dynamic. Since this grey level is usually not observed in the chart, the displayed values are actually interpolated. For raw images, the noise level is also given in an 8 bits equivalent encoding to allow camera comparison. The grain size is given in pixels, and also in mm for a 20×30 cm equivalent format, to allow camera comparison.

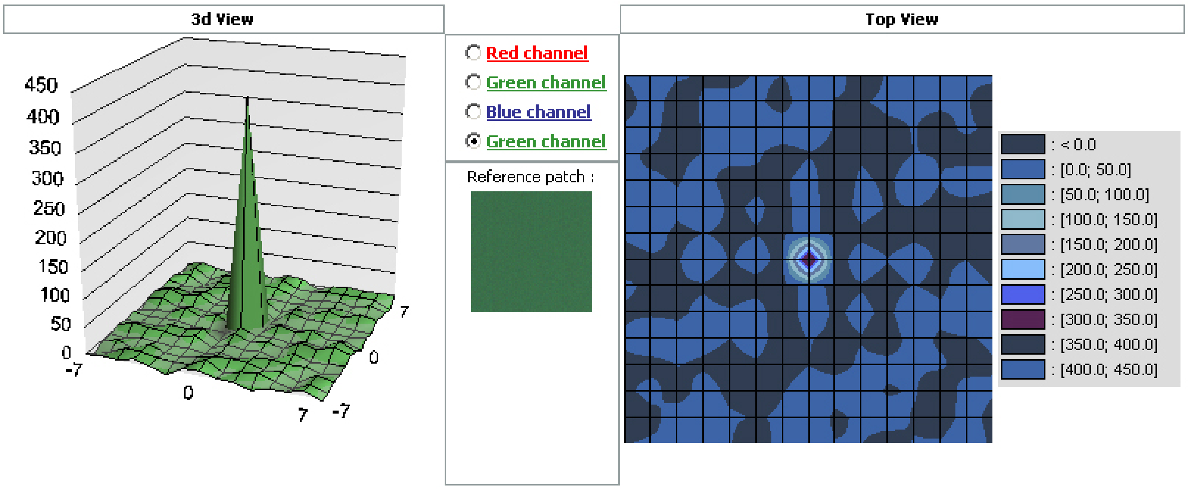
Noise values at grey level = 2056 (interpolated from measures)

	SNR	Std. Dev.		Grain size		Grain Asymmetry
	in dB	in grey level (12 bits)	in grey level (8 bits)	in pixels	in µm, 20x30cm eq.	
R Red channel	32	52.1	3.3	1.0	84.1	1.00
G Green channel	32	53.9	3.4	1.0	84.1	1.00
B Blue channel	32	53.9	3.4	1.0	84.1	1.00
G Green channel	32	53.4	3.3	1.0	84.1	1.00

- The Intensity tab displays the noise standard deviation and the signal to noise ratio as a function of grey level, for R, G, B and luminance (Y). For raw images, the dynamic of the sensor is used. For RGB images, grey levels are encoded on 8 bits.



- The grain and structure tab shows the grain structure, that is the autocorrelation function also for R, G, B and luminance. The left plot shows a 3D representation of the autocorrelation function, and the right plot shows the level lines of the autocorrelation, which corresponds to a top view of the left plot. The size and the asymmetry of the grain may be checked on the patch used for the computation. The coordinates on the *x* and *y* plane are measured in pixels.



- The dynamic range/tonal range tab presents the dynamic range and the tonal range for R, G, B and Y in different units in a table. The dynamic range is expressed both in grey levels and in exposure values (EV), and the tonal range is expressed both in steps and bits. Results are given only when the sensor reaches the saturation value. When a channel is not saturated, Analyzer does not return a value.

	Dynamic Range	Dynamic Range (Ev, stop)	Tonal range (steps)	Tonal range (bits)
R Red channel	-	-	-	-
G Green channel	902.70	9.82	82.16	6.36
B Blue channel	-	-	-	-
G Green channel	812.62	9.67	82.56	6.37

The contrast dynamic range is also displayed for RGB measurements, going along with a scale of grey levels, and an image of the density filter crops displayed side to side. The two green lines show the first and last distinguishable filters for the contrast dynamic range measurement.

Contrast dynamic range	859.33	9.75

Scale of grey levels:

17.7 Measurement accuracy

- Accuracy of the strength of noise coloration is ±0.5 grey level.
- Accuracy in noise coloration index depends on the standard deviation σ as follows: $\pm\frac{0.5}{\sigma} \times 100$.
- Accuracy of the grain size is ±0.5 pixel.
- The accuracy of the noise intensity is ±0.2 grey level on the measured standard deviation.
- The accuracy of SNR depends on the standard deviation σ as follows: $\pm 10 \log_{10} \frac{\sigma + 0.2}{\sigma - 0.2}$.
- The accuracy of the Tonal Range is 0.3 bits
- The accuracy of the Dynamic Range is 0.5 EV

17.8 Measurement scale

SNR RGB	SNR raw	Qualitative effect
$x > 45$ dB	$x > 38$ dB	noise is scarcely noticeable
38 dB < x < 45 dB	32 dB < x < 38 dB	noise is scarcely visible
26 dB < x < 38 dB	20 dB < x < 32 dB	noise is present but acceptable
$x < 26$ dB	$x < 20$ dB	image is very grainy

Real coloration index	Qualitative effect
$x < 1.5$ GL	coloration is scarcely noticeable
1.5 GL < x < 10 GL	coloration is clearly visible
$x > 10$ GL	coloration is unacceptable

The following table gives a subjective scale of grain size, with a 1:1 screen display.

Grain size	Qualitative effect
$x < 2$ pixels	Small grain
2 pixels < x < 4 pixels	Medium grain
$x > 4$ pixels	Very large grain

Dynamic Range	Qualitative effect
$x > 10$ Ev	Very good, equivalent to a high-end DSLR at low ISO
8 Ev < x < 10 Ev	Acceptable, equivalent to a high-end DSLR at high ISO or Low ISO Bridge camera
$x < 8$ Ev	Poor, typical of camera phones in indoor conditions

Contrast Dynamic Range	Qualitative effect
$x > 9$ EV	Very good, equivalent to a high end DSLR at low ISO
7 EV < x < 9 EV	Acceptable, equivalent to a high-end DSLR at high ISO or Low ISO bridge camera
$x < 7$ EV	Poor, typical of camera phones in indoor conditions

Tonal Range	Qualitative effect
$x > 7$ Bits	Very good, low noise
6 Bits < x < 7 Bits	Acceptable
$x < 6$ Bits	Poor, noisy image

17.9 Setup parameters influencing the measurement

Depending on the camera body, other secondary parameters may influence the noise in an image:

- The sharpening filter applied to the image
- Activation of a noise reduction filter
- Compression ratio
- Resolution

17.10 Measurement validity

An isolated value of noise is not meaningful. It is always necessary to associate it with the parameters that influence it. Claiming, for example, that the SNR of a camera is 45 dB has no meaning. On the other hand, indicating that the SNR of a camera is 45 dB at 400 ISO with an average grey level of 160 is meaningful. If the parameters of sharpness, compression and resolution can be adjusted, you must also record them to validate the measurement.

17.11 Comparing two cameras

Measurements can be compared at identical exposures if ISO values are identical. In such a case, grey level dynamics are identical on images to be compared; and measurement accuracy is compatible between images. The comparison is pretty straightforward: the lower the noise, the better the camera. Coloration index is also fundamental: the luminosity noise is often less visually disturbing than a strong colored noise.

Tonal range and dynamic range can be compared in RGB on the one hand and raw images on the other hand. A RGB shot should not be compared with a raw shot since a reduction noise filter and a gamma correction may have been applied on the RGB shot.

17.12 Shooting

a) **Install the appropriate target**
   This is either the X-Rite ColorChecker® Classic or HDR Noise chart (see Section 4.12).

b) **Decide on the important parameters, if applicable:**

   - ISO sensitivity
   - Exposure correction (EV)

- Embedded processing parameters:
  - Noise reduction filter
  - Digital zoom function
  - Compression ratio (TIFF format retrieves complete data, while JPEG format loses some data)
  - Sharpening filter
  - Resolution
- Any other special camera modes for saturation, contrast, etc

You may need to alter the exposure time and the aperture to obtain a good exposure.

c) **Special conditions for framing the photograph** (see also Section 5).
To correctly detect and measure the test target in the image, ensure that:

- There is no dust on either the lens or the sensor.
- The test target is correctly oriented, with the text at the bottom of the produced image.
- The edges of the test target are parallel to the edges of the image.
- The test target is correctly exposed and uniformly lit. ,
- The white balance is correct.
- There are at least 64×64 pixels visible for each patch in the digital image.
- The test target covers the frame as much as possible, and is completely inside the frame.

Take all necessary precautions to avoid shaking the camera when shooting. It is better to use a cable release or to trigger the shot from a computer connected to the camera via a FireWire cable.

When shooting the transmission charts (HDR Noise chart), you can include the luminance values in a sidecar file for the patches that can be measured with a luminance-meter. If Analyzer does not find a sidecar file, it uses the manufacturer's densities.

17.13 Sidecar parameters

You can use the `[Common]` section to measure noise on the X-Rite ColorChecker® classic chart for raw and RGB formats when automatic detection fails. The coordinates are the positioning coordinates of the chart itself, not the markers in the frame.

```
[Common]
// Manual X-Rite ColorChecker\textregistered\ classic chart position
X1=... // x coordinate of the top-left corner
Y1=... // y coordinate of the top-left corner
X2=... // x coordinate of the top-right corner
Y2=... // y coordinate of the top-right corner
X3=... // x coordinate of the bottom-left corner
Y3=... // y coordinate of the bottom-left corner
X4=... // x coordinate of the bottom-right corner
Y4=... // y coordinate of the bottom-right corner
```

For more accurate Noise measurements, it is recommended to provide patch luminance.

If a Noise chart is used, 16 patch luminances should be given:

```
[DensityChart] // luminance of the HDR Noise chart patches section(cd/m2)
Patch1=1662
Patch2=1300
Patch3=1038
Patch4=773
Patch5=614
Patch6=466
Patch7=400
Patch8=296
Patch9=247
Patch10=188.4
Patch11=140.3
Patch12=52.8
Patch13=14.2
Patch14=1.1
Patch15=0.1
```

If a HDR Noise chart is used, 28 patch luminances should be given:

```
[DensityChart] // luminance of the HDR Noise chart patches section(cd/m2)
Patch1 = 5120
Patch2 = 3980
Patch3 = 3180
Patch4 = 2580
Patch5 = 1851
Patch6 = 1476
Patch7 = 1238
Patch8 = 1029
Patch9 = 872
Patch10 = 607
Patch11 = 443
Patch12 = 278
Patch13 = 176.7
Patch14 = 110
Patch15 = 63
Patch16 = 46.9
Patch17 = 31.8
Patch18 = 17.9
Patch19 = 11.6
Patch20 = 6.8
Patch21 = 3.3
Patch22 = 2.0
Patch23 = 1.6
Patch24 = 0.8
Patch25 = 0.6
Patch26 = 0.3
Patch27 = 0.1
Patch28 = 0.00512
```

18 – DP: Defective Photosites

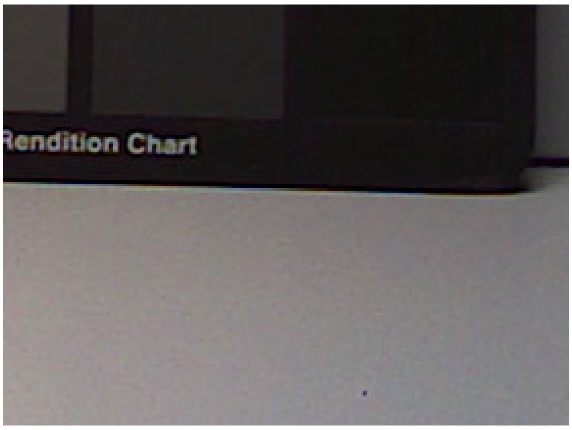
18.1 Introduction

An imaging sensor is a mosaic of photosensitive cells or photosites, usually arranged in a regular grid. Each photosite converts photons (particles of light) into charges that are converted into digital values by an analog-to-digital converter (ADC) during image acquisition. Each photosite digital value becomes a pixel (short for “picture element”) of the acquired image.

While all photosites are supposed to have the same response to light intensity, manufacturing imperfections mean that some photosites have different responses. Close responses (slightly different sensitivities) yield some fixed pattern noise that can be removed by a calibration. However, responses may be very different, or even not related to light intensity, in which case the photosites concerned are considered defective.

Since this measurement needs to access the values output by the sensor directly, it works only with raw images.

Example of hot photosites



Example of dark photosite

18.2 Definitions

There are two kinds of defective photosites:

Bright photosites have a higher-than-average response (over 10% of sensor dynamic with no light on the sensor).

Dark photosites have a lower-than average response (50% of the average value of the sensor overall, when illuminated).

If a photosite has a response proportional to exposure time even with no light, it is called a *hot photosite* (or *hot pixel*). It can be considered a defective photosite only if the exposure time is long enough. If a photosite has a response unrelated to light (fixed or random), it is called a *dead photosite* (or *dead pixel*).

Although they are combined in the same measurement of defective photosites, bright photosites and dark photosites require two separate shots for detection, with two charts, under completely different shooting conditions.

18.3 Influencing factors

The Defective Photosites measurement depends on the following parameters:

- ISO sensitivity/gain setting
- Exposure time
- Room temperature

Other secondary parameters may influence the measurement:

- Electronic noise
- Vignetting

18.4 Measurement of defective photosites

Analyzer provides measurements for both Bright Photosites and Dark Photosites:

- Bright photosites: For this measurement, you shoot an image either using a device preventing any light rays from reaching the sensor, or in a black room. The image is then split into areas with a default size of 200×200 pixels. The mean m and the standard deviation σ of the grey level are determined in each area. We say that a pixel corresponds to a bright photosite (which is a defective photosite) if the difference between its grey level GL and the mean grey level is larger than k times the standard deviation, i.e. $GL > m + k\sigma$. The default value of k is 15.

- Dark photosites: You shoot a white sheet under uniform lighting. First the mean value of the grey level is computed in a 200×200 window located in the image center. Then the image is split into several windows, also with a size 200×200. Again, the mean grey level value is computed in each window. The windows for which the mean grey level is lower than 75% of the mean grey level of the central window are excluded. In all the other windows, dead pixels are defined as those whose grey level is lower than 50% of the mean value in the reference window.

It is possible to change the values of the numerical threshold between defective pixels and normal pixels.

From the raw image, Analyzer outputs:

1. The number of defective photosites and the number of analyzed photosites
2. The percentage of analyzed photosites among all the sensor photosites.

For an image shot in a black room (or with a blinding device) this percentage should be 100%.

For dark photosites detection (white chart) this percentage might drop to 50%.

You must check that the coefficient k chosen is suitable. If its value is too large, no defective photosites are detected. If it is too small, then photosites with a value close to the mean value are incorrectly considered as defective.

18.5 Measurement in raw format

Since this measurement needs to access the values output by the sensor directly, it works only with raw images.

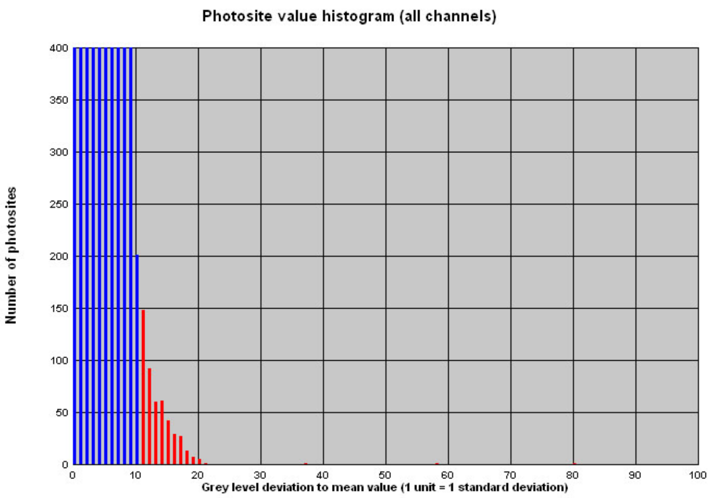
18.6 Analyzer output

18.6.1 Bright photosites

- The Summary tab displays the proportion of photosites of the sensor that have been used to compute the results. This should be 100%. The number of defective pixels per megapixel is given, as well as the mean value of the observed grey levels (this corresponds to the dark signal) and the standard deviation of grey levels. The grey levels are directly measured in the image, so results depend on the image depth.

	Analyzed photosites (%)	Defective photosites (by Mphotosite)	Mean (12 bits)	Standard deviation (12 bits)
Mean of all channels	100	81.19	127.93	2.70

- The Histogram tab shows the tail of the empirical histogram of grey levels. The origin of the *x* axis is the mean of the grey levels, and each graduation equals the noise standard deviation. The *y* axis is the number of photosites with a value in the corresponding interval. Photosites with values represented in blue are considered as normal. Bright photosites are displayed in red bars (we set $k = 10$ on this graph).

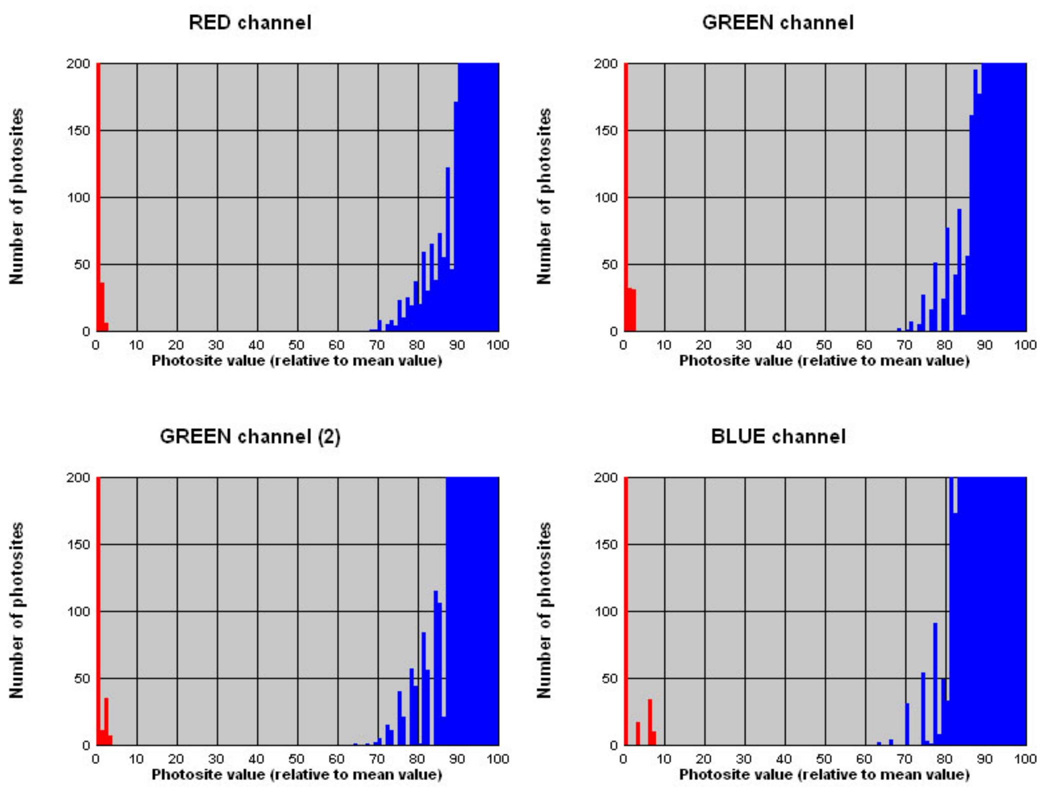


18.6.2 Dark photosites

- For each channel, the Summary tab displays the percentage of photosites that were used to compute the result (which may not be 100% because of vignetting), the number of dark photosites (per megapixel in the sensor) and the mean value. The values for the different channels may be different due to lack of white balance at this stage.

		Analyzed photosites (%)	Defective photosites (by Mphotosite)	Mean (10 bits)
R	Red Channel	98.2	731.45	118.31
G	Green Channel	98.2	731.45	84.78
B	Blue Channel	98.2	731.45	33.29
G	Green Channel	98.2	731.45	82.98

- The Histogram tab shows a part of the histogram of the photosite values for each channel (R, Gr, Gb, B). The *x* axis is the ratio with the mean value (so that the right end of the axis is 100% of the mean value). The *y* axis gives the number of photosites with the corresponding values. Values less than 50% of the mean value are displayed in red, and considered as dark defective photosites. The histograms are displayed for the R, Gr, Gb and B channels.



18.7 Measurement accuracy

For a fixed aperture, ISO sensitivity and exposure time, and for a factor *k* set to 15, the measurement accuracy is better than 1% with a DSLR and better than 2% for a camera phone.

For images shot at different ISO sensitivities, different exposure times or apertures, the accuracy is about 2% for a DSLR but can be up to 20% for a camera phone. This difference shows that camera phone sensors are more sensitive to influencing factors.

18.8 Measurement scale

Quality of sensors	Number of defective photosites
High	0 to 50
Medium	51 to 500
Low	Greater than 500

18.9 Set up parameters influencing the measurement

The room temperature and the time elapsed between two shots may influence the measurement of bright photosites.

The room lumination and the image crop may influence the measurement of dark photosites.

18.10 Measurement validity

An isolated value of the number of defective photosites is not meaningful. It is always necessary to associate it with the parameters that influence it. Claiming, for example, that the number of defective photosites is 1000 has no meaning. On the other hand, indicating that the number of defective photosites is 1000 at

ISO speed 400, exposure time 4s and room temperature 20 °C is meaningful.

18.11 Comparing two cameras

To compare two cameras or two sensors, the following parameters must be kept equal:

- ISO Sensitivity
- Exposure time
- Aperture
- Room luminance.

The number of defective photosites per megapixel directly provides a quality factor for the sensor.

18.12 Shooting

The Defective Photosites measurement needs the following hardware:

- A tripod for a stable shooting.
- A blinding device preventing passage of light rays.
- A white chart.

Follow these steps to set up for the detection of bright photosites:

1. Set the camera on the tripod.
2. Set the blinding device on the camera or set up the camera in a black room.
3. Set the ISO sensitivity or gain.
4. Set the aperture of the lens.
5. Set a long exposure time (one or several seconds).
6. Shoot.

Follow these steps to set up for the detection of dark photosites:

1. Set the camera on the tripod.
2. Set the uniformly-lit chart 1 meter away from the camera.
3. Set the ISO sensitivity or gain.
4. Set the aperture of the lens.
5. Use a lightmeter to determine a suitable exposure time.
6. Set the exposure time.
7. Shoot.

19 – RCN: Row and Column Noise

19.1 Introduction

Row and column noise are row-wise and column-wise artifacts that come from the electronic structure of the sensor.

These artifacts are due to row-wise or column-wise operations performed on the sensor, one of which is amplification. The main goal of the sensor is to count the number of photons hitting each of its photosites. This "number of photons" is not directly usable, and must be amplified before analog-to-digital conversion. CCD sensors may have two column amplifiers: one for even columns of photosites, another one for odd columns. The manufacturing process implies that there are some differences between two amplifiers with the same design, though the amplification of odd and even columns may be different as well. This discrepancy creates a high-frequency column noise for which every other column is over- or under-amplified.

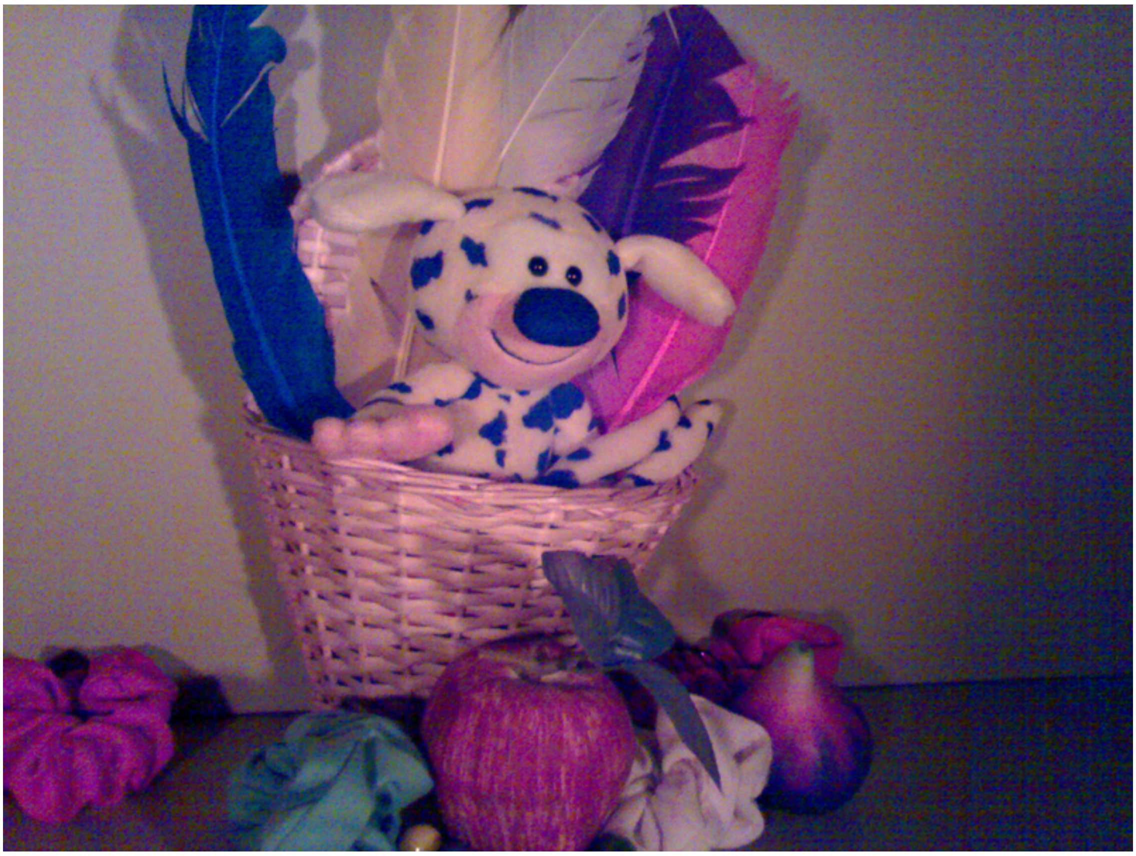


Image from a camera phone in low light mode. Row and column noise is particularly visible in dark area on the right

These artifacts may also be caused by the power supply of the sensor, or by some interference around the camera. For example, the presence near the camera of hardware that generates electromagnetic waves, such as a monitor, will reduce the quality of the photographs.

These artifacts may be fixed (i.e., at the same position for every image from the camera) or not. In the former case, they will appear at the same place on every image taken by the camera, and can then be easily corrected by a simple calibration.

Row and column noise is measured on dark images, taken in a dark room to avoid light leaks. Resulting images thus contain noise only, as no photon hits the photosites. The goal of this measure is then to find row-wise and column-wise artifacts in white noise if they exist. The image must be in raw format.

Row and column noise depends on ISO sensitivity and exposure time. It is more visible with a high ISO, and is attenuated by long exposure time. Indeed, for a given grey level, short exposure time needs high gain, and thus causes higher noise and lower SNR.

19.2 Definitions

19.2.1 Dark Signal

Dark signal is due to the current that flows out of a sensor when no photons have hit it (dark current). It is determined by computing the average of the pixels values on image. See Section 24 for more on Dark Signal measurement.

19.2.2 Variances of Noises

The noise model is as follows. Let $_{ij}$ be the value of the photosite measured at column i and row j. This value is decomposed as the sum of several terms.

- A constant term DS, which corresponds to the dark signal
- A random value γ_i which only depends on the column the photosite belongs to, called column noise.
- A random value P_j only depending on the row, called raw noise.
- A white noise W_{ij}.
- Note that the total noise can be further decomposed into spatial and temporal components. However, this would require several images.

The values of the column noise are independent from one column to another. In the same way, the values of the row noise are independent from one row to another. The white noise values are independent from one photosite to another.

Moreover, the column noise, the row noise, and the white noise are mutually independent.

As a consequence, the variance of the noise at a pixel is the sum of the variance of the white noise, row noise and column noise.

$$V = V_w + V_r + V_c$$

The total variance V is directly estimated on the image. Let C_i be the mean value on the image on the i-th column and R_j the mean value on the j-th row. They are estimates of the row and column noise. The image

$$Y_{ij} = X_{ij} - C_i - R_j$$

is an estimate of the image without row and column noise. Hence, its variance also estimates the variance of the white noise.

In the same way, the value $X_{ij} - R_j$ is approximately free from row noise. Hence its variance is the sum of the white noise and column noise. The value of the column noise is then deduced by subtraction.

The same is done with row noise by correcting only column noise.

If the row variance or the column variance computed by the method above is less than zero, it is set to zero.

19.2.3 Average distance between rows/columns

This corresponds to the computing of SMIA fixed pattern noise as described in the SMIA Camera Characterization Specification as "Horizontal Fixed Pattern Noise" and "Vertical Fixed Pattern Noise" (HFPN and VFPN), but on one image only instead of one hundred as specified by the norm. The average distance between columns is computed the following way:

$$F_{\text{hor}} = \frac{1}{\text{FSD}} \cdot \sqrt{\frac{1}{M-1} \sum_{i=0}^{M-2} (C_i - C_{i+1})^2},$$

where M is the number of columns in the image, FSD the dynamic of the sensor, and C_i the average of pixel value of the i-th column. In Analyzer, FSD has been set to "1" to have result values with comparable normalization in all graphs and tabs.

The same formula is applied on rows to compute the average distance between rows.

F and *V* are related by the following formulas:

$$F_{\text{hor}} = \sqrt{2 \cdot (V_c - \text{cov}_c)}$$
$$F_{\text{vert}} = \sqrt{2 \cdot (V_r - \text{cov}_r)}$$

where cov is the covariance of two consecutive rows or columns. If cov is equal to zero, this means than there is no correlation between rows, or between columns. If it is different to zero, this means that two consecutives rows or columns are correlated, and peaks will appear in the spectrum, showing which frequencies are dominating in the signal composed of rows or columns.

19.2.4 Row and column spectra

These spectra are obtained by computing the Fourier transform on the signal composed of average columns values, and on the signal composed of average rows values.

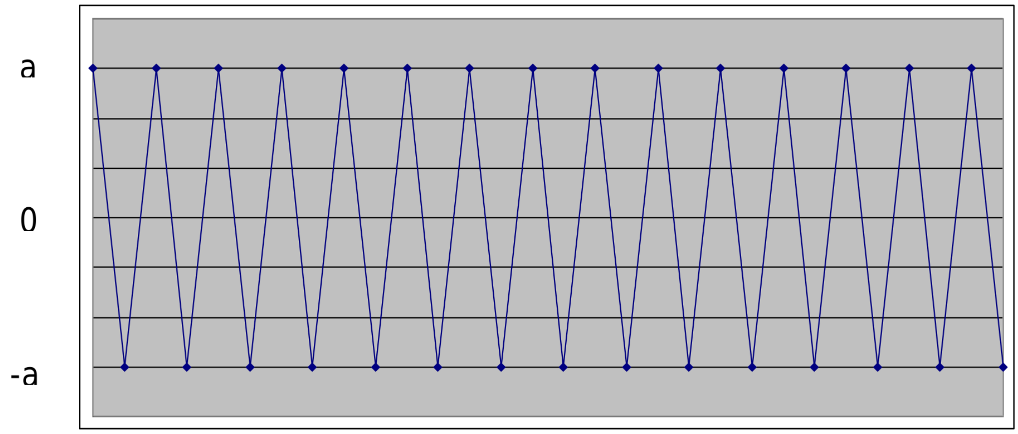
A frequency of 0.5 (cycles per pixel) corresponds to the Nyquist frequency. The dark signal is subtracted from row and column mean values before computing the spectrum, so the value at frequency 0 will always be 0.

Frequencies of peaks are found and displayed. Peaks are the local extrema with amplitude larger than K times the mean of amplitudes (in practice $K = 5$).

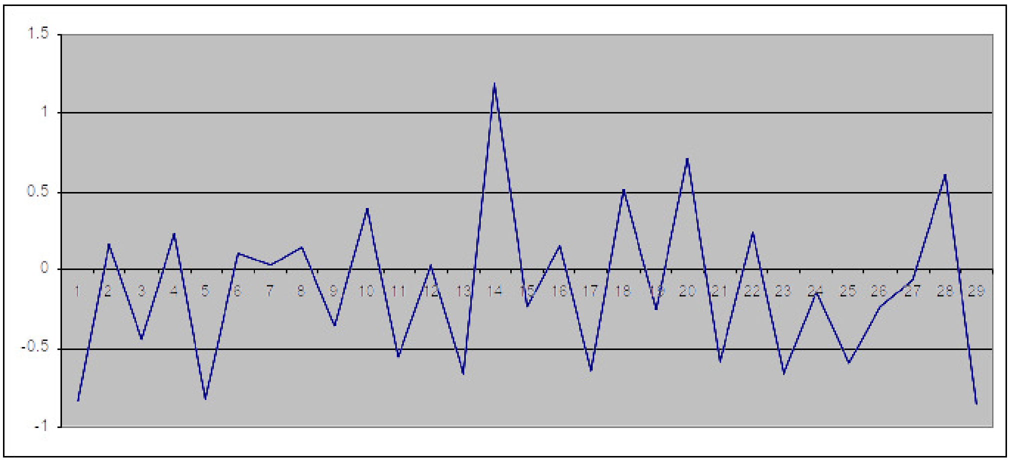
Peaks are due to a correlation between rows or columns. For example, presence of a peak in the column spectrum at a frequency of 0.5 cycles/pixel (Nyquist frequency) means that columns show a repetition pattern with a 2 pixels period.

Suppose now that this peak is the only point of the spectrum with an amplitude > 0, and its amplitude is "*a*."

This means that columns form a perfect periodic signal with a standard deviation value of a, with columns of value “–*a*” or “*a*” (plus an offset).



Theoretical perfect signal of frequency 0.5 cycles per pixel and amplitude ‘a’



Effective signal of frequency 0.5 cycles per pixel with noise (Canon 350D, a = 0.25)

For this signal, FPN will have a value of 2 (the mean difference between two columns is 2*a*), and the correlation coefficient will be a^2.

Values of standard deviation, FPN and correlation coefficient are thus strongly related with Fourier Transform coefficients. For the FPN, we can compute its value from Fourier coefficients as follow:

Knowing the formula of FPN^2

$$\text{FPN}^2 = \frac{1}{M-1}\sum_{n=0}^{M-2}\left(C-n-C_{n+1}\right)^2$$

We use Parseval Theorem to estimate FPN from Fourier coefficients:

$$\text{FPN}^2 = \sum_{k=1}^{M-1}\left|\hat{C}_k\right|^2\left|e^{\frac{2i\pi k}{M-1}-i\pi}-1\right|^2$$

(The same calculation holds for rows).

If we go back to our example, all Fourier coefficients but the one at frequency 0.5 have a value of 0, and at frequency 0.5 (Fourier coefficient $M-1$) its value is a.

Then $\text{FPN}^2 = |a|^2\left|e^{i\pi}-1\right|^2 = 4a^2$, $\text{FPN} = 2a$.

In the same way, the relation between the Fourier coefficients and the row and column variances are

$$V_c = \sum_{k=1}^{M-1}\left|\hat{C}_k\right|^2 \quad \text{and} \quad V_r = \sum_{k=1}^{M-1}\left|R_k\right|^2$$

For values obtained with the real signal, see the results of the Canon 350D in examples, Section 19.7.

19.3 Influencing factors

The following parameters have an influence on the measure of row and column Noise:

- The gain (or ISO speed) of the sensor.
- The exposure time.
- The temperature: dark signal can double every 8 °C for some cameras.

19.4 The measurement of row and column noise

The measurement consists essentially in computing row and column averages and then deducing from these averages the presence or not of row-wise and column-wise artifacts.

For each column i of the input image, the average C_i of its pixel values is computed. The same operation is done for each row R_j.

The measurements are then computed from these means, as described in the definition section above.

19.5 Measurement in raw format

Since this measurement needs to access the values output by the sensor directly, it works only with raw images.

19.6 Analyzer output

Analyzer returns the following data:

- The Summary tab contains two arrays of values. The first one gives the values of dark signal and standard deviation, and the repartition of variances between white noise, column noise, and row noise. Values are given in the sensor dynamic and in 8 bits. Variances are also given in percent.

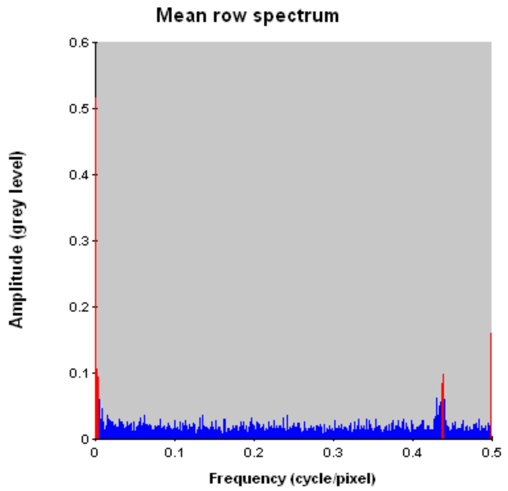
	in grey levels (12 bits)	in grey levels (8 bits)	in percent
Dark signal	258.18	16.14	
Standard deviation	7.21	0.45	
Variance of white noise	50.36	0.20	96.80
Variance of column noise	1.43	0.01	2.75
Variance of row noise	0.23	0.00	0.45

The second array contains values of fixed pattern noise and the correlation coefficient. These values are given horizontally and vertically, in the sensor dynamic. This fixed pattern noise value is related to the measurements described in the SMIA Camera Characterization Specification as “Horizontal Fixed Pattern

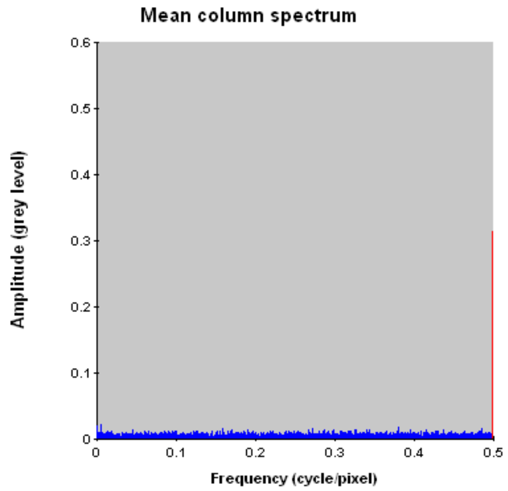
Noise" and "Vertical Fixed Pattern Noise". Vertical FPN is related to the variance of row noise, while horizontal FPN is related to the variance of column noise.

	vertical	horizontal
FPN	0.81	1.21
FPN max	1.51	2.76
Correlation coefficient	-0.09	0.70

- The *2D graphs* tab contains the row and column spectra, computed by Fourier Transform. The "mean row spectrum" is the spectrum of the means of rows. The number of row means computed is equal to the height, in pixels, of the image. It is the same for columns, the number of column means is equal to the width of the image. A frequency of 0.5 corresponds to the Nyquist frequency. Frequency peaks are shown in red, and their module and frequencies are given in the array below.



Frequency (cycle/pixel)	Amplitude (grey level)
0.0004	0.52
0.4388	0.10
0.5000	0.16



Frequency (cycle/pixel)	Amplitude (grey level)
0.5000	0.31

19.7 Examples

The following tables are the measurement results obtained with a 2 Mp sensor for camera phones. The picture has been taken at maximum gain, exposure time 20 ms, in a room where temperature is controlled at 21 °C. There was no light in the room.

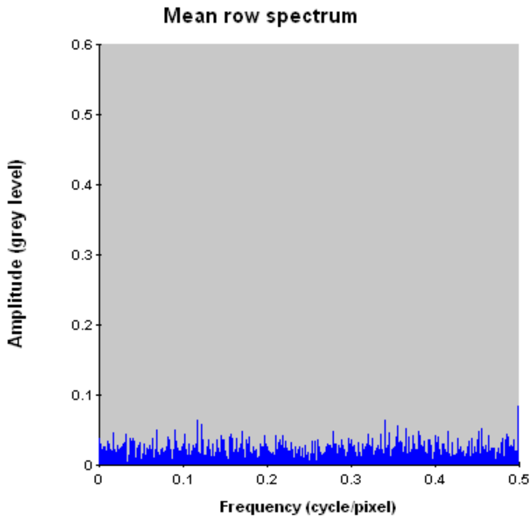
	in grey levels (10 bits)	in grey levels (8 bits)	in percent
Dark signal	7.06	1.76	
Standard deviation	4.04	1.01	
Variance of white noise	13.12	0.82	80.40
Variance of row noise	0.62	0.04	3.82
Variance of column noise	2.58	0.16	15.79

	vertical	horizontal
FPN	1.83	1.15
FPN max	6.12	2.76
Correlation coefficient	0.95	-0.02

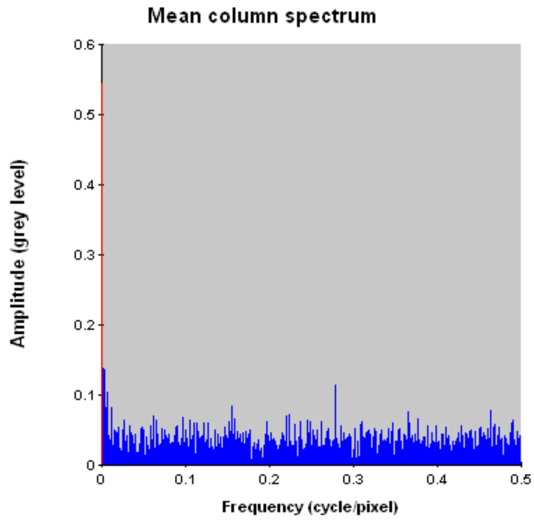
The row noise variance and the column noise variance respectively represent 4% and 16% of the total variance. This is a high level of column noise, and a lower row noise, but both visible at this gain and this exposure time.

The low value of horizontal correlation coefficient (-0.02) compared to the variance of row noise (0.62), and the absence of peaks in the mean row spectrum show that there is no correlation between rows, and no repeatable pattern.

Mean column spectrum has a peak at low frequency, which means that columns follow a low frequency component.

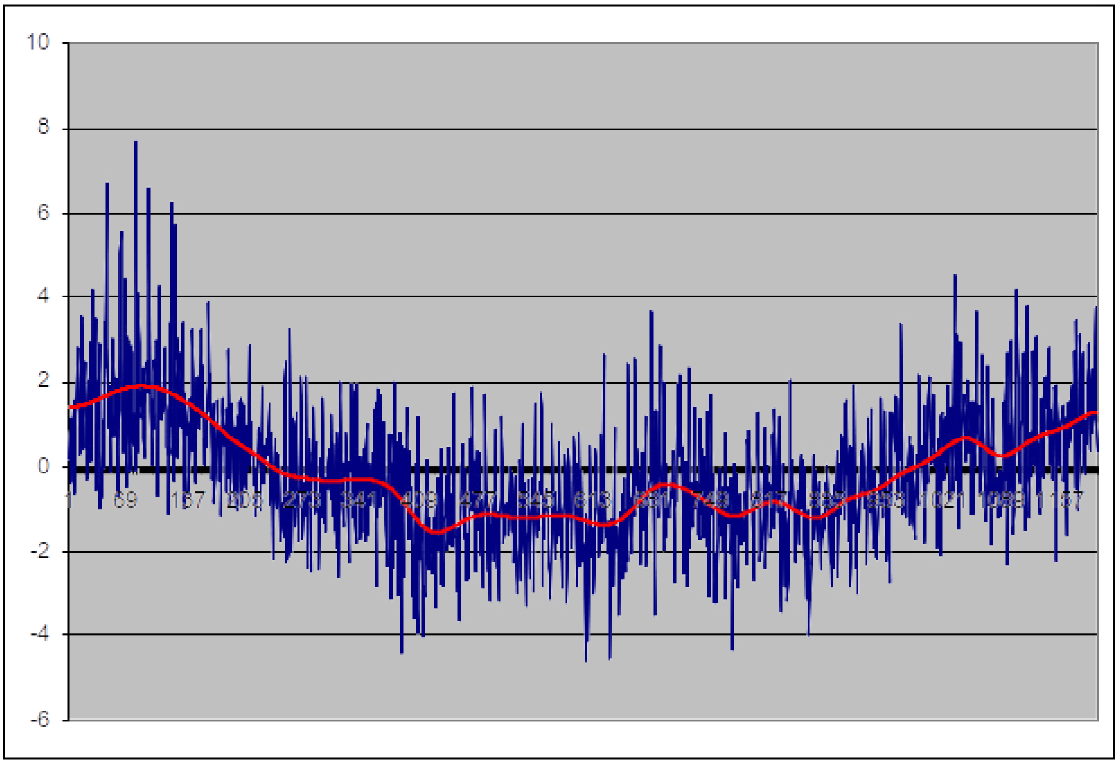


Frequency (cycle/pixel)	Amplitude (grey level)
-	-



Frequency (cycle/pixel)	Amplitude (grey level)
0.0006	0.54

To see what a low-frequency component is, we can look at the profile of column means in the exported Microsoft Excel file. It gives the mean grey level of each column, centered at zero. This profile is shown below. The curve in red is the profile on a sliding window. In absence of correlation between columns, this red line would be constant at zero. However, an oscillation whose period is about the size of the image was detected. Its origin may come from power supply interference.



The second example is a measurement from a DSLR Canon 350D. The image has been taken at ISO 1600, with an exposure time of 0.25 ms, in a room at a temperature of 21 °C.

	in grey levels (12 bits)	in grey levels (8 bits)	in percent
Dark signal	258.06	16.13	
Standard deviation	7.21	0.45	
Variance of white noise	50.21	0.20	96.65
Variance of row noise	1.55	0.01	2.99
Variance of column noise	0.19	0.00	0.36

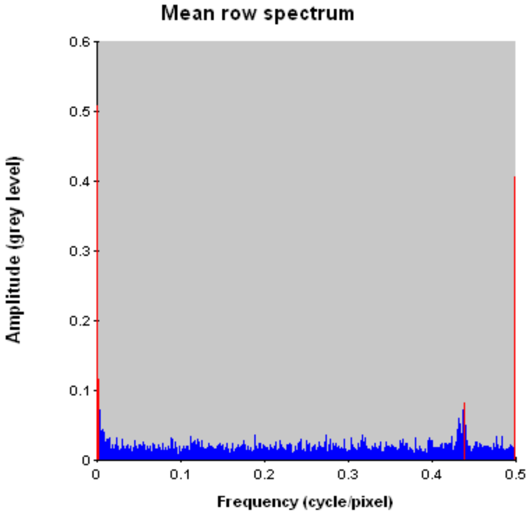
	vertical	horizontal
FPN	0.71	1.43
FPN max	1.41	4.14
Correlation coefficient	-0.05	0.54

The proportion of variance is less than 3% for row and column noise, which means there are no visible row-wise or column-wise artifacts at this ISO and this exposure time. With a correlation coefficient of 0.54

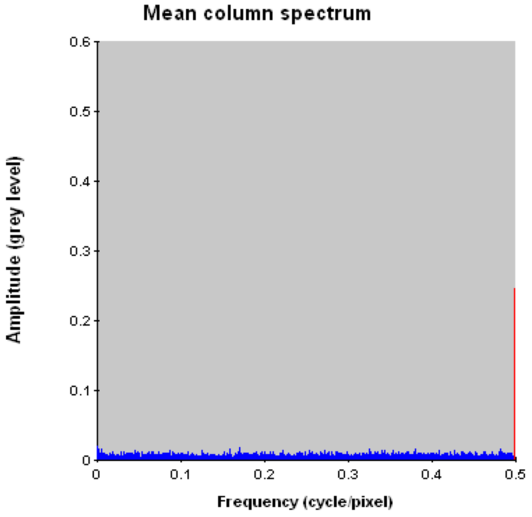
between adjacent rows, we can consider that the rows are correlated.

Looking at the mean row spectrum, we see two main frequencies: near 0 (low frequency), and at Nyquist frequency (0.5 – high frequency). Row noise comes from two factors, a low-frequency component, and a repetitive pattern every other row.

Column noise is negligible, less than 1% of the total variance.



Frequency (cycle/pixel)	Amplitude (grey level)
0.0004	0.51
0.4391	0.08
0.5000	0.41



Frequency (cycle/pixel)	Amplitude (grey level)
0.5000	0.25

19.8 Measurement accuracy

- Repeatability of dark signal is 2 grey levels in the sensor dynamic
- Repeatability of standard deviation is ±3%
- Repeatability of proportion of variance is ±1.5

19.9 Measurement scale

Row or column noises are visible when their proportion is greater than 3% of the total noise at a selected gain (ISO) and exposure time.

Proportion of row or column noise	Qualitative level
< 3%	Hardly noticeable.
Between 3% and 10%	Visible.
> 10%	Very visible, can appear in dark areas of images without correction.

19.10 Setup parameters influencing the measurement

The measurement of the row and column noise may be influenced by the following parameters:

- The crop of the image: some cameras have white or black lines or columns that, if considered as right lines or columns, may alter the results. Crop parameters of the image must be given in a sidecar file to make sure that the measurement is done only on the useful part of the image.
- Light and electromagnetic waves: the picture must be taken in the dark, in a room free of electromagnetic waves (such as WiFi networks or GSM).

19.11 Validity of the measurement

An absolute value of row and column noise is not relevant. It is always necessary to associate it with the influencing parameters. For example, claiming that the proportion of column noise in the noise is 20% is meaningless. On the other hand, it is perfectly meaningful to indicate that a sensor at ISO 3200 with an exposure time of 20 ms in a room at 21 °C has a proportion of column noise of 20%.

19.12 Comparing two cameras

Proportions of row and column noise, at same ISO and same exposure time, can be compared. It is better to have a low proportion of row and column noise.

Frequency spectrum can also be compared, to see which frequencies are dominating.

Here is a comparison of two camera phones sensors, a 2 Mp (CP1) and a 3 Mp (CP2). Both images have been taken with an exposure time of 20 ms, at ISO 1600, in the same room at 21 °C.

	in grey levels (10 bits)	in grey levels (8 bits)	in percent
Dark signal	40.67	10.17	
Standard deviation	8.37	2.09	
Variance of white noise	68.45	4.28	97.66
Variance of row noise	0.89	0.06	1.26
Variance of column noise	0.76	0.05	1.08

	in grey levels (10 bits)	in grey levels (8 bits)	in percent
Dark signal	9.6	2.4	
Standard deviation	8.5	2.12	
Variance of white noise	60.76	3.8	84.19
Variance of row noise	9.36	0.59	12.97
Variance of column noise	2.05	0.13	2.84

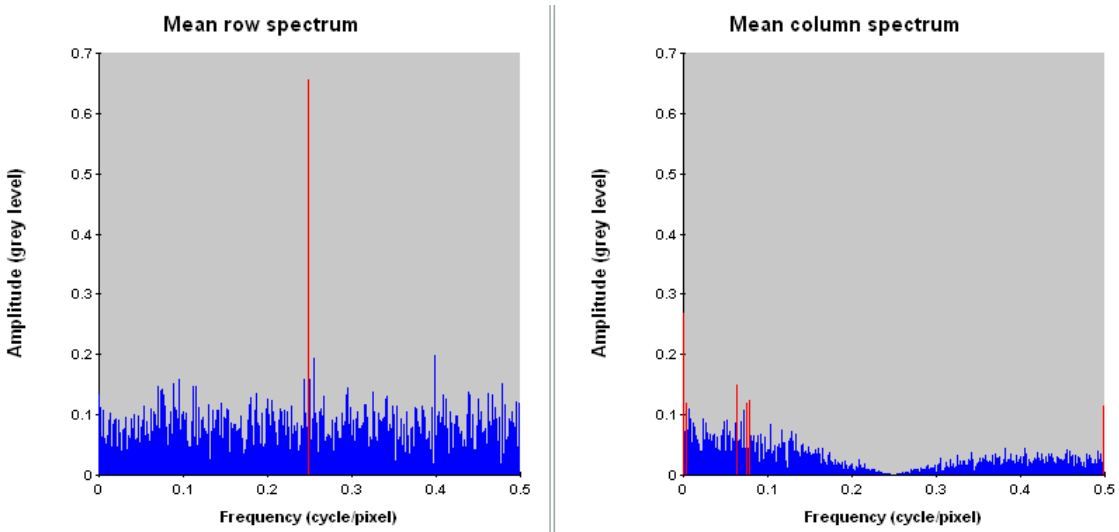
Summary values for two camera phone sensors (top: CP1 – bottom: CP2)

The total noise is very similar for the two sensors, with a standard deviation around 8.5.

For the CP1 sensor, the proportion of row and column noise is about 1% of the total variance. This is not visible on real images. The CP2 sensor has high row noise, about 13%, which is highly visible.

We can look at the CP2 spectrum to see the origin of the row noise. In the mean row spectrum, there is obviously a single peak at frequency 0.25 cycle/pixel (half Nyquist). There is no low-frequency component.

In the mean column spectrum, we can see that the amplitude has a zero value, which means that the spectrum is a sinc (a sine cardinal). As the sinc is the Fourier transform of a door function, it means that during the reading of the photosites, a door function performed a convolution. In this particular case, this sinc is due to a downsampling performed on the image to reduce noise: image size is reduced by two and then rescaled to its original size.



Frequency (cycle/pixel)	Amplitude (grey level)
0.2500	0.66

Frequency (cycle/pixel)	Amplitude (grey level)
0.0005	0.27
0.0654	0.15
0.0796	0.12
0.5000	0.11

Row and column spectra

19.13 Shooting

The RCN measurement uses a dark picture taken in a dark room. The image must be in raw format.

To avoid any problem due to an uncontrolled environment, it is preferable to take the pictures in a room which has a controlled temperature and is free of strong electromagnetic waves.

As row and column noise depend on the gain and exposure time, the image should be taken with a high gain and a low exposure time to avoid other sorts of noise and to make and row and column noise visible.

19.14 Sidecar parameters

See also Section 4.5.

The following sidecar parameters can be used the crop zone of the image:

```
[Crop]      // analysis area section
Left= ...   // left position
Right= ...  // right position
Top= ...    // top position
Bottom= ... // bottom position
```

20 – Video-N: Video Noise

20.1 Introduction

Noise in images is caused by many different factors, such as photonic noise, dark current noise, etc., all of which are described in the Noise measurement chapter (Section 17). All these noise sources can be divided into two categories: spatial noise and temporal noise.

"Temporal noise" describes the noise that varies through time: a single photosite, given the same amount of light, in the same shooting conditions, produces two different responses at two different instants. This noise can be reduced by averaging many images of the same scene. For illuminated photosites, photonic noise is the major contributor to temporal noise. Dark current noise and reset noise contribute to temporal noise, too.

"Spatial noise" describes the variation between photosites. Two photosites, given the same amount of light and the same shooting conditions, produce two different responses on average. Averaging many images will not eliminate this noise. Spatial noise is due to variability between photosites: slightly different sizes of capacitance leads to different sensitivities (yielding photo response non-uniformity or PRNU), or the value of the photosites in the dark may also differ (resulting in dark current non-uniformity or DCNU).

Beyond regular small variability between photosites, some photosites may react very differently from what is expected. They can remain much too bright or dark, or blink unpredictably. These photosites are hot, dead, or blinking, respectively, and thus are not reliable for measurements.

Dead, hot, and blinking photosites can be corrected by calibration. Calibration can also compensate for spatial noise in general because the noise is in essence fixed and is often called Fixed Pattern Noise (FPN), so it is important to measure the contribution of both temporal and spatial noise.

Taking several images are necessary to do this. Fixed patterns can be especially annoying in a video sequence, with an effect similar to looking through a dirty window pane.

The variation of exposure and white balance over time is also useful to know.

20.2 Definitions

The Analyzer measurement computes spatial and temporal noise on a sequence of frames on a uniform white chart. These two types of noise are independent, so their variances add up to the total variance of noise that can be measured in a single image:

$$V_{\text{total}} = V_{\text{spatial}} + V_{\text{temporal}}$$

Averaging the images of a sequence will reduce the temporal noise, but not the spatial noise. On an average of F frames, the total variance is

$$V_{\text{mean image}} = V_{\text{spatial}} + \frac{1}{F} \cdot V_{\text{temporal}}$$

Increasing the number of frames in the analyzed sequence increases the accuracy of the estimation of spatial noise. You can then also estimate the value of temporal noise using subtraction.

Below is an exhaustive description of the different values that appear in Analyzer Video Noise measurement. As this measurement is performed on raw or RGB sequences, image elements are photosites (raw) or pixels (RGB). To simplify, we use "pixel" to describe these image elements in the next sections of this manual, as well as in the Analyzer user interface.

20.2.1 Spatial noise

Spatial noise is computed on mean images of the video sequence. Two mean images are computed:

- Image I_{mean} is the mean image of the sequence. It is computed by averaging the levels of each pixel over time. Suppose that there are F frames in the sequence, each pixel $I_{\text{mean}}(x, y)$ is:

$$I_{\text{mean}}(x, y) = \frac{1}{F} \sum_{f=1}^{F} I_f(x, y)$$

- Image I_{flat} is the mean image with vignetting corrected. Denoting by G_c the grey level the image center, G_p the average grey level around (x, y) in I_{mean}, and D the dark current, the value of the flat image at (x, y) is

$$I_{\text{flat}}(x,y) = \left(I_{\text{mean}}(x,y) - D\right) \cdot \frac{G_c - D}{G_p - D}$$

The **spatial noise** is computed on I_{mean}. It describes the average difference between a pixel and its neighbors.

The spatial noise is computed on the whole image: it is the SMIA “Photo-Response Non-Uniformity”, as described in the SMIA Camera Characterization Specification.

Its definition is:

$$\text{PRNU}_{\%} = \frac{\sigma_{\text{local}}}{\mu}$$

where μ is the mean grey level of image I_{mean}, and σ_{local} its local deviation (this local deviation is given in the Analyzer interface as the “Noise Standard Deviation”). It is defined by

$$\sigma_{\text{local}} = \sqrt{\frac{1}{W \cdot H - 1} \cdot \sum_{x=1}^{W} \sum_{y=1}^{H} \delta_{\text{local}}(x,y)^2}$$

where each $\delta_{\text{local}}(x,y)$ is, for a pixel, the difference to its neighbors mean grey levels:

$$\delta_{\text{local}}(x,y) = I_{\text{mean}}(x,y) - \frac{1}{(2 \cdot K + 1)^2 - 1} \cdot \left(\left(\sum_{n=x-K}^{x+K} \sum_{m=y-K}^{y+K} I_{\text{mean}}(n,m)\right) - I_{\text{mean}}(x,y)\right)$$

given I_{mean} the pixel value at (x,y) and K a locality parameter, set to 5. The PRNU is expressed as a percentage. In the case the target is uniformly lit and the sequence is in raw format, this value indicates the variability of the response of the pixels.

This computation assumes that temporal noise makes no contribution to the mean image and that this is correct for an infinite number of frames. The computation also makes more sense for a uniform image (uniformly-lit target and no vignetting). To account for the residual temporal noise and illumination variation through the image field, Analyzer also estimates the noise variance locally, and removes the contribution of temporal noise. The definition is the following:

$$\text{SpatialNoise}_{\%} = \sqrt{\frac{1}{W \cdot H - 1} \cdot \sum_{x=1}^{W} \sum_{y=1}^{H} \delta_{\%}(x,y)^2}$$

where

$$\delta_{\%}(x,y)^2 = \frac{\max\left(0, \delta_{\text{local}}(x,y)^2 - \frac{1}{F}\sigma_{\text{local}}(x,y)^2\right)}{\mu_{\text{local}}(x,y)^2}$$

where $\sigma_{\text{local}}(x,y)^2$ and $\mu_{\text{local}}(x,y)$ are respectively the temporal noise and the mean grey level in the neighborhood of the pixel (x,y). The definition of the local temporal noise is given below in the blinking pixels section (defective pixels).

The row and column noise values are computed on I_{flat}. The definition of these values is given is the RCN measurement (Section 19.2). Correcting the vignetting before doing these measurements is necessary, because vignetting creates low frequency variations on image.

20.2.2 Temporal noise

Temporal noise is computed on a ROI (Region Of Interest) in the center of the images, to limit the influence of vignetting. By default the area of the ROI is 5% of the area of the input images.

The **variance of the temporal noise** provides the amount of temporal noise in the ROI. It is computed by averaging the temporal noise of each pixel of the ROI.

With $I_f(x,y)$ the grey level of the pixel at position (x,y) at frame f, and $\overline{I_{\text{mean}}(x,y)}$ the mean level of this pixel over the frames, the temporal noise is:

$$\sigma_T^2 = \frac{1}{\text{ROI}_{\text{size}}} \sum_{x \in \text{ROI}_{\text{width}}} \sum_{x \in \text{ROI}_{\text{height}}} \sigma_T(x,y)^2$$

where

$$\sigma_T(x,y)^2 = \frac{1}{F}\sum_{f=1}^{F}\left(I_f(x,y) - I_{\text{mean}}(x,y)\right)^2$$

A similar computation is performed for row and column temporal noise, again in the ROI:

$$\sigma^2_{\text{Col}_T} = \frac{1}{\text{ROI}_{\text{width}}}\sum_{x\in\text{ROI}_{\text{width}}}\left\{\frac{1}{F}\sum_{f=1}^{F}\left(C_x^f - \overline{C_x}\right)^2\right\}$$
$$\sigma^2_{\text{Row}_T} = \frac{1}{\text{ROI}_{\text{height}}}\sum_{y\in\text{ROI}_{\text{height}}}\left\{\frac{1}{F}\sum_{f=1}^{F}\left(R_y^f - \overline{R_y}\right)^2\right\}$$

20.2.3 Defective pixels

Dead and hot pixels are computed on I_{mean}. These pixels are pixels with a grey level that differs significantly from their neighborhood. They can be totally fixed and have exactly the same grey level in all frames, or vary over time.

A pixel is considered as "hot" if its grey level is larger than a threshold defined as

$$T_{\text{hot}} = \mu_{\text{local}}(x,y)\cdot(1 + K_{\text{defective}}\cdot\text{SpatialNoise}_{\%})$$

with $K_{\text{defective}}$ set by default to 20.

A pixel is considered as "dead" if its grey level is under a threshold defined as

$$T_{\text{dead}} = \max\left(K_{\text{dead}}\cdot\mu_{\text{local}}(x,y), \mu_{\text{local}}(x,y)\cdot\left(1 - K_{\text{defective}}\cdot\text{SpatialNoise}_{\%}\right)\right)$$

with K_{dead} set to 0.5. This means that whatever the computed spatial noise, a pixel is considered as dead if its grey level is less than half the grey level of its neighbors.

Blinking pixels are pixels with very high temporal noise. They can have the same mean grey level as their neighbors or be totally different. From one frame to another, their grey level can be significantly different.

A pixel is considered as blinking if its temporal noise differs from the local temporal noise:

$$\sigma_T(x,y)^2 > K_{\text{blinking}} \cdot \sigma_{\text{local}}(x,y)^2$$

the definition of the local temporal noise being

$$\sigma_{\text{local}}(x,y)^2 = \frac{1}{(2 \cdot K + 1)^2} \sum_{i=x-K}^{x+K} \sum_{j=y-K}^{y+K} \sigma_T(i,j)^2$$

with parameter K set to 15.

Parameters K_{dead}, $K_{\text{defective}}$ and K_{blinking} can be modified by user.

20.2.4 Exposure and white balance

The exposure and white balance are mainly described by graphs that show the evolution of grey levels, and CIELAB values over the frames. Several other values are also computed:

The **flicker value** corresponds to the SMIA "frame to frame flicker" measurement. It measures the frame-to-frame stability of the camera. It is defined by:

$$\text{Flicker}_{\%} = \frac{\sigma_{\text{frame}}}{\overline{\mu_{\text{ROI}}}}$$

with

$$\sigma_{\text{frame}} = \sqrt{\frac{1}{(F-1)} \sum_{k=1}^{F} \left(\mu_k - \overline{\mu_{\text{ROI}}}\right)^2}$$

where μ_k is the average pixel grey level in the ROI, in the k^{th} frame, and $\overline{\mu_{\text{ROI}}}$ the mean grey level over all frames in the ROI.

20.3 Influencing factors

As described earlier in the Noise measurement Section 17, three parameters influence the measurement of noise:

- The lens aperture.
- The exposure time.
- The ISO sensitivity setting (or gain).

Note also that the temperature inside the laboratory may have an influence on the measurement: for some cameras, dark signal can double every 8 °C, leading to an increase of noise.

20.4 Measuring Video Noise

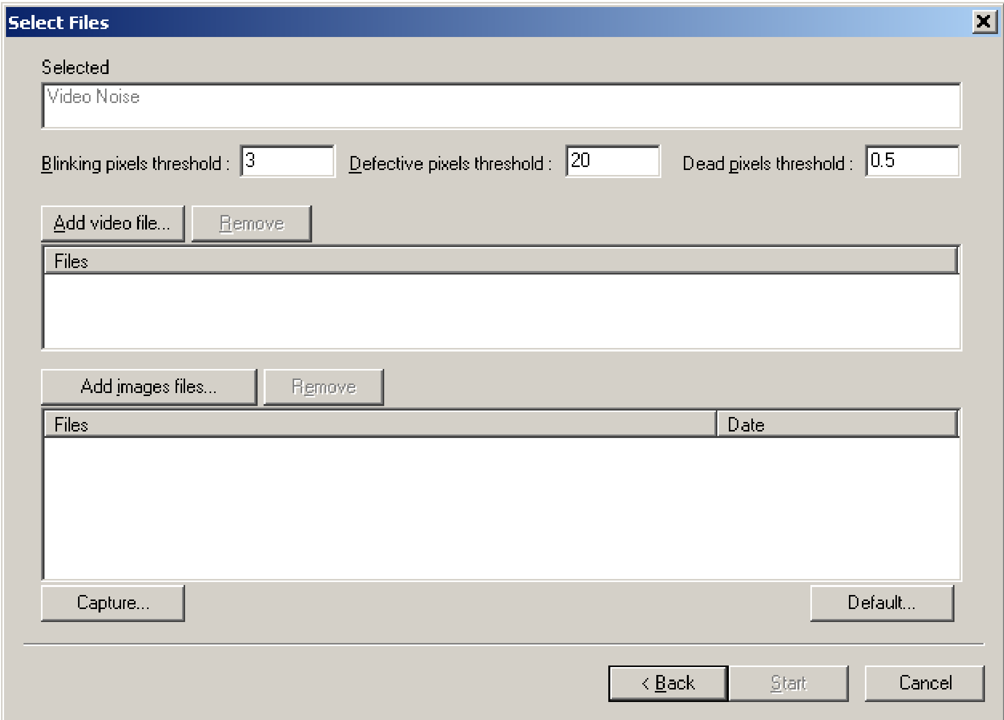
Analyzer uses series of white images to perform the Video Noise measurements. The series can be provided

- From a video file, generated by the camera or any other tool.
- From a list of image files.
- From direct acquisition of the video stream from a DirectShow® compatible camera.

Analyzer uses the Microsoft DirectShow® API to read video files. For some video file formats, the installation of specific codecs may be needed to read the files. These codecs should be provided with your camera or hardware. If it is not the case, it is possible to use generic codecs from third party, but then the quality of resulting images is not guaranteed.

To check if Analyzer will read a file, check with Windows Media Player® (WMP): any video file read by WMP can be read by Analyzer. Conversely, if a file cannot be read by WMP, it would not be read by Analyzer either.

These different reading options are available in the interface, during the image selection:

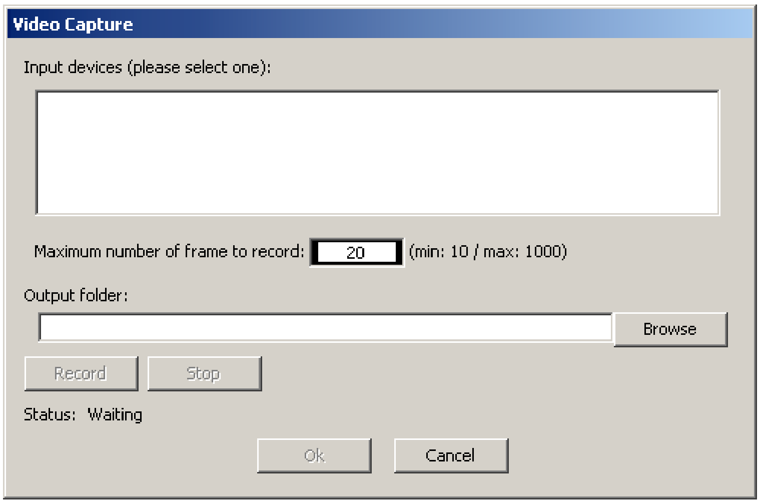


Video acquisition

There are three buttons for video acquisition

- "Add video file..." to select a video file (Any file read be Windows Media Player® can be read by Analyzer. You may have to add specific codecs to read some video formats.)
- "Add images files..." to select a sequence of images. All images must have the same size, precision and number of channels. One video measurement will be done from all the selected images, ordered by name or date (columns "Files" and "Date")
- "Capture..." to acquire images from a connected imaging device.

When selecting the "Capture..." button, the following window opens:



Acquisition window

A list of connected devices appears. The user must select a device and an output folder, where the images of the sequence will be saved.

Three input parameters can be modified by the user, with names "blinking pixels threshold", "defective pixels threshold" and "dead pixels threshold". They corresponds to the parameters K_{blinking}, $K_{\text{defective}}$ and K_{dead} in the definitions section 20.2. The "Default..." button resets these parameters with default values.

Given the input image stream, Analyzer computes temporal noise, spatial noise, exposure and white balance as described in the definitions section 20.2.

The different result values in grey levels are given in the sensor precision if the input images are in raw format. If the input images are in RGB format, precision is 8 or 16 bits.

20.5 Measurement in raw format

Analyzer can measure Video Noise for both raw and RGB sequences. The presentation and the meaning of the results are almost the same. However, Noise measurements on raw and RGB are complementary and quantify different aspects of a camera.

As previously described in the section on Noise measurement (Section 17), several operations during raw conversion change the distribution of the noise:

- Demosaicing
- White balance with strong amplification on one or two channels
- Color rendering
- Tone curve
- Noise filtering
- Compression (both spatial and temporal.

Compression also creates quantization noise that may be structured by the compression itself (as with the 8×8 JPEG blocking effect), and may be particularly strong for a video file if the resulting file size is drastically reduced.

Furthermore, results for white balance in the CIELAB color space have no meaning for raw images, and appear only on RGB results.

Note also that to accurately measure raw images, you must set the black level of the sensor using a sidecar file. Without this parameter, the black level value is set to 0. In this case, the vignetting correction may not be accurate, and the SNR computation of temporal noise will be biased.

20.6 Analyzer output

Analyzer outputs the following data:

- The summary tab contains several significant values from the three other tabs (spatial noise, temporal noise and exposure and white balance). These values are
  - The mean grey level in the ROI, for each channel
  - The spatial noise value (with correction), in percent
  - The temporal noise value (as a SNR in dB)
  - The rate of defective pixels per Mpix (dead, hot and blinking)
  - The flicker, in percent
  - The mean CIELAB *a** and *b** values in the sequence for RGB images, or mean red/green and blue/green values for raw image sequences.
- Spatial noise tab

– The first table contains the spatial noise, in percent, for each channel

	R	G	B	G
Mean gray level (10 bits)	309.64	405.77	234.56	404.47
Spatial noise	1.26 %	1.08 %	1.36 %	1.03 %
Spatial noise (no temporal correction)	1.38 %	1.22 %	1.55 %	1.19 %
Standard deviation (gray level 10 bits)	4.26	4.96	3.63	4.79

Grey levels are provided in the input images precision (8 bits for RGB images, sensor dynamic for raw ones)

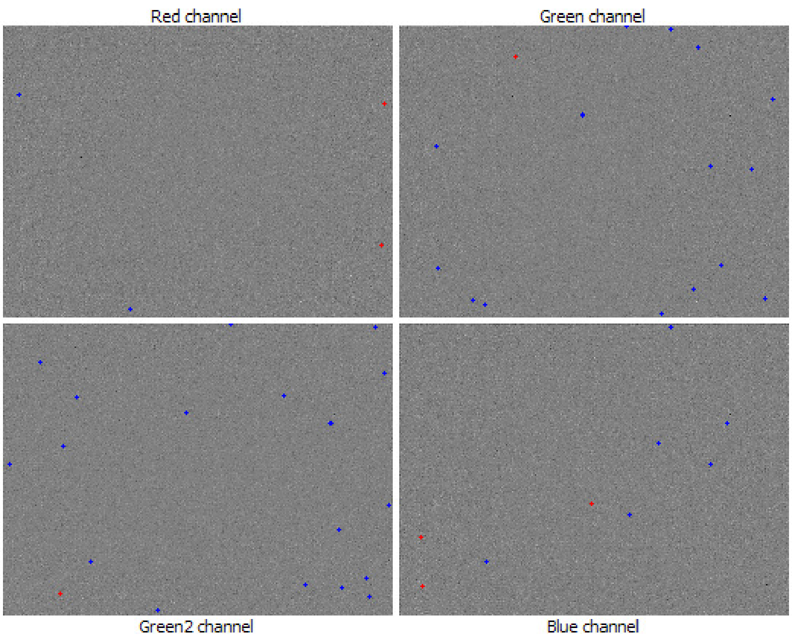
The spatial noise "without correction" (SMIA PRNU measurement) is the standard deviation / mean grey level.

– The second and third tables contain the RCN results for the flat mean image. These results are explained in the chapter about RCN (Section 19.5).

– The fourth table contains the number of dead and hot pixels for each channel. The absolute number of defective pixels is given, and the corresponding rate per Mpix.

– The spatial noise maps contain, for each channel, the spatial noise of all pixels ($\delta_{\%}(x, y)$ value in the definitions section 20.2).

Dead and hot pixels are displayed with respectively blue and red crosses.

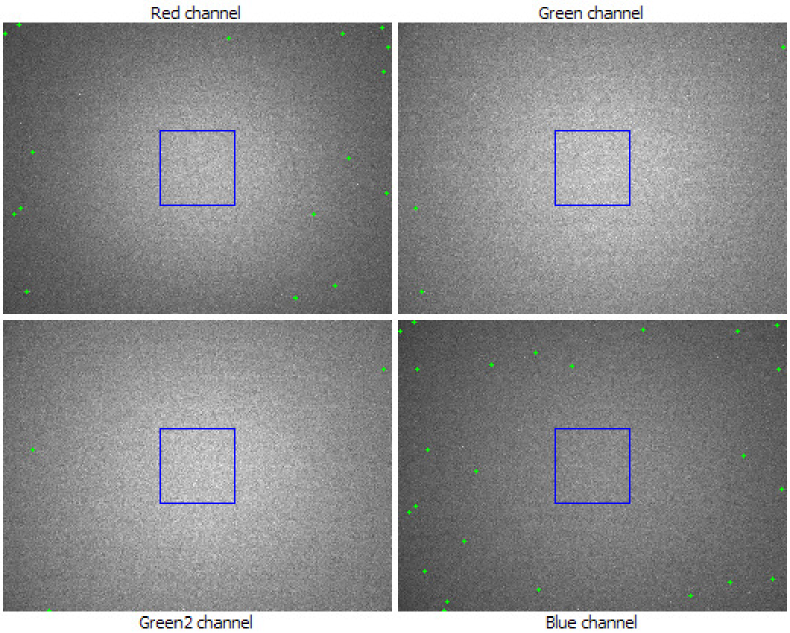


- Temporal noise tab

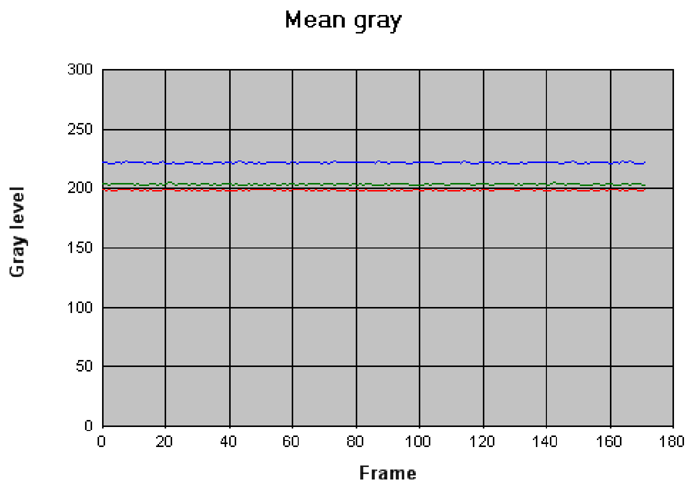
– The first table contains the following values: the mean pixel grey level, the SNR of the temporal noise (in dB), and the variance of temporal noise. These values are computed in the ROI designated by a blue square in the temporal noise images.

- The second table contains the row and column temporal noises, and the white temporal noise.
- The third table contains the number of blinking pixels, for each channel. The absolute number of defective pixels is given, and the corresponding rate per Mpix.
- The temporal noise maps contain, for each channel, the temporal noise value of all pixels ($\sigma_T(x, y)$ in the definition section).

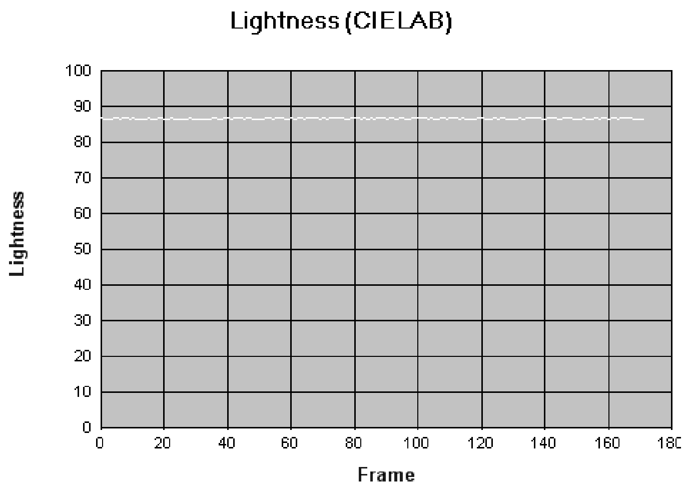
  Blinking pixels are displayed with green crosses. The ROI is displayed with a blue square.



- The exposure and white balance tab contain the following results
  - The first table contains the flicker value, in percent, for each channel.
  - Exposure is described by mean green level for raw sequences, and by mean CIELAB L^* for RGB sequences.
  - The mean grey graph contains the mean grey levels in the ROI for each channel, for each frame.

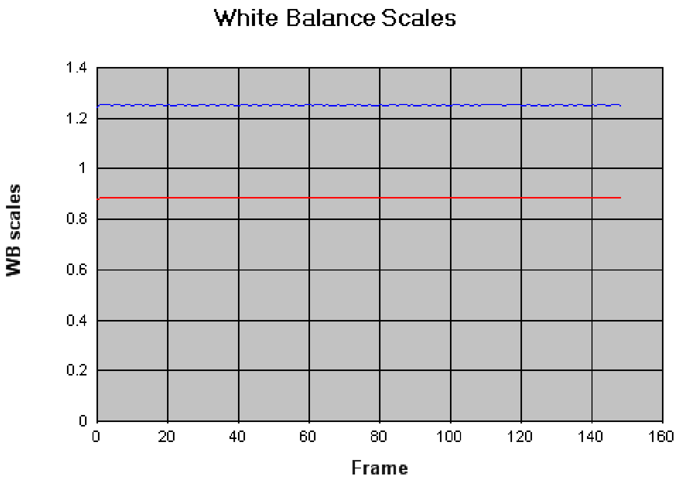


– For RGB videos only, a graph of the CIELAB L^* value is given, in the ROI, for each frame.

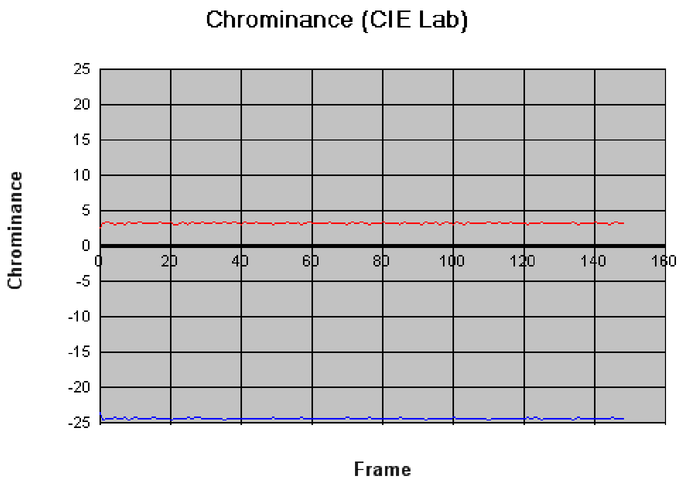


– The mean Red/Green and Blue/Green ratios are provided for raw videos. Green level is the mean of the two green channels; for RGB videos, mean CIELAB a^* and b^* are given.

– Mean Red/Green and Blue/Green are also given over the frames:



– For RGB videos only, a chrominance graph that displays CIELAB a^* and b^* for each frame is given.



20.7 Measurement accuracy

Accuracy of the measurements is linked with the number of frames F in the video, with the size N of the ROI, and with the noise level in images. We will consider that noise follows a normal (ie Gaussian) distribution.

With σ the theoretical standard deviation of the noise, accuracies of mean grey levels are as follows:

- The accuracy of ROI grey levels, in exposure and white balance, is $\pm\frac{\sigma}{\sqrt{N}}$.

- The accuracy of grey levels in the mean image is $\pm\frac{\sigma}{\sqrt{F}}$.

The accuracy of variances (spatial noise, temporal noise) depends on the number of samples. For example, if the number of frames is doubled, the variance of the temporal noise variance is divided by two.

20.8 Measurement scale

20.8.1 Temporal SNR

SNR RGB	SNR raw	Qualitative effect
$x > 45$ dB	$x > 38$ dB	Noise is scarcely noticeable.
36 dB < x < 45 dB	38 dB < x < 32 dB	Noise is present but acceptable.
$x < 36$ dB	$x < 20$ dB	The image sequence is very grainy.

20.8.2 Spatial noise

Spatial noise	Qualitative level
< 0.2%	No visible spatial noise.
Between 0.2% and 1%	Spatial noise may be visible, but acceptable.
> 1%	Visible spatial noise.

20.8.3 Row and column noise (for temporal and spatial noise)

Proportion of row or column noise	Qualitative level
< 3%	Hardly noticeable.
Between 3% and 10%	Visible.
> 10%	Very visible, can appear in dark areas of images without correction.

20.8.4 Defective pixels

Defective pixels per Mpix	Qualitative level
0	High quality sensor
> 0 and < 5	Medium quality sensor
> 5	Low quality sensor

20.8.5 White balance

White balance measure (CIELAB a^* and CIELAB b^* value)	Qualitative level
< 5	Images appear white.
> 5 and < 11	Images appear slightly colored.
> 11	White balance failed, images are not white.

20.9 Setup parameters influencing the measurement

Depending on the camera body, other secondary parameters may influence the noise in an image:

- The sharpening filter applied to the image.
- Activation of a noise reduction filter.
- Activation of a defective pixel correction.
- Compression ratio.
- Resolution.

20.10 Validity of the measurement

It is always necessary to associate a Noise measurement with the parameters that influence it. Claiming, for example, that the SNR of a camera is 45 dB has no meaning. On the other hand, indicating that the SNR of a camera is 45 dB at 400 ISO with an average grey level of 160 is meaningful. On raw sequences, you must also indicate the exposure time.

If you adjust the parameters of sharpness, compression, resolution and/or defective pixel correction, you must indicate this for a complete measurement report.

20.11 Comparing two cameras

For RGB comparisons, you can compare measurements at identical exposures and identical ISO sensitivity values. In such case, the precision of grey levels identical on the images to be compared.

For raw comparisons, as the exposure time has an influence on the spatial noise (i.e., on defective pixels and on row and column noise), the exposure time must be identical in the two measurements.

RGB measurements and raw measurements should not be compared, because the processing applied on raw images to obtain RGB images changes the distribution of noise.

Here is a comparison of two raw measurements for two different sensors in the same market segment. The measurement is done at gain 16 and the exposure time is 10 ms for both sensors, with sequences acquired at a constant temperature of 21 °C.

Overall noise values are similar for the two sensors:

Summary results for sensor 1:

	R	G	B	G
Mean Pixel Value in ROI (in gray level - 10 bits)	587.68	596.07	305.04	577.93
Spatial Noise Value (in %)	1.43 %	1.34 %	2.30 %	1.25 %
Temporal SNR (in dB)	22.8 dB	22.9 dB	20.2 dB	22.82 dB

Summary results for sensor 2:

	R	G	B	G
Mean Pixel Value in ROI (in gray level - 10 bits)	649.76	658.65	355.29	660.05
Spatial Noise Value (in %)	1.64 %	1.43 %	1.98 %	1.38 %
Temporal SNR (in dB)	22.9 dB	22.9 dB	20.6 dB	22.93 dB

The results show that their temporal noise is similar, and their spatial noise values are also close, but that their number of defective pixels is very different:

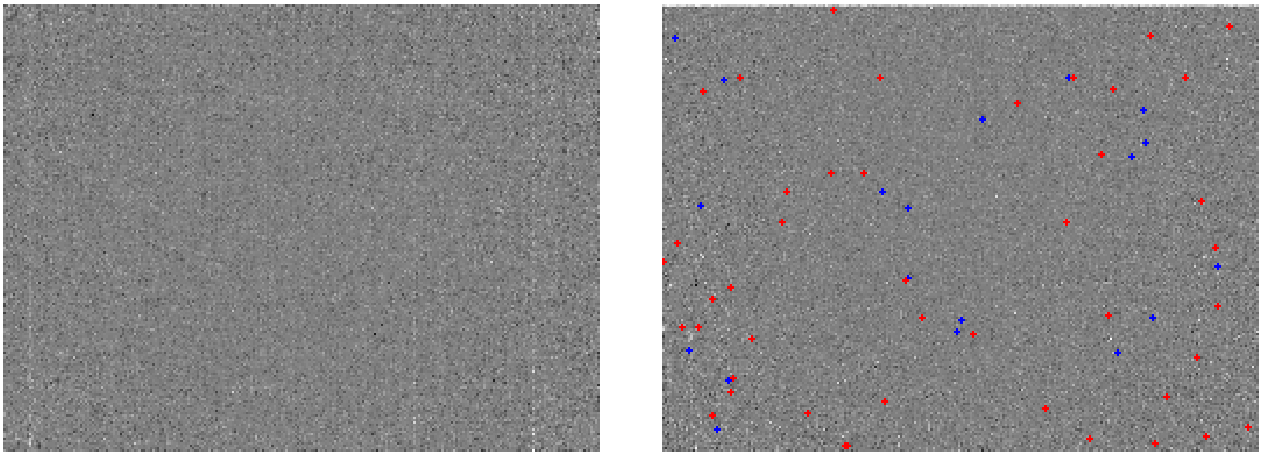
Defective pixels for sensor 1:

	R	G	B	G
Dead pixels (per Mphotosite)	0.0	0.0	0.0	0.5
Hot pixels (per Mphotosite)	0.0	0.0	0.5	0.5
Blinking pixels (per Mphotosite)	0.0	0.0	0.0	0.0

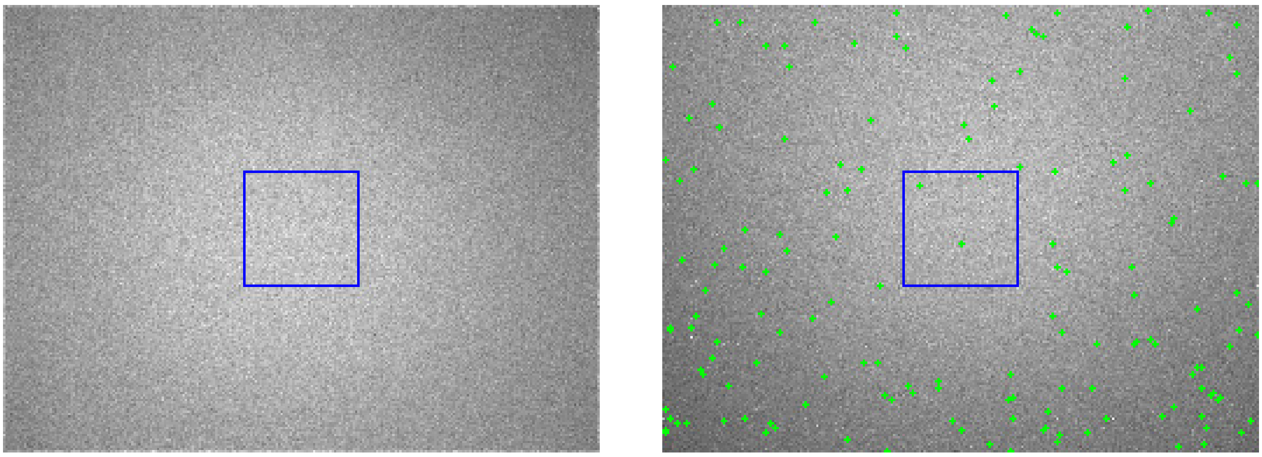
Defective pixels for sensor 2:

	R	G	B	G
Dead pixels (per Mphotosite)	1.6	15.9	1.6	17.5
Hot pixels (per Mphotosite)	42.1	34.9	38.1	34.1
Blinking pixels (per Mphotosite)	148.4	122.3	231.8	106.4

Looking at the spatial and temporal noise maps, sensor 2 has defective pixels distributed in the entire image, while sensor 1 has nearly no defective pixels, but exhibits some column noise (5% of the total spatial noise).



Spatial noise images – left: sensor 1 – right: sensor 2



Temporal noise images – left: sensor 1 – right: sensor 2

Thus even if they look similar at first sight (same temporal noise and spatial noise), the second sensor is of lower quality in terms of defective pixels.

20.12 Shooting

a) **Install the appropriate hardware**
   The Noise measurement on video needs the following hardware:

   (a) a tripod for a stable shooting.
   (b) A white chart, or a retro-lighting device such as the one used for Noise measurement.

   If you use a white chart, it must be uniformly illuminated. Consult the laboratory setup Section 3 for more information about setting up uniform illumination.

b) **Decide on the important parameters, if applicable:**

   - ISO sensitivity or sensor gain.
   - Exposure correction (EV).
   - On-board processing parameters:
     - Noise reduction filter
     - Correction of defective pixels
     - Digital zoom function
     - Compression ratio (TIFF format can record uncompressed or lossless compressed images, while JPEG format implies information loss).
     - Sharpness filter
     - Resolution
   - Any special modes of the camera for saturation, contrast, etc.

   Set up the exposure to have grey levels around 50% of the sensor dynamic. Be aware that using wide apertures may increase vignetting.

   Also, if you use a retro-lighting device, be aware that to avoid flicker, the selected exposure time must be a multiple of the half-lighting period. For example, for a 50Hz lighting device, the camera exposure time should be a multiple of 10 ms: 10 ms, 20 ms, 30 ms, etc. To increase exposure time without saturating the sensor, you can add a neutral density filter between the light source and the camera.

   Note that the frequency of the Kyoritsu LV-9502 light box is 50 kHz, leading to a 0.01 ms period. No flicker should be visible with this device, unless a very short exposure time is used.

c) **Special conditions for framing the photograph**

- The image must be totally white. Only the target (white chart or retro-lighting) must be visible.
- No dust either on the lens, the sensor, and the target.
- If possible, defocus the lens to limit the influence of residual dust on the lens or the target.

20.13 Sidecar parameters

For video files, sidecars must have the same name than their associated video file, plus the .ini extension.

For a list of image files, only the sidecar of the first image of the list is read.

You can use the `[Common]` section to change the ROI for the temporal Noise measurement. The ROI is described by its top-left corner and its bottom right corner:

```
[Roi]      // ROI section
Left=...   // x coordinate of the top-left corner
Top=...    // y coordinate of the top-left corner
Right=...  // x coordinate of the bottom-right corner
Bottom=... // y coordinate of the bottom-right corner
```

It is also possible to define a crop in images, to remove dead extreme rows or columns:

```
[Crop]      // analysis area section
Left= ...   // left position
Right= ...  // right position
Top= ...    // top position
Bottom= ... // bottom position
```

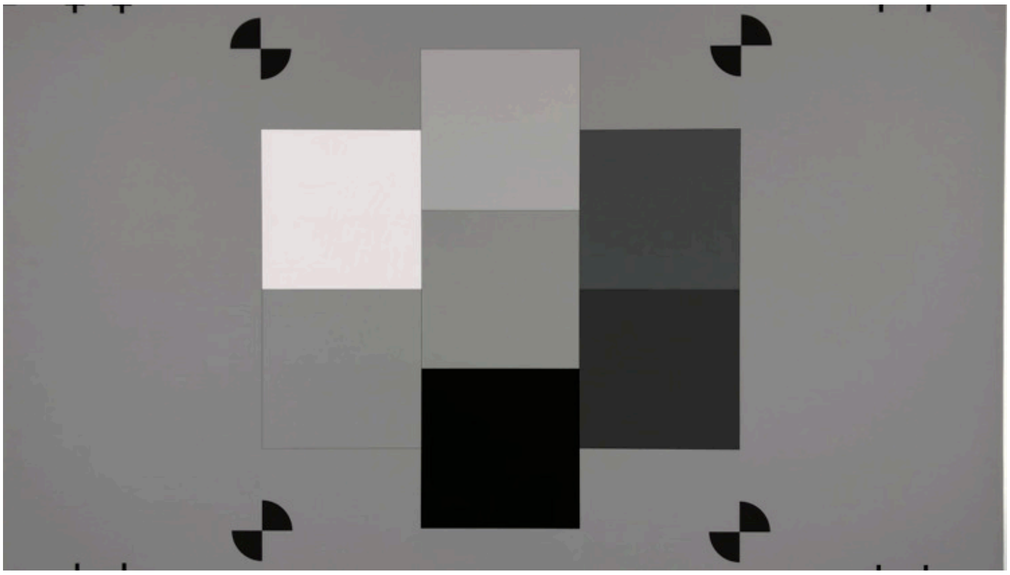
For raw images, giving the dark current is needed if it is not 0:

```
[Black]         // Black value section
BlackValue= ... // value to subtract to have 0 black (must be in 15b for raw images)
```

21 – VVN: Visual Video Noise

21.1 Introduction

Visual Noise for still images has been standardized in IEEE P1858 and ISO 15739. Although these standards are supposed to provide good perceptual correlations, while the general formulae are valid, there is still an effort in determining the parameters for the metrics. With an appropriate set of parameters, these metrics can be applied to video frames independently and the average value or the standard deviation can be assigned to the whole video sequence. However, since photonic noise on the sensor varies with time, temporal noise adds up to the spatial noise in videos. This creates blinking that can be annoying and distracting to the viewer. We use the DXOMARK Visual Noise chart, which can be seen in Figure 21.1. This chart is an ISO 14524 compliant OECF test chart and it has large patches to be able to work with video resolutions that are usually smaller than photo resolutions.



DXOMARK Visual Noise chart

21.2 Definitions

The Temporal Visual Noise metric is computed in the CIE-$L^*a^*b^*$ color space. Exposure and white balance are compensated to isolate the temporal noise from other distinct effects (exposure drift, white-balance drift, etc.). We measure temporal noise variances $\sigma^2_{L^*}$, $\sigma^2_{a^*}$, and $\sigma^2_{b^*}$ as spatial averages (over the pixels of an entire patch) of the temporal variances (over all frames for a single pixel). For computational reasons, the variances are computed using Welford's online algorithm[7]. Since noise depends on luminance, these variances are computed on seven ROIs with different reflectances. A normalization is required to compare different devices with different exposures: the noise is given for CIELab L^* = 50, linearly interpolated from the two closest uniform grey patches to lightness value L^* = 50.

The perception of temporal noise shows a good correlation to the square root of a weighted sum of the noise variances. Thus, we set all weights to 1, and we define the Temporal Visual Noise (TVN) as:

$$\mathrm{TVN} = \sqrt{\sigma_{L^*}^2 + \sigma_{a^*}^2 + \sigma_{b^*}^2}. \tag{16}$$

Notice that this is the average euclidean distance of each pixel of a correctly exposed patch from its average.

The perception of luminance and chromatic noise is different. Namely, users tend to be more sensitive to chromatic noise. Denoising algorithms for luminance and chroma noise are different as well. To evaluate how colored the noise is, we define the Chromaticity Index (CI) as:

$$\mathrm{CI} = \frac{\sigma_{a^*}^2 + \sigma_{b^*}^2}{\sigma_{L^*}^2 + \sigma_{a^*}^2 + \sigma_{b^*}^2}. \tag{17}$$

21.3 Influencing factors

The Visual Video Noise measurement is generally affected by several parameters of the device in video mode:

- the behavior of the Auto-Exposure (AE) and Auto-White Balance (AWB) algorithms, including:
  - exposure bias,
  - metering mode and/or exposure point in the field,
  - fixed custom settings (aperture, ISO, custom white balance,...),
  - tone mapping, color space, HDR and other enhancement algorithms;
- framerate or capture rate (e.g. fast- or slow-motion modes),
- choice of lens/filter, if applicable on the device under test,
- plus any other behavior of the Image Signal Processor (ISP) that affects exposure or color.

[7] Welford, B. P. "Note on a method for calculating corrected sums of squares and products." Technometrics 4, no. 3 (1962): 419-420.

21.4 Measuring Visual Video Noise

The measurement is performed using the DXOMARK Visual Noise chart. This measurement is available for videos. The VisualVideoNoiseMeasure supports a variety of input parameters. For more information about these inputs, please read the inline help of the function:

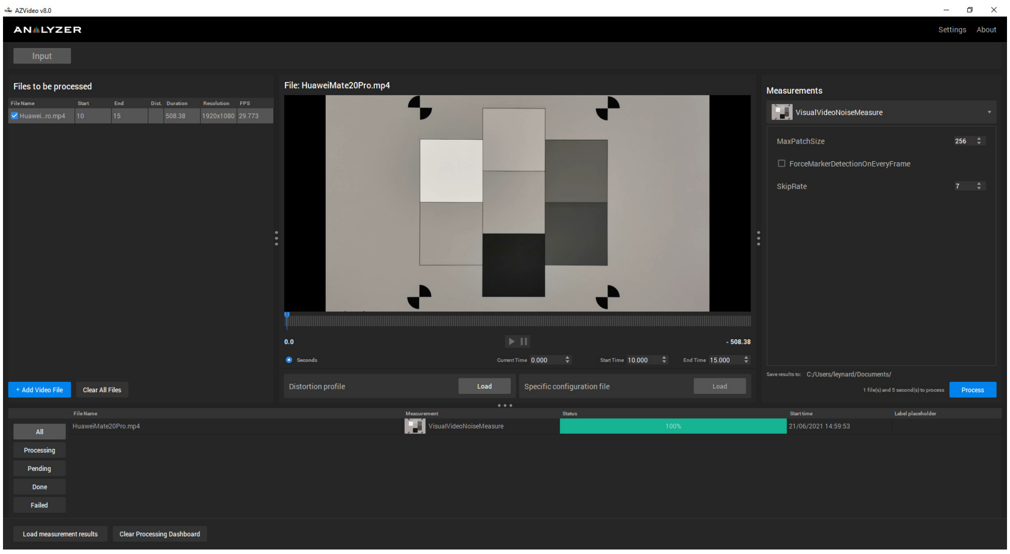
```
from dxomark.core.videomeasure import VisualVideoNoiseMeasure
help(VisualVideoNoiseMeasure.Inputs)
```

It is possible to run the measurement from the AZVideo interface. Three input parameters can be set by the user:

MaxPatchSize Size of the patch being considered for the temporal and spatial metrics computation;

ForceMarkerDetectionOnEveryFrame Marker detection is performed on every frame. If not checked, the previous marker detection results will be used;

SkipRate Number of frame to skip between two measured frames.



AZVideo interface for Visual Video Noise measurement

Given the input video stream and the parameters, the Temporal Visual Noise metric will be estimated as described in the definitions section 21.2.

21.5 Workflow Manager output

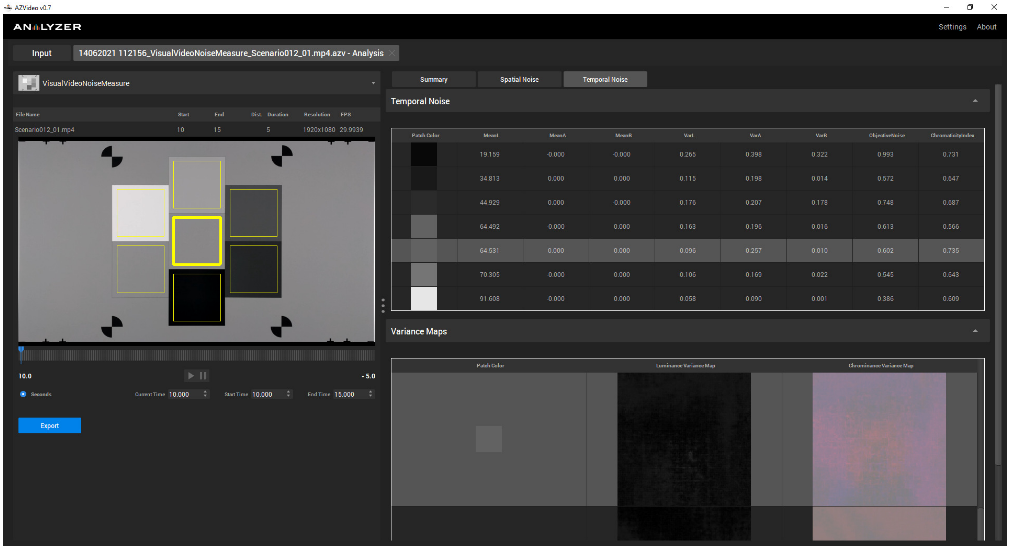
The output of the Visual Video Noise measurement is available in the Workflow Manager has the following structure:

21.5.1 Spatial noise

- MeanL: Average CIE-L^* level for each patch.
- MeanA: Average CIE-A^* level for each patch.
- MeanB: Average CIE-B^* level for each patch.
- VarL: Variance of the CIE-L^* level for each patch.
- VarA: Variance of the CIE-A^* level for each patch.
- VarB: Variance of the CIE-B^* level for each patch.
- VarL_L50: Variance of the CIE-L^* level interpolated for $L^* = 50$.
- VarA_L50: Variance of the CIE-A^* level interpolated for $L^* = 50$.
- VarB_L50: Variance of the CIE-B^* level interpolated for $L^* = 50$.
- ObjectiveNoise: Objective spatial visual noise for each patch.
- ObjectiveNoise_L50: Objective spatial visual noise for $L^* = 50$.
- ChromaticityIndex: Chromaticity index computed as described in the definitions section 21.2 for each patch.
- ChromaticityIndex_L50: Chromaticity index for $L^* = 50$
- FrameByFrame: dictionary, only if 'GetAllFrameData' in input parameter was set
  - MeanL: Average CIE-L^* level for each patch for each frame.
  - MeanA: Average CIE-A^* level for each patch for each frame.
  - MeanB: Average CIE-B^* level for each patch for each frame.
  - VarL: Variance of the CIE-L^* level for each patch for each frame.
  - VarA: Variance of the CIE-A^* level for each patch for each frame.
  - VarB: Variance of the CIE-B^* level for each patch for each frame.
  - ObjectiveNoise: Objective spatial visual noise for each patch for each frame.
  - TimeStamp: Frames timestamp in second on which spatial noise was computed.

21.5.2 Temporal noise

- MeanL: Average CIE-L^* level for each patch
- MeanA: Average CIE-A^* level for each patch
- MeanB: Average CIE-B^* level for each patch
- VarL: Variance of the CIE-L^* level for each patch
- VarA: Variance of the CIE-A^* level for each patch
- VarB: Variance of the CIE-B^* level for each patch
- VarL_L50: Variance of the CIE-L^* level interpolated for $L^* = 50$
- VarA_L50: Variance of the CIE-A^* level interpolated for $L^* = 50$
- VarB_L50: Variance of the CIE-B^* level interpolated for $L^* = 50$
- ObjectiveNoise: Objective temporal visual noise for each patch
- ObjectiveNoise_L50: Objective temporal visual noise for $L^* = 50$
- ChromaticityIndex: Chromaticity index computed as described in the definitions section 21.2 for each patch
- ChromaticityIndex_L50: Chromaticity index for $L^* = 50$
- VarianceMaps
  - L: Variance CIE-L^* channel per pixel of each patch
  - A: Variance CIE-A^* channel per pixel of each patch
  - B: Variance CIE-B^* channel per pixel of each patch



Variance Maps as displayed in AZVideo. This visualization allows to detect spatial patterns in the temporal noise (e.g., blocking).

21.5.3 General

- MarkerPositions: List of markers coordinates for first frame. Only if 'ForceMarkerDetectionOnEveryFrame' is false
- PatchesPosition: List of patches coordinates in the form: [[[top_left_X, top_left_Y], [bottom_right_X, bottom_right_Y]], ...]
- InverseToneCurve: Inverse Tone Curve
- PatchTargetExposure: Target CIE-L^* value for each distinct patch.

21.6 Measurement accuracy

Repeatability for both spatial and temporal noise is ±0.1.

21.7 Measurement scale

Tables below provide a subjective scale of spatial noise results depending on the shooting conditions. In low-light conditions, a slightly higher amount of noise is considered acceptable.

In bright-light conditions (300–1000 lux):

Spatial noise	Subjective evaluation
Below 1	No visible noise.
Between 1 and 3	Visible noise.
Above 3	Noise is objectionable.

In low-light conditions (5–300 lux):

Spatial noise	Subjective evaluation
Below 3	No noise or acceptable noise for the shooting conditions.
Between 3 and 6	Visible noise.
Above 6	Noise is objectionable.

Tables below provide a subjective scale of temporal noise results depending on the shooting conditions. In low-light conditions, a slightly higher amount of noise is considered acceptable.

In bright-light conditions (300–1000 lux):

Temporal noise	Subjective evaluation
Below 0.6	No visible noise.
Between 0.6 and 1	Visible noise.
Above 1	Noise is objectionable.

In low-light conditions (5–300 lux):

Temporal noise	Subjective evaluation
Below 1	No noise or acceptable noise for the shooting conditions.
Between 1 and 2	Visible noise.
Above 2	Noise is objectionable.

21.8 Setup parameters influencing the measurement

Depending on the camera body, other secondary parameters may influence the noise in the image:

- A sharpening filter applied on the image
- An activation of a noise reduction filter
- An activation of a defective pixel correction
- The compression ratio
- The resolution

21.9 Validity of the measurement

The Visual Video Noise measurement is performed on static lighting environment. We consider constant lighting at different luminances from 1lux to 1000lux, and different color temperatures from 2300K to 6500K. Make sure, if you use a lighting sequence, that the device has enough time to adjust the exposure and the white balance.

21.10 Comparing two cameras

Measurements of Visual Video Noise, both spatial and temporal, can be compared at identical exposures on condition that the viewing conditions are the same.

In such a case, the comparison is pretty straightforward: the lower the noise, the better the camera.

Chromaticity indices are also fundamental: the luminosity noise is often less visually disturbing than a strong colored noise.

21.11 Shooting

1. Install the DXOMARK Visual Noise chart (see Section 21.1).
2. To correctly detect and measure the test target, make sure that:
   - The chart is correctly oriented.
   - The markers appear on the images.
   - The dark crosses appear at the border of the image height.

22 – STB: Stabilization

22.1 Introduction

This measurement evaluates the efficiency of a stabilization system for video and still cameras. To achieve this, you must measure two types of phenomena: motion blur for still images and videos, and image distortions of video.

The first noticeable defect of a non-stabilized video is the global shakiness of the image, mainly due to the instability of a hand-held camera around the three axes of camera rotation. The second noticeable defects are those due to the rolling shutter used in CMOS sensors. If these two types of defects are decreased enough by the stabilization system, only the possible motion blur (especially in low-light conditions) is noticeable. So a good video stabilization system should be able to reduce these three types of defects: global shakiness, rolling shutter-induced defects, and motion blur.

In still photography, you measure only motion blur, as stabilization systems in photography are designed to allow photographers to shoot at longer exposure times.

The Stabilization measurement is performed on both video files and still images, so it can evaluate all types of stabilization systems: optical, in-body, and software.

Optical stabilization systems use gyroscopes to measure the angular displacement of the camera around the pitch and yaw axes. Then a lens or a group of lenses tilts to keep the image of an object at the same location on the sensor, regardless of the shakiness of the camera. The lens can be tilted only in two directions so it is impossible for this type of stabilization system to compensate for motions around the roll axis (also known as the optical axis).

In-body or sensor stabilization systems use the same operating principles, except that the moving part is not a lens but the image sensor itself. The sensor is mounted on a stage that can be translated and even rotated, thus compensating for motions around all three axes of rotation.

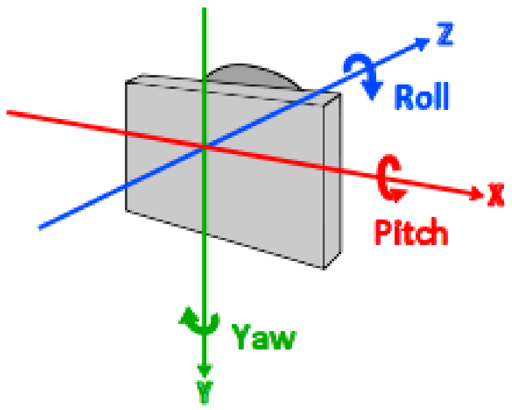
Software stabilization systems (or Digital Image Stabilization) can be as simple as just increasing ISO sensitivity to allow the use of higher shutter speeds to reduce motion blur. On the other hand, they can be very complex, decreasing global image motion as well as rolling shutter-induced distortions by performing an advanced motion estimation based on gyroscopes and/or the video stream from the sensor.

The aim of this measurement is to evaluate global motion, rolling shutter-induced distortions, and motion blur.

22.2 Definitions

22.2.1 Global motions

The global motions measured in video streams for the Video Stabilization measurement are directly due to the motions applied by the user to the camera. These motions can be broken down into rotations and translations applied on *X*, *Y* and *Z* axes (see figure below).



Axis conventions

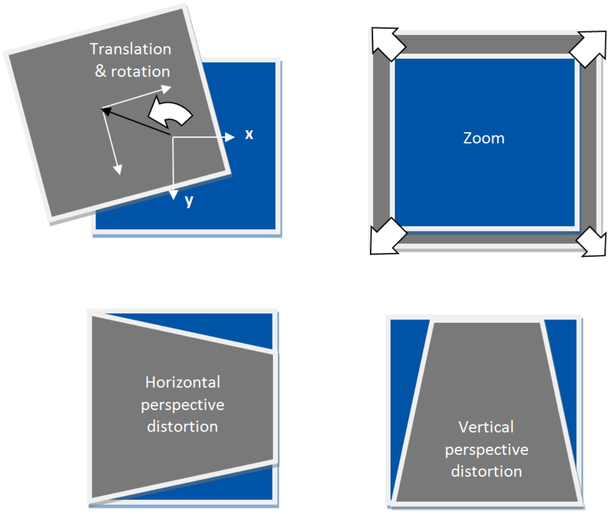
The effects of these motions on the image depend on the camera-to-target distance, except for the rotation around all three axes. The *Z* rotation of the camera will induce a rotation of the image around the same axis, while *X* and *Y* rotations of the camera produce, respectively, *Y* and *X* translations as well as vertical and horizontal perspective modifications on the image.

If the target is at infinity (or far from the camera), the *X* and *Y* translations of the camera produce negligible deformations on the image. If the target is close to the camera, the *X* and *Y* translations of the camera become considerable and produce, respectively, *X* and *Y* translations on the image.

The vertical perspective modification will be described by the output parameter named "Vertical keystoning".

The horizontal perspective modification will be described by the output parameter named "Horizontal keystoning".

Thus six parameters must be measured to completely describe global motions: *X* translations, *Y* translations, optical axis rotation, horizontal and vertical perspective modifications, and zoom. These transformations can be visualized as follows:

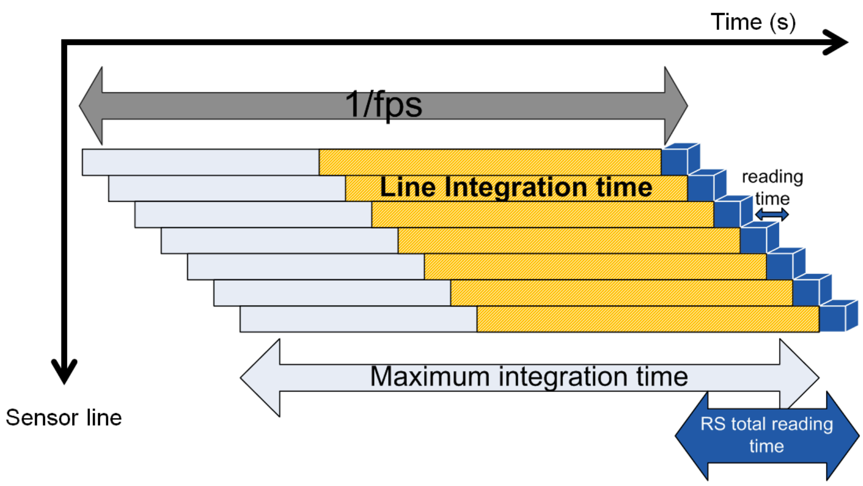


Visualization of global motions

Among these types of motions, the most noticeable are *X* and *Y* translations and *Z* rotation. The inconvenience of these translations and rotation depends on their amplitude and frequency. High-frequency vibrations are intolerable, whereas lower-frequency vibrations are less disturbing or even desirable for allowing smooth panning.

22.2.2 Rolling-shutter-induced distortions

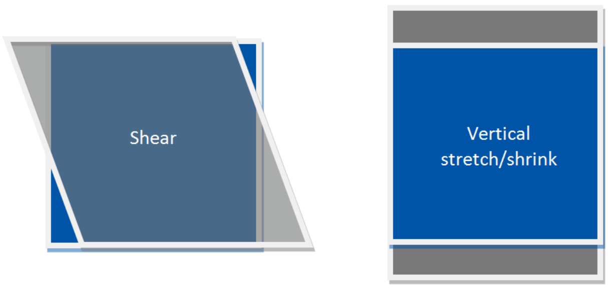
On most CMOS sensors, the lines are integrated and read at different times. This acquisition technique is called Electronic Rolling Shutter. The following figure presents a schematic of the acquisition of one frame.



Schematic of the acquisition of one frame

If the camera moves between the integration of the first and the last line of the sensor, the image will be distorted in two different ways, depending on the motion direction. Horizontal panning (or yaw) leads to slanting vertical lines; this defect is called "shear," since the right angle between a horizontal and a vertical line is not preserved. Vertical panning (or pitch) leads to stretching or shrinking of object height; this defect is called "Vertical stretch/shrink." The slower the rolling shutter, the greater the defects.

These two types of distortion can be represented as follows:



Visualization of rolling-shutter-induced distortions

22.2.3 Motion blur

When shutter speed is too slow, the instability of a hand-held camera may lead to blurred images. Indeed, due to camera motion during exposure, several pixels integrate the same ray, which leads to blur, as showed in the following image.

Unlike defocus blur which is isotropic (as shown the background of the above images), motion blur is generally directional. This direction depends on the camera movement during exposure.

In photography, a rule-of-thumb says that to obtain a sharp image, the exposure time (in seconds) must be smaller than the inverse of the 35 mm equivalent focal length. If this rule is not enforced, the image will most certainly be blurred, unless the camera is fitted with a stabilization system or mounted on a tripod. The stabilization system allows the use of longer exposure times, depending on its efficiency.

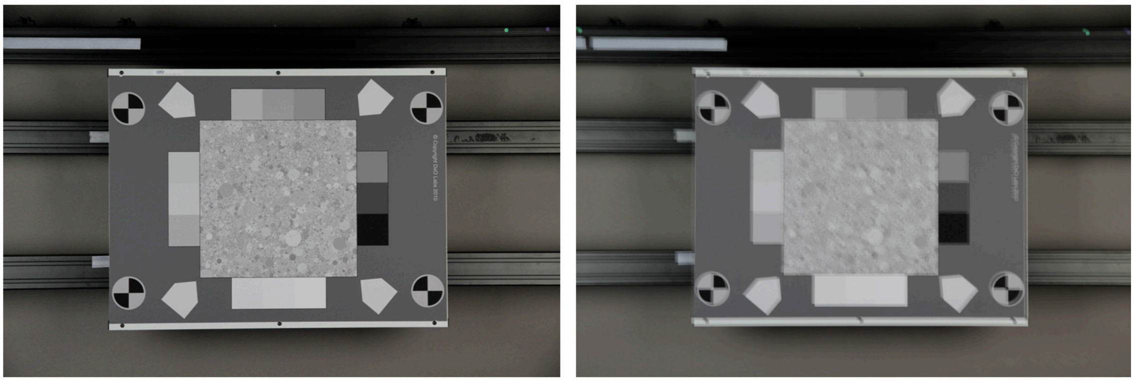


Illustration of motion blur

The amount of motion blur in an image is thus an indicator of the efficiency of the stabilization system in still photography. For a given exposure time, an image should be sharper with a stabilization system. There are limits on the exposure time value: if it is too long, the stabilization system will not be able to compensate for the motion. If the exposure time is too short, the image will be sharp even without a stabilization system.

22.3 Influencing factors

Several parameters influence the phenomena defined above:

- The motion applied to the camera tested.
- The focal length of the lens.
- Specifications of the sensor: CCD (global shutter) or CMOS (almost always a rolling shutter), vertical blanking, reading time.
- The illumination (more light generally leads to a shorter exposure time and to a lower amount of blur).

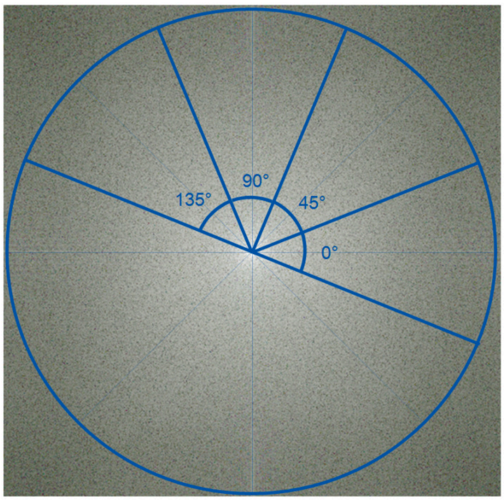
- The rigidity of the camera's mechanical autofocus. Depending on its rigidity, the autofocus can be mechanically triggered by some motions. In the resulting video, some frames may be partially blurry and stretched, which the Stabilization measurement will treat as a zoom or shear deformation.

22.4 The Stabilization measurement

Both the Video Stabilization measurement and the Photo Stabilization measurement are performed on the Texture Chart. The Photo Stabilization measurement measures motion blur, whereas the Video Stabilization measurement also evaluates global motion and rolling shutter-induced distortions.

For each still image or each video frame, the first step is detecting the markers on the chart. The marker positions identify the location of the elements used for the motion blur measurement: the grey level patches, the SFR patches, and the textured ("Dead Leaves") area. These coordinates are also used by the Video Stabilization measurement for calculating the parameters describing global motion and rolling shutter-induced distortions.

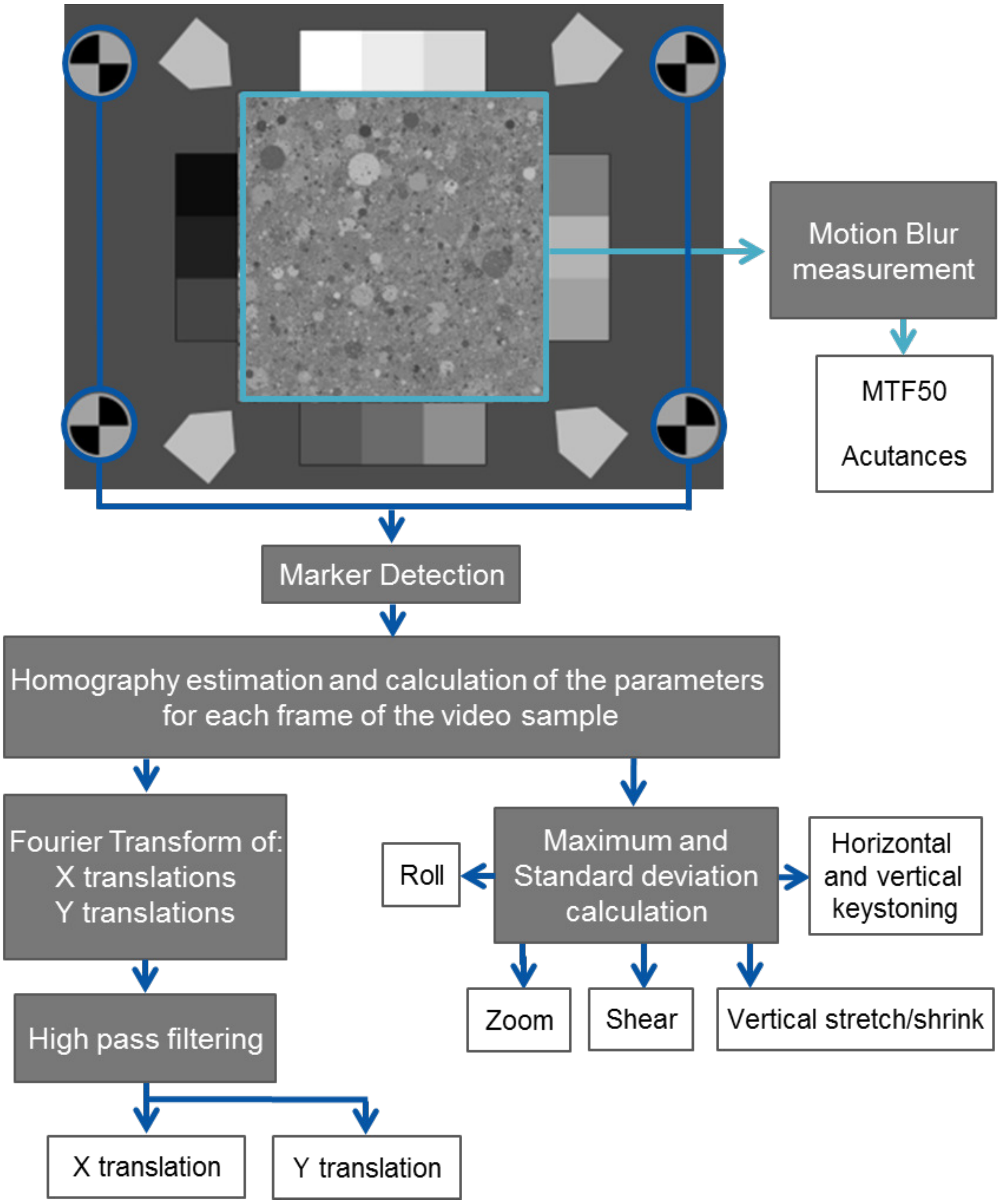
The motion blur measurement uses the Texture Preservation ("Dead Leaves") measurement to compute the texture MTF. The main steps of the measurement are equivalent to the one presented in the Texture Preservation Section 10. But while the Texture Preservation measurement computes the average of all FFT 2D profiles to output one MTF profile and one acutance for each channel, the motion blur measurement computes the average of FFT 2D profiles on four angular sectors (see the figure below) in order to output MTF50 and acutances for these four sectors, but only on the luminosity channel. The still photography measurement gives information about the direction of motion blur. The following figure presents the location of angular sectors on the FFT 2D image of the texture area.



Angular sectors for the Blur measurement

Information about motion blur is the only data returned for the still photography measurement, since still image stabilization aims at sharper images.

The following diagram presents the different steps of the Video Stabilization measurement:



Steps of the Video Stabilization measurement

Global motions and rolling shutter-induced distortion parameters are obtained by the homography between each frame and a reference (the first frame, which explains why the camera must be immobile during the acquisition of the first images). These homographies use the four markers detected in each frame of the video sample to make the estimate. Parameters are deduced from homography as follows:

The homography H is represented by a 3×3 matrix that defines a planar projective transformation. This linear transformation of homogeneous coordinates can be decomposed as follows:

$$H = \begin{pmatrix} A & t \\ w^T & v \end{pmatrix} = \begin{pmatrix} I & t \\ 0 & 1 \end{pmatrix} \begin{pmatrix} K & 0 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} sR & 0 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} I & 0 \\ w^T & v \end{pmatrix}$$

Where $t = \begin{pmatrix} t_x \\ t_y \end{pmatrix}$ gives directly the X and Y translations,

And

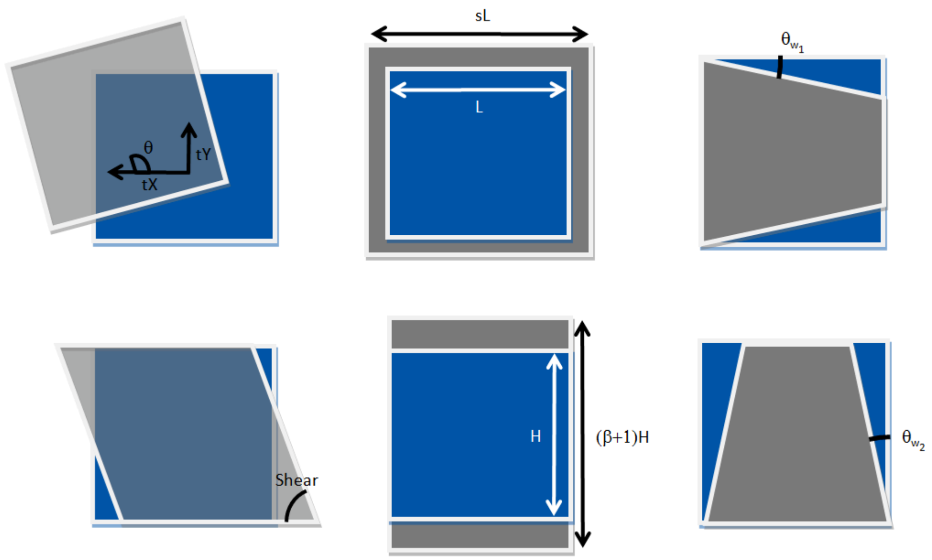
$$\begin{aligned} A &= sKR + t \cdot w^T \\ &\approx sKR = s \cdot \begin{bmatrix} 1 & \alpha \\ 0 & 1 + \beta \end{bmatrix} \cdot \begin{bmatrix} \cos(\theta) & -\sin(\theta) \\ +\sin(\theta) & \cos(\theta) \end{bmatrix} \end{aligned}$$

Writing $A = \begin{bmatrix} a & b \\ c & d \end{bmatrix}$, the other parameters can be expressed as follows (see the below figure for visualization of the parameters):

- The roll or rotation around optical axis Z is given by $\theta = \arctan\left(\frac{c}{d}\right)$
- The zoom ratio is given by $s = \dfrac{ad - bc}{\sqrt{c^2 + d^2}}$
- The vertical stretch/shrink is given by $\beta + 1 = \dfrac{c^2 + d^2}{ad - bc}$
- The shear is given by Shear $= \arctan\left(\dfrac{\alpha}{1 + \beta}\right)$ with $\alpha = \dfrac{ac + bd}{ad - bc}$
- Writing $w^T = (w_1 w_2)$, the keystoning parameters are given by:

$$\begin{aligned} \theta_{w_1} &= \arctan(w_1 \cdot Y) \\ \theta_{w_2} &= \arctan(w_2 \cdot X) \end{aligned}$$

where Y is the half height and X is the half width of the chart in the reference image.



Visualization of the measured parameters

These calculations are made for each frame of the video sample. To obtain the final metrics, the following steps are executed:

- The Fourier transforms of *X* and *Y* translations are computed and a high-pass filter is applied. This filter allows taking into account only high frequency vibrations that are responsible for the bad quality of non-stabilized videos. As an analogy to spatial modulation transfer function (MTF), the final metrics are equivalent to a temporal standard deviation of the translation measurements after having removed the low frequency components. The metrics for *X* and *Y* translations are given in pixels, in pixels equivalent to a Full HD display and in percentage of chart diagonal in images.
- The final metric for the roll parameter is the standard deviation of the roll values obtained through all the frames. The unit used here is degrees.
- The final metrics for the zoom parameter are the maximum and the standard deviation of the zooming variation over the frames given in percentage of the reference image width.
- The final metrics for the Horizontal keystoning are the maximum and the standard deviation of the values over the frames. It is given in degrees.
- The final metrics for the Vertical keystoning are the maximum and the standard deviation of the values over the frames. It is given in degrees.
- The final metrics for the shear is the maximum and the standard deviation of the values over the frames given in degrees.

- The final metrics for the vertical stretch/shrink is the maximum and the standard deviation of the values over the frames given in percentage of the reference image height.

22.5 Measurement in raw format

The Stabilization measurement uses the Texture measurement and is used for RGB images only.

22.6 Analyzer output

Analyzer returns two different sets of data depending on the type of stabilization measurement: video or still photography.

- The Shooting conditions tab contains the resolution of the video (or of the series of images) on which the measurement has been made, as well as the frame rate, the format, and the number of frames (or images) processed.

Resolution (pixel)	1920 x 1080
Frame rate (fps)	25
Format	AVI
Frame count	550

- The Summary tab contains four sections:
  - A first section, "Translation, rotation and zoom," presents the metrics related to global motions. The undesirable translations (the ones with a frequency higher than 1 Hz) on the *X* and *Y* axes are given in actual pixels in the input frames/images; in pixels normalized on a Full HD display; and as a percentage of the chart size in the input frames/images. The undesirable rotations (the ones with a frequency higher than 1 Hz) around the optical axis are given in degrees. The zoom parameters (maximum and standard deviations) are given in percent.

	Measured value (pixel)	Full HD normalized (pixel)	Image field normalized
Horizontal translation	2.1	2.1	0.20 %
Vertical translation	1.3	1.3	0.12 %

	Measured value (°)
Roll (Z axis rotation)	0.1

	Maximum	Std Dev
Zoom	0.09 %	0.03 %

– The second section, "Keystoning," provides the parameters of the distortions due to perspective changes, in degrees.

	Maximum	Std Dev
Horizontal (°)	0.1	0.0
Vertical (°)	0.1	0.0

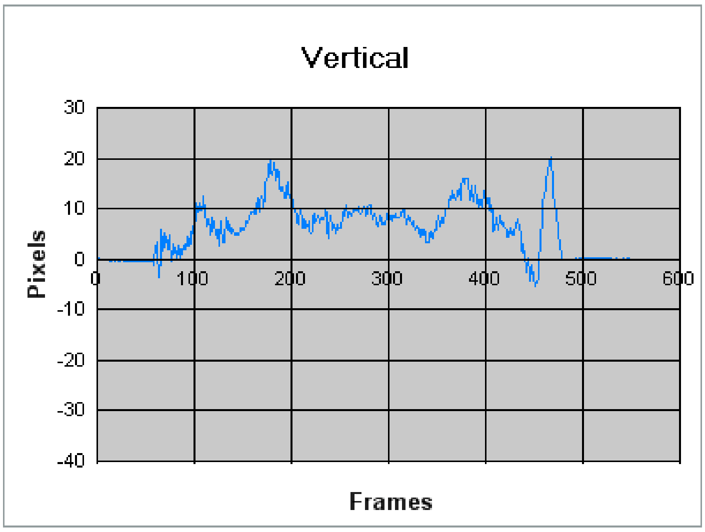
– The third section, "Rolling shutter effects," describes the parameters referring to the rolling shutter-induced distortions. The values are in degrees for the shear and in percentage for the vertical stretch/shrink.

	Maximum	Std Dev
Shear (°)	0.3	0.0
Vertical stretch / shrink	0.24 %	0.07 %

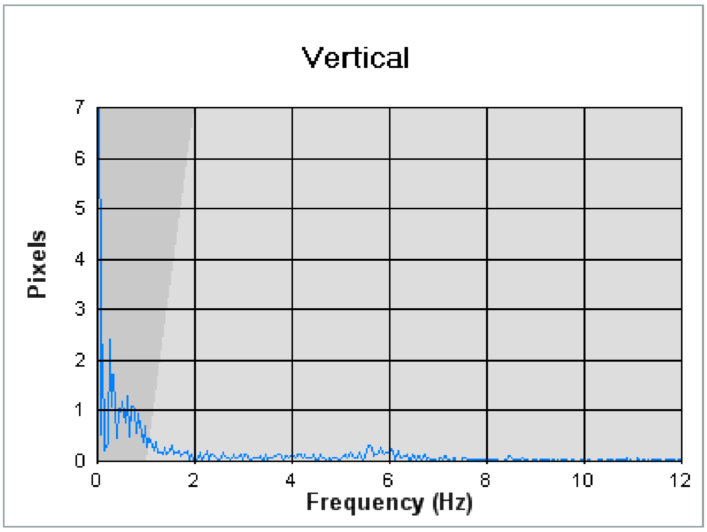
– The fourth section, "Motion Blur," presents the parameters describing motion blur. The values for acutance and MTF50 (in cycle per pixel) are those from the most blurred direction (see the figure "Angular sectors for the Blur measurement" in Section 22.4).

	Temporal average	Temporal Std Dev
Acutance [5 - HDTV Viewing]	0.49	0.02
MTF 50% (cycles/pixel)	0.10	0.00

• The Motion tab contains three graphs. The first graph presents the *X* axis translations, in pixels, between each frame of the video or each image of the series, and the reference image. The second graph displays the *Y* axis translations, in pixels, between each frame of the video or each image of the series, and the reference image. The last graph presents the *Z* axis rotations, in degrees, between each frame of the video or each image of the series, and the reference image. Here is an example of the second graph:



- The *Spectrum* tab contains three graphs. The first graph presents the spectrum of the *X* axis translations, in pixels, between each frame of the video or each image of the series, and the reference image. The second graph presents the spectrum of the *Y* axis translations, in pixels, between each frame of the video or each image of the series, and the reference image. The third graph presents the spectrum of the *Z* axis rotations, in degrees, between each frame of the video or each image of the series, and the reference image. Here is an example of the second graph:



The Photo Stabilization measurement returns the following data:

- The *Summary* tab contains three tables. They present the average and standard deviations of the minimum, average, and maximum sharpness over the four directions in each image of the series. The first table gives these values in acutance, the second table in MTF50 (cycle per pixel), and the last table in MTF50 (line pair per millimeters).

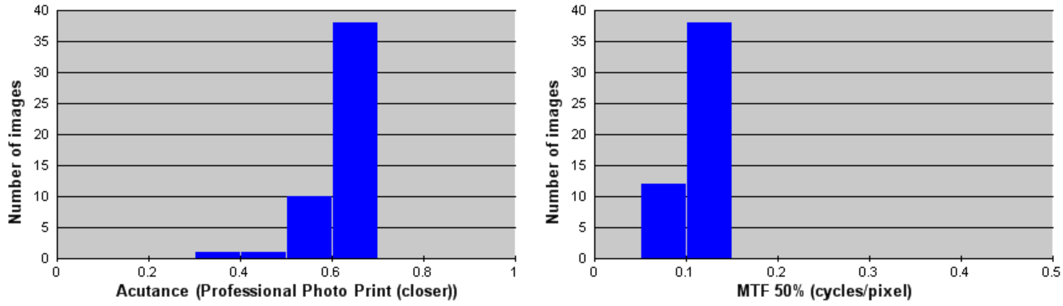
	Acutance [3 - Professional Photo Print (closer)]		
	Minimum	Average	Maximum
Average over the series	0.59	0.60	0.63
Standard deviation over the series	0.06	0.06	0.06

	MTF 50% (cycles/pixel)		
	Minimum	Average	Maximum
Average over the series	0.11	0.12	0.12
Standard deviation over the series	0.01	0.02	0.02

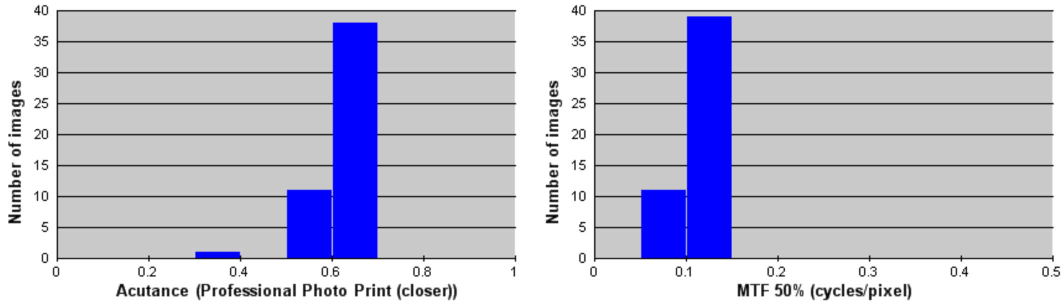
	MTF 50% (lp/mm) 20x30cm print		
	Minimum	Average	Maximum
Average over the series	1.83	1.92	2.03
Standard deviation over the series	0.23	0.26	0.30

- The *Histograms* tab contains six graphs. The three graphs to the left correspond to the first table in the previous tab. Each one of these three graphs displays the repartition of the acutance values over the series of images. The three graphs to the right correspond to the second table in the previous tab. Each one of these three graphs displays the repartition of the MTF50 values (in cycle per pixel) over the series of images.

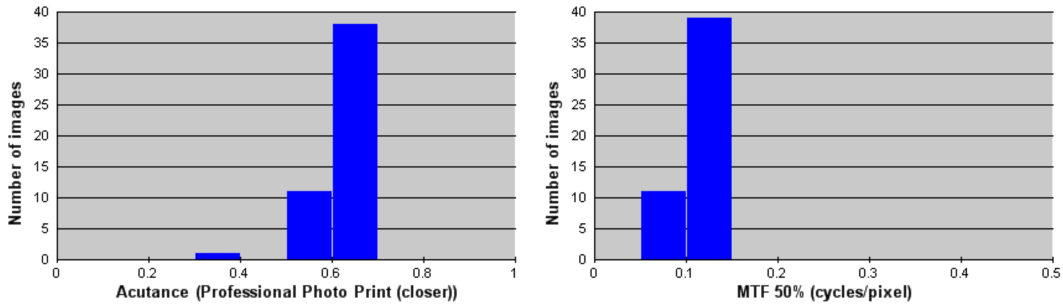
MINIMUM



MEAN



MAXIMUM



- Each of the last three tabs, named “Acutance,” “MTF50 (cy/pix),” and “MTF50 (lp/mm),” respectively, contains one table. These tables provide the sharpness values for each direction and for each image of the series. They also give the minimum, average, and maximum sharpness over the direction for each image, as well as the average and standard deviations over the series of images (which are the values given in the Summary tab). The sharpness values are given in acutance, in MTF50 (cycle per pixel), or in MTF50, depending on the tab. Here is an example for the Acutance tab:

Exposure time	Aperture	ISO	File name	Acutance [3 - Professional Photo Print (closer)]						
				Direction				Minimum	Average	Maximum
				0°	45°	90°	135°			
2 ms	5.6	400	_DSC2110.JPG	0.50	0.52	0.54	0.50	0.50	0.52	0.54
2 ms	5.6	400	_DSC2111.JPG	0.50	0.53	0.55	0.51	0.50	0.52	0.55
2 ms	5.6	400	_DSC2112.JPG	0.50	0.53	0.54	0.51	0.50	0.52	0.54
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
2 ms	5.6	400	_DSC2157.JPG	0.33	0.32	0.38	0.32	0.32	0.34	0.38
2 ms	5.6	400	_DSC2158.JPG	0.64	0.63	0.61	0.61	0.61	0.62	0.64
2 ms	5.6	400	_DSC2159.JPG	0.63	0.62	0.61	0.61	0.61	0.62	0.63
Average over the series				**0.62**	**0.60**	**0.60**	**0.60**	**0.59**	**0.60**	**0.63**
Standard deviation over the series				**0.07**	**0.06**	**0.04**	**0.06**	**0.06**	**0.06**	**0.06**

22.7 Examples

As a first example, here are the results of a video measurement performed on the Canon 70-200 IS f/2.8L USM lens at 70 mm mounted on the Canon EOS 5D Mark II. Image Stabilization (or IS) is the trademark of Canon's stabilization system.

Two Video Stabilization measurements were performed: one with IS off and the other with IS on mode 1. For these measurements, we mounted the DSLR and its lens on our vibration platform in order to apply the exact same motion in both cases, thus making it possible to compare each output parameter value both with and without stabilization.

It is best to use the same video mode for both measurements because certain parameters, such the video frame rate, may change the results. Parameters for both videos are as follows:

Resolution (pixel)	1920 x 1088
Frame rate (fps)	29.97
Format	MOV
Frame count	604

Here are the video metrics for both measurements. The most important values are outlined in black for each parameter.

IS off

	Measured value (pixel)	Full HD normalized (pixel)	Image field normalized
Horizontal translation	4.8	4.8	0.32 %
Vertical translation	2.9	2.9	0.19 %

	Measured value (°)
Roll (Z axis rotation)	0.1

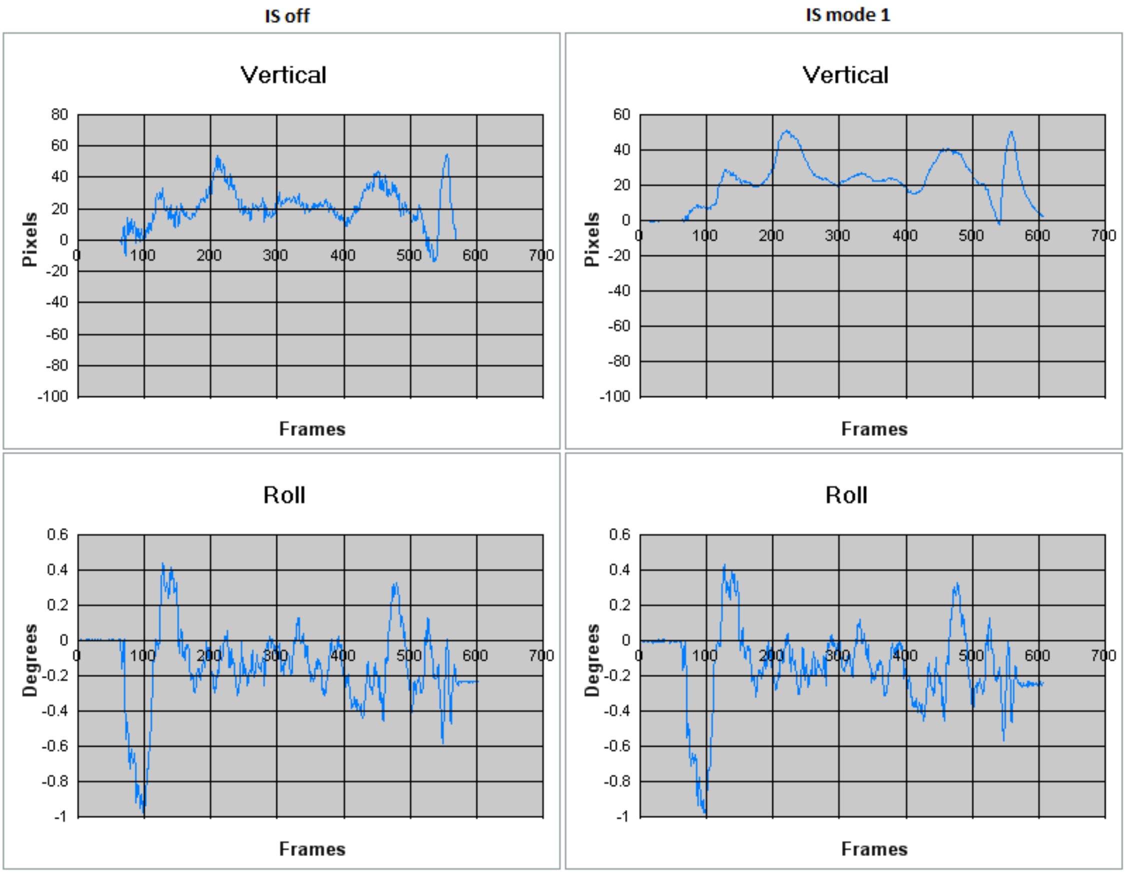
IS mode 1

	Measured value (pixel)	Full HD normalized (pixel)	Image field normalized
Horizontal translation	2.4	2.4	0.16 %
Vertical translation	0.7	0.7	0.05 %

	Measured value (°)
Roll (Z axis rotation)	0.1

As explained above, the first column of the motion acutance section refers to the values measured in the image; the second and third columns refer to normalized values. Here, both videos have been shot under the exact same conditions (resolution, focal length, target-to-camera distance), so any column can be used for comparison. Horizontal and vertical motion acutances are respectively 2 and 3.8 times lower with IS activated: camera motion is significantly decreased. But no improvement can be seen for Roll: this is due to the fact that the lens tested uses an optical stabilization system. With such systems it is not possible to correct the defects due to the rotation of the camera around the optical axis.

The effects of the stabilization system on vertical translations and on the roll can be visualized on the following graphs.

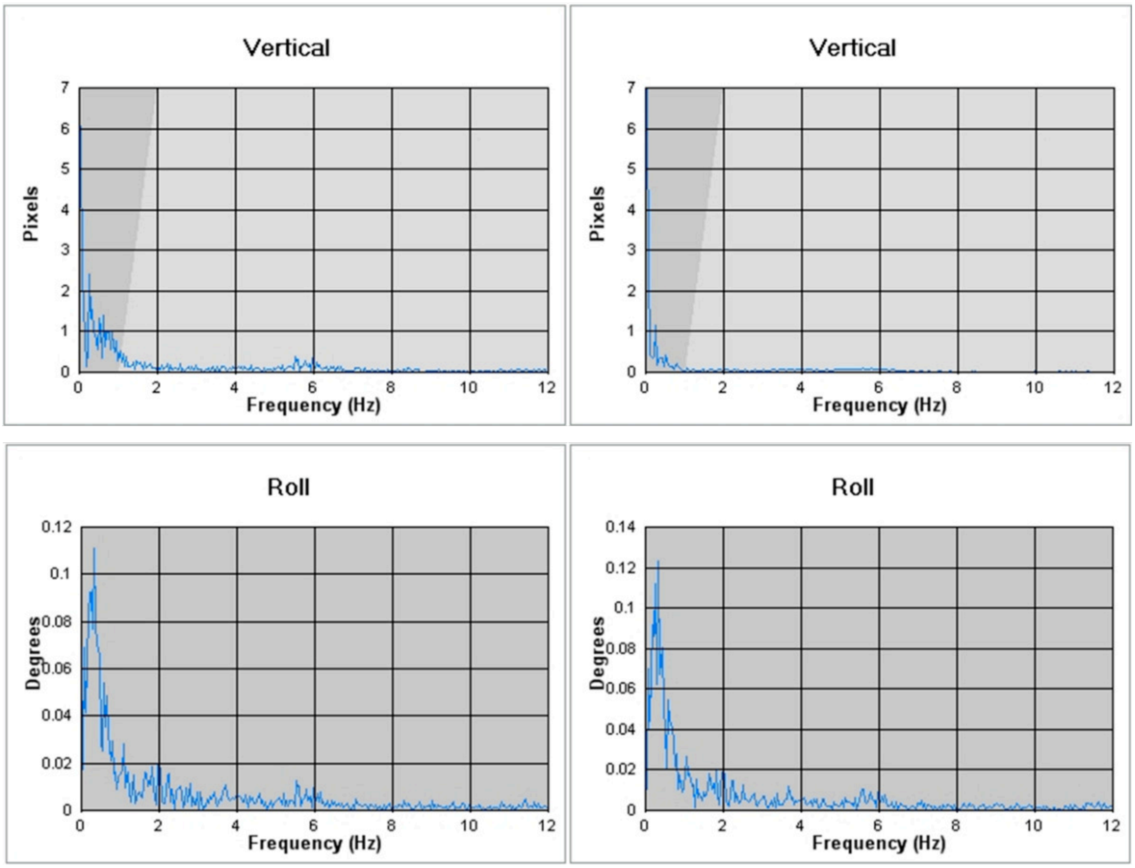


The signal matching the vertical translations in the image is significantly smoothed by the stabilization system, which means that the amplitude of high-frequency vibrations has been decreased. The same thing can be noticed about the horizontal translations. But as explained earlier, the rotations around the optical axis (roll) are exactly the same with or without the stabilization system activated.

The reduction of high-frequency vibrations for vertical translations can be observed on the following graphs. Obviously, no reduction can be seen for the rotations around the optical axis.

IS off

IS mode 1



Below are the results for the translations along the optical axis (or zoom). The values are very low because no motion has been applied on this axis. Optical stabilization systems cannot correct this defect.

IS off

	Maximum	Std Dev
Zoom	0.06 %	0.01 %

IS mode 1

	Maximum	Std Dev
Zoom	0.04 %	0.01 %

The perspective deformations are very low for these videos, so it is not worth showing the values here. But the values for the rolling shutter-induced parameters are presented below. Both shear and vertical stretch/shrink standard deviations are lower when the stabilization system is activated. When watching (at real-size and at normal playing speed) the videos taken for these measurements, the rolling shutter-induced defects are scarcely or simply not noticeable.

IS off	Maximum	Std Dev
Shear (°)	1.1	0.2
Vertical stretch / shrink	0.96 %	0.23 %

IS mode 1	Maximum	Std Dev
Shear (°)	0.5	0.1
Vertical stretch / shrink	0.51 %	0.08 %

The images are sharp even without the stabilization activated due to the good lighting conditions. Activating the stabilization improve the sharpness very little.

IS off	Temporal average	Temporal Std Dev
Acutance [5 - HDTV Viewing]	0.85	0.06
MTF 50% (cycles/pixel)	0.27	0.03

IS mode 1	Temporal average	Temporal Std Dev
Acutance [5 - HDTV Viewing]	0.86	0.03
MTF 50% (cycles/pixel)	0.27	0.01

The second example is about the Photo Stabilization measurement. As presented in the section above about Analyzer output, the Stabilization measurement gives the sharpness measured on a series of images taken at the same exposure time. With two measurements based on two series of images taken at a well-chosen exposure time, it is possible to observed the gain of the stabilization system.

Here are the results obtained for two series of images (vibration reduction off, vibration reduction mode normal) taken with a Nikkor 18-105 VR mounted on a Nikon D7000, at an exposure time of 1/30 second and a focal length of 35 mm. This camera has an APS-C sensor, so according to the rule-of-thumb in photography, the exposure time should be at most of 1/60 to obtain sharp images without stabilization.

	Vibration Reduction Off		
	Acutance [3 - Professional Photo Print (closer)]		
	Minimum	Average	Maximum
Average over the series	0.47	0.52	0.58
Standard deviation over the series	0.09	0.08	0.07

Vibration Reduction Normal		
Acutance [3 - Professional Photo Print (closer)]		
Minimum	Average	Maximum
0.54	0.57	0.61
0.08	0.07	0.05

	MTF 50% (cycles/pixel)		
	Minimum	Average	Maximum
Average over the series	0.09	0.10	0.11
Standard deviation over the series	0.02	0.02	0.02

MTF 50% (cycles/pixel)		
Minimum	Average	Maximum
0.10	0.11	0.12
0.02	0.02	0.01

	MTF 50% (lp/mm) 20x30cm print		
	Minimum	Average	Maximum
Average over the series	1.41	1.59	1.81
Standard deviation over the series	0.32	0.29	0.27

MTF 50% (lp/mm) 20x30cm print		
Minimum	Average	Maximum
1.67	1.79	1.94
0.30	0.25	0.22

The previous tables show that the average sharpness over the series of images is 5 points higher in acutance with the Nikon Vibration Reduction activated. These results have been obtained with two series of 50 images, but for a more precise comparison, we recommend you use 200 images per series to overcome the statistical bias.

The Photo Stabilization measurement can be used to evaluate the gain in f-stop provided by a stabilization system in still photography, according to the CIPA standard for the measurement and description of an image stabilization system on digital cameras [1]. The method consists of measuring motion blur for several series of images taken at different exposure times and is described in the next chapter.

22.8 Measurement accuracy

For accurate measurement of acutance and MTF values, see Texture Preservation section and MTF measurement sections in this manual (Section 10 and Section 7).

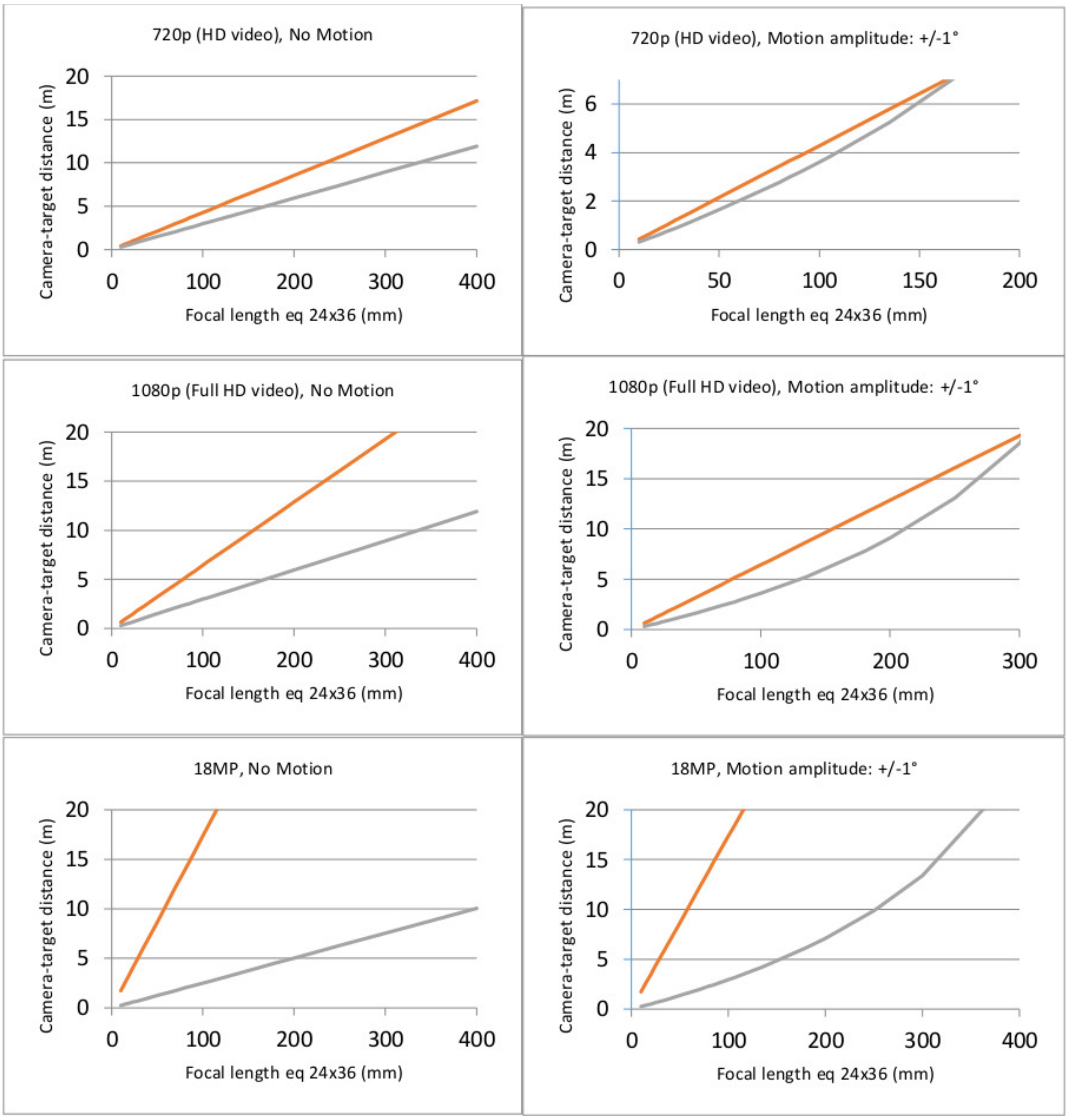
The following table gives the repeatability of each video parameter:

	Repeatability (3σ)
Horizontal translation	0.3 pixel
Vertical translation	0.3 pixel
Roll (Z axis rotation)	0.03°
Zoom	0.06%
Horizontal keystoning	0.03°
Vertical keystoning	0.03°
Shear	0.03°
Vertical stretch/shrink	0.06%

Note that the repeatability entirely depends on the motion applied during video recording and are therefore indicative only.

The Stabilization measurement accuracy depends on the shooting conditions: the chart should fill the field as much as possible, and should never be entirely out of the during the entire video. This leads to minimum and maximum distances where the camera should be placed for shooting. You must respect the minimum shooting distance in order to keep the chart in the field, depending on the focal length, the aspect ratio, and the amplitude of the motion applied to the camera. Respect the maximum distance such that the texture patch is greater than 256 pixels in the image (the minimum size allowed for the Texture measurement), depending on the focal length, the aspect ratio, and the resolution of the image.

The following graphs present these distances for a few useful cases: 720p HD video, 1080p Full HD video, and 18 megapixel images. For each resolution, the distances are given for two cases: no motion applied to the camera, and a 1° amplitude motion applied to the camera.



Measurable focal length/camera-target distance combination (distance max, distance min)

The measurement accuracy may be decreased if the video contain a too high number of very blurred images.

22.9 Measurement scale

The following table gives a subjective scale of the video metrics. See the Texture Preservation Section 10 for the scale of acutance values.

Qualitative level	Good	Fair	Bad
Horizontal & Vertical Translations	Between 0 and 0.1%	Between 0.1 and 0.2%	Over 0.2%
Roll	Between 0 and 0.1°	Between 0.1 and 0.2°	Over 0.2°
Zoom	Between 0 and 0.1%	Between 0.1 and 0.2%	Over 0.2%
Shear	Between 0 and 0.1°	Between 0.1 and 0.2°	Over 0.2°
Keystoning	Between 0 and 0.1°	Between 0.1 and 0.2°	Over 0.2°
Vertical Stretch/Shrink	Between 0 and 0.2%	Between 0.2 and 0.3%	Over 0.3%

22.10 Set up parameters influencing the measurement

The following setup parameters may change the results of the Stabilization measurement:

- Digital zoom function (this must normally be deactivated, unless this is the subject of the test).
- Resolution (you must set this to the highest available value to obtain accurate measurements).
- Compression ratio should be as low as possible.
- Aspect ratio (no specific aspect ratio is mandatory, but the factory default setting is desirable).
- Deactivate such special camera settings as noise reduction, saturation filter, contrast enhancer, and so on.
- Exposure quality (the image must be neither over or under-exposed).
- Shooting mode (when possible, use the manual exposure shooting mode in order to control the aperture, the shutter speed, and the ISO setting).
- ISO sensitivity (set to a low enough value that noise is as low as possible).

- Aperture (set to as constant value as possible so that you can compare different results).
- The focus (an inaccurate autofocus will influence the accuracy of the motion blur measurement).
- The codec pack used to read the videos: changing the video codec pack can change the way video frames are extracted. Since the video frames are the input source for our measurements, the results may be slightly different depending on what codec pack you use.
- The autofocus must be in video mode. Since a change of focus usually comes with a magnification change, the camera autofocus can change the measurement results. A mechanical or software autofocus instability can affect the measurement accuracy. We therefore advise you to lock the focus whenever possible unless this is the subject of the measurement.
- The quantity of light coming onto the chart, especially in video mode. If the chart is not illuminated enough, the exposure time will be longer on some cameras. Together with a large motion, this results in strong motion blur which can affect chart marker detection and therefore the measurement. We therefore recommend shooting videos using high levels of illumination (> 1000 lux), unless testing low-light stabilization is the purpose of the measurement.

22.11 Validity of the measurement

Both Video and Photo Stabilization measurements inform the user about a camera's the ability to compensate for a given motion. You must specify the motion used for the measurements; the results are meaningful only when associated with a motion.

Another important point is that both video and photo easurements are specific to a given focal length. This is due to the fact that for the same motion applied to the camera, the image displacement on the sensor will be greater with a longer focal length, meaning that all the defects that are measured will be higher.

So to compare two cameras, the 35 mm-equivalent focal lengths should be close to one another.

The Stabilization measurement allows all possible configurations:

- A Video Stabilization measurement based on a video file. In this case, you need no further information to perform the measurement.
- A Video Stabilization measurement based on a series of images. In this case, you must specify an appropriate frame rate (it should be at least 23.8 frames per second). The results will be different depending on the frame rate chosen. The results are meaningful only if the images are extracted from

a video file and/or the shooting procedure is compliant with the one proposed in the point immediately following.

- A Photo Stabilization measurement based on a series of images. This measurement is meaningful only if all the images haven been taken at the same shutter speed and ideally with the same setup parameters (see the information about the setup parameters influencing the measurement above).

22.12 Shooting

Both Video and Photo Stabilization measurement use a texture chart, but the shooting protocols are different.

The Stabilization Platform Protocol manual contains platform preparation details.

Before shooting the following points must be executed:

- Decide on the important parameters: focal length, stabilization mode, aperture, focusing, resolution, ISO, sharpness, digital zoom, etc.
- Meet the following special shooting conditions:
  - The target must be centered in the image.
  - The visible background behind the target must be uniform in color; we recommend using a uniform 18% grey.
  - The borders of the target must be parallel to the image borders.
  - The lighting must be uniform.

> **Note:** It is important to record of all the parameters and settings associated with each video or series of shots. Depending on the model, not all cameras record all the EXIF data, and if the measurements are to be used to compare two cameras, the recording conditions for the image files must be strictly identical. Generally, cameras do not record EXIF data for video files.

There are several ways to apply a motion to the camera. The recommended solution is to use a vibration platform that allows you to apply the same pre-recorded motion to the subject cameras. But even without this vibration platform, here are the steps that you must respect when shooting a video for the Stabilization measurement:

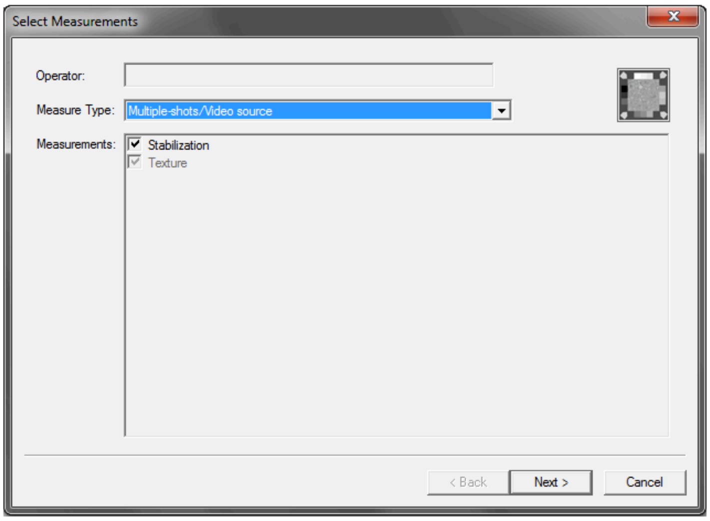
- Before starting recording the video, place the camera in front of the chart on a tripod.
- Focus on the chart and if possible, fix the focus by setting the camera to manual focus.
- During about the first five seconds of the video, the camera should stay on the tripod.
- After about five seconds, remove the camera from the tripod and continue the recording handheld for about 15 seconds.
- Make sure that the chart stays in the viewing field during the recording.

For the Photo Stabilization measurement, take the series of images at the same exposure time with the tested camera attached to the moving platform.

22.13 Launching Analyzer Stabilization measurement

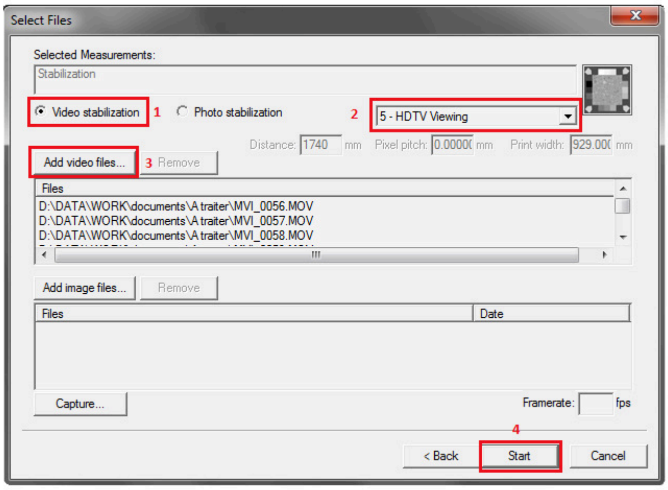
- Select the texture chart in the Analyzer chart menu.

- To select the Stabilization measurement, choose “Multiple shots/video source” in the Measure Type dropdown menu.

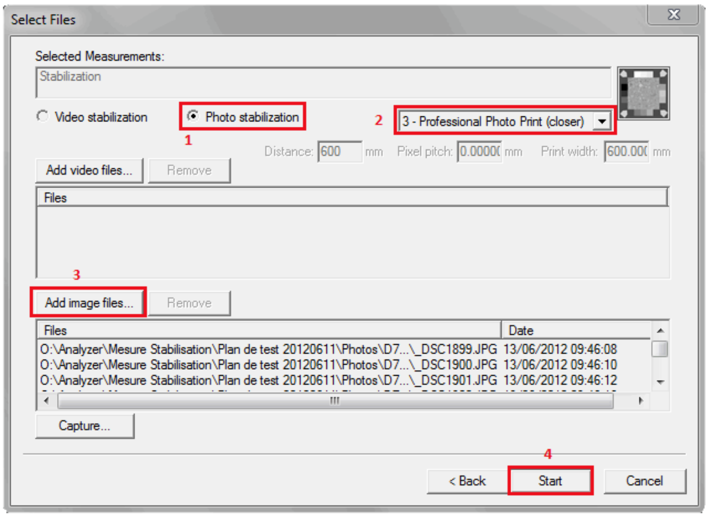


- To launch a Video Stabilization measurement on one or more video files:

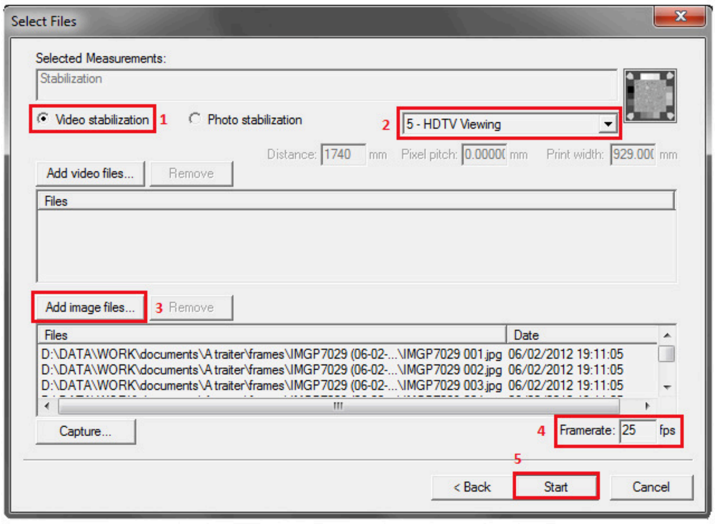
  1. Select "Video stabilization."
  2. Choose a use case (see the Texture Preservation Section 10 for more information about use cases).
  3. Select the video file(s).
  4. Click "Start." You can launch several video measurements on the same time using the same procedure described here.



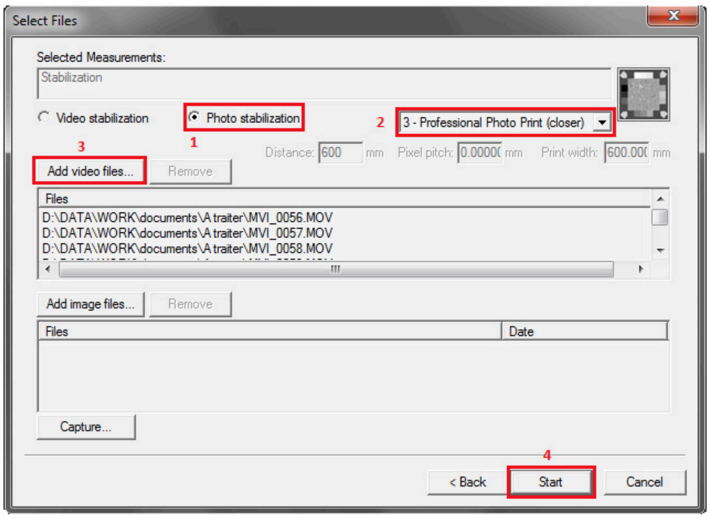
- To launch a Photo Stabilization measurement on a series of images, follow the procedure described above.



- To launch a Video Stabilization measurement on a series of images, select “Video stabilization,” choose a use case, select the images, enter an appropriate frame rate, and click “Start”.



- To launch a Photo Stabilization measurement on a video file, select “Photo Stabilization,” chose a use case, select the video file(s), and click Start. You can launch several video measurements on the same time (follow the same general procedure as for a series of video images, above).



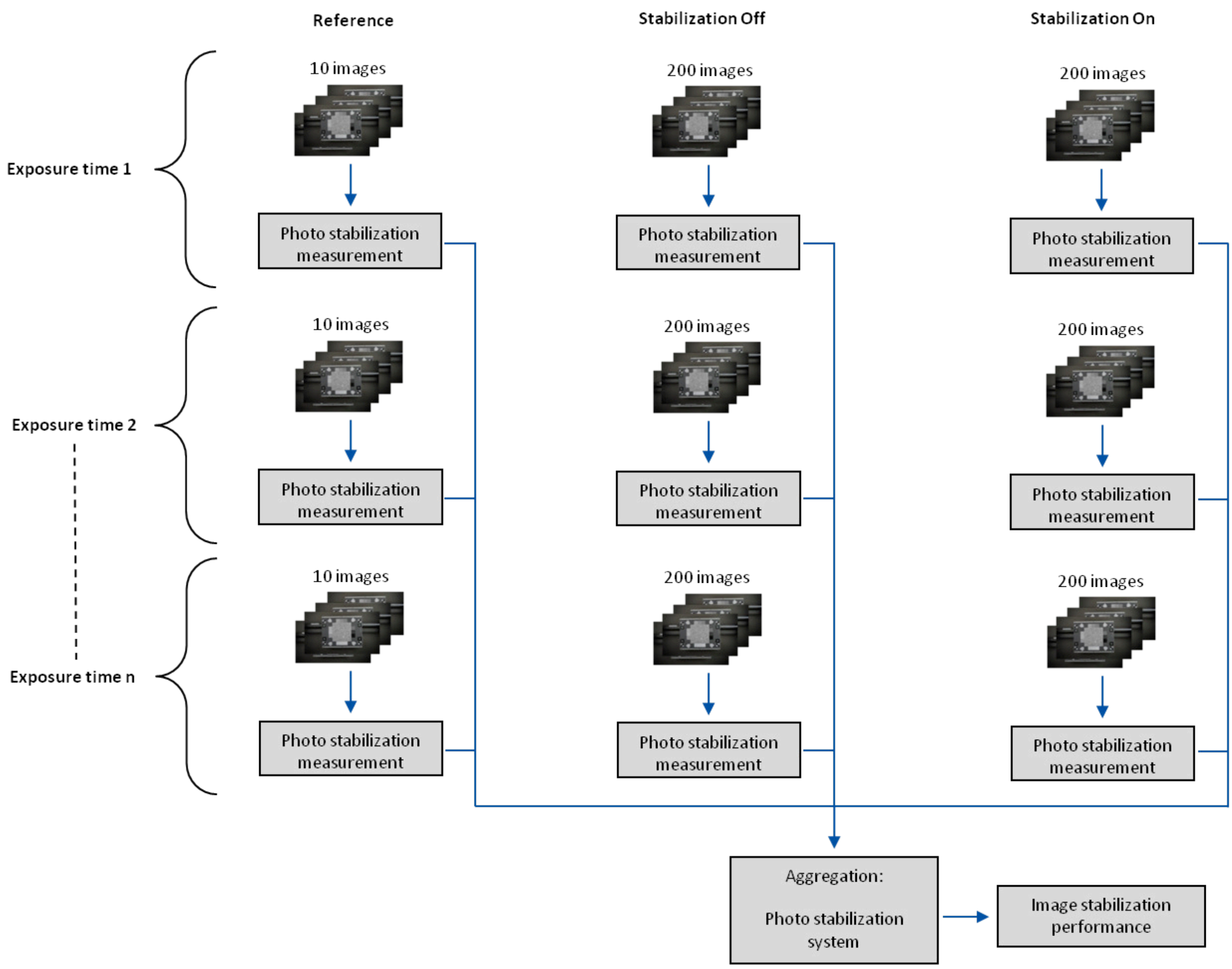
[1] CIPA Standard DC-X011-2012, Measurement and Description Method for Image Stabilization Performance of Digital Cameras (Optical Method),
http://www.cipa.jp/image-stabilization/documents_e/DC-X011-2012_E.pdf.

23 – STB aggregation: Photo Stabilization

23.1 Introduction

The purpose of a photo stabilization system is to enable the photographer to shoot images at longer exposure time than possible without stabilization because of the motion blur induced by natural shaking. This means that the performance of the system can be measured by the ratio of the exposure time with and without stabilization, for a given amount of motion blur. The STB measurement (Photo Stabilization measurement) computes the motion blur for a given configuration (exposure time, illumination level, stabilization on or off, etc.). Because of the statistical nature of the measurement, many shots (about 200) are necessary to output a single blur value. To evaluate the gain of the stabilization system, it is necessary to shoot several series under different shooting conditions and aggregate the results of each series in a single meta result. This is exactly what the “STB” aggregation does. It features a simple workflow of selecting the images taken under different conditions, or the results of previously-computed Stabilization measurements.

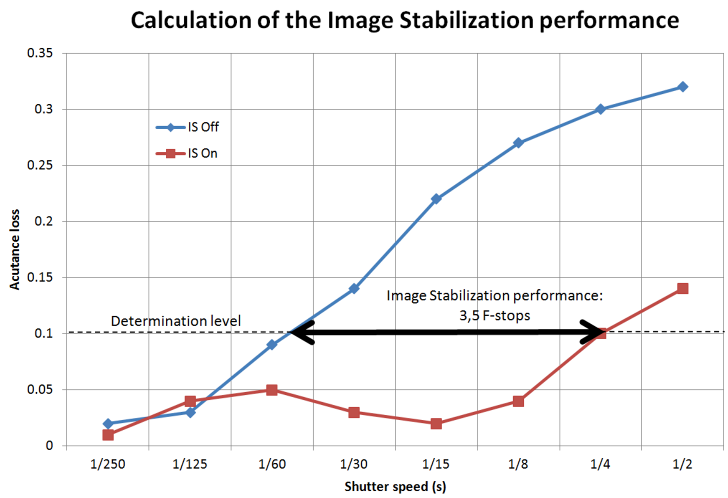
The following diagram illustrates the process.



This measurement is compliant with the CIPA standard draft DC-X011-2012 for the "measurement and description of an image stabilization system on digital cameras" [1].

23.2 Evaluating the image stabilization system performance

The gain in f-stop is the difference between the exposure time needed to stay under a certain amount of motion blur, with and without the stabilization system activated. The determination level corresponds to the lowest acutance loss that results in a noticeable motion blur compared to a sharp image — a level of 0.1. To compute this difference, you will need to take several series of images at different exposure times, with and without the stabilization system activated, plus a reference series. You must test least five shutter speeds split by one f-stop. The first shutter speed to be tested is the one equal to the inverse of the 24×36 mm equivalent focal length of the tested camera. (See the sub-section below about shooting protocols for further information.) With these shots, you will be able to plot the acutance loss for the shutter speed for each stabilization mode you test.



Calculation of the Image Stabilization performance. Without stabilization, the acceptable motion blur (0.1 acutance loss) is attained for exposure time 1/60 s. With stabilization, it is possible to use 1/4s exposure time. Therefore, the stabilization system gains 3.5 f-stops

The previous graph can be obtained when measuring the performance of the stabilization system on the Canon 15-85 IS USM at 50 mm mounted on a Canon EOS 600D. For this example, 9 exposure times were tested to show the general behavior of the curves, but 5 would have been enough. Since the sensor is an APS-C format, the 24×36 mm equivalent focal length is 80 mm. According to the rule-of-thumb in photography, the minimal exposure time to use in order to take a sharp image without stabilization is about 1/80 s.

If you correctly execute the shooting procedure, for each stabilization mode and each tested exposure time, you will have three series of images (one of at least ten images for the reference, and two others of 200 images). The measurements compute the acutance losses from the reference and the two other series, and will then calculate the image stabilization performance (in f-stops). These calculations use the temporal average of the average blur over the direction.

To perform the Aggregation measurement, you can use either series of images or the results of already-made photo stabilization measurements, giving you some flexibility in the workflow, especially when not enough exposure times were tested in the first place. In this case, you do not need to perform the Blur measurements again on the images for which it was already done, but only on the new images. The previous results can be used to save time.

As this measurement is based on the Photo Stabilization measurement, the influencing parameters, the measurement accuracy and the validity of the measurement are the same.

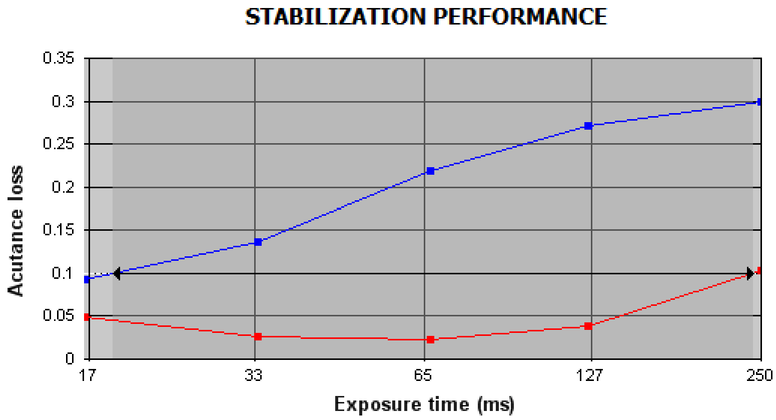
23.3 Analyzer output

The following data are returned for the CIPA Photo Stabilization measurement:

- The Summary tab contains three sections:
  - The first section gives the image stabilization performance in f-stops of the tested camera. This value is only meaningful for the focal length used for the tests.

	stops
Image stabilization performance	3.5

  - The second section shows the plots of the acutance loss values with respect to the exposure time (in seconds), with and without stabilization. The graph below highlights the gain of the stabilization system being tested.



  - The third part presents the acutance measured on the different series of images as well as the acutance loss values that have been used to generate the previous graph.

It also presents in a separate array the exposure times that cross the determination level (for series with IS both off and on).

	IS off (ms)	IS on (ms)
Exposure at acutance loss 0.1	18.65	242.43

Exposure time	Aperture	ISO	Acutance		Reference on mount	Acutance loss	
			IS off	IS on		IS off	IS on
16.67 ms	5.6	250	0.69	0.73	0.78	0.09	0.05
33.33 ms	5.6	125	0.64	0.75	0.78	0.14	0.03
66.67 ms	7.1	100	0.55	0.75	0.77	0.22	0.02
125 ms	10	100	0.47	0.70	0.74	0.27	0.04
250 ms	14	100	0.43	0.63	0.73	0.30	0.10

23.4 Measurement validity

The CIPA protocol strongly depends on the motion that is applied during the shooting. Therefore a measurement is meaningful only when associated with a given motion. Instead of saying that a stabilization system allows a gain of 2 stops, it should be said that a stabilization system allows a gain of 2 stops for a specified motion.

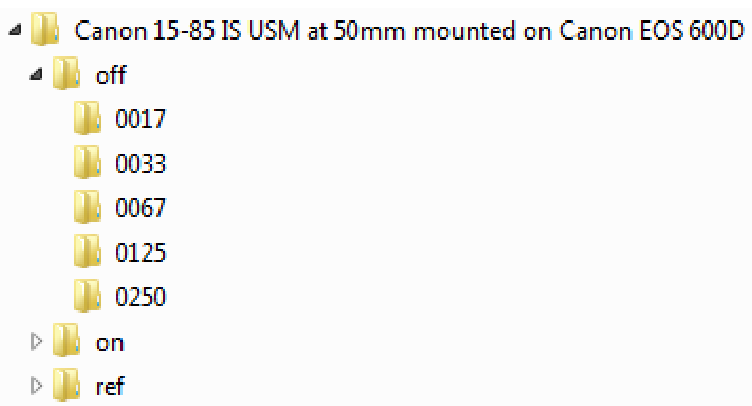
23.5 Shooting

To successfully perform the CIPA Photo Stabilization measurement, do the following:

- Set the shutter speed to the closest value of the inverse of the 24×36 mm equivalent focal length of the camera being tested.
- Reference series:
    1. Place the camera on the vibrating platform without applying any motion, or place it on a tripod in front of the chart.
    2. If possible, set the stabilization mode to “Off” (stabilization deactivated).
    3. Take at least 10 images, if possible with a remote control. The time between shots should be approximately 1 second.

- Off series (execute the following steps without stabilization):
  1. Apply a motion to the camera through the platform or hand-hold the camera in front of the chart.
  2. Take 10 images with a shooting interval of approximately 1 second. However, stop shooting after 30 seconds even if you have taken fewer than 10 images, and turn the camera off.
  3. Repeat the previous step until you have taken 200 images.
- On series (execute the following steps after activating the stabilization mode to be tested):
  1. Apply a motion to the camera through the platform or hand-hold the camera in front of the chart.
  2. Take 10 images with a shooting interval of approximately 1 second. However, stop shooting after 30 seconds even if you have taken fewer than 10 images, and turn the camera off.
  3. Repeat the previous step until you have taken 200 images.
- Repeat these three shooting series for each shutter speed to be tested (decreasing the shutter speed by one f-stop per set of series at most). We recommend testing at least 5 shutter speeds:
  – A shutter speed that approximately equals the inverse of the 24×36 mm equivalent focal length (for example 1/60 second for a 35 mm lens mounted on an APS-C DSLR).
  – A shutter speed 1 stop slower than the inverse.
  – A shutter speed 2 stop slower than the inverse.
  – A shutter speed 3 stop slower than the inverse.
  – A shutter speed 4 stops slower than the inverse.

Please keep in mind that the images have to be processed by series, so we strongly recommend that you carefully classify the images in your file system by series (Reference, Stabilization Off, and Stabilization On) and by shutter speed. The folders are named “Ref”, “Off,” and “On,” and each of these three folders will contain the subfolders with the images. These subfolders are named according to the shutter speed used to shoot the images they contain. Your directory should look like the one below:



Ideally, the aperture and ISO setting have to be as constant as possible, even if the shutter speed changes. Thus you will need a lighting setup with variable illuminance capability. However, for some optics, optical blur may not vary too much over a small range of apertures (for instance, from f/5.6 to f/8.0), so it is possible to use different apertures. In any case, you should carefully record the aperture that is used for each series, along with the testing conditions.

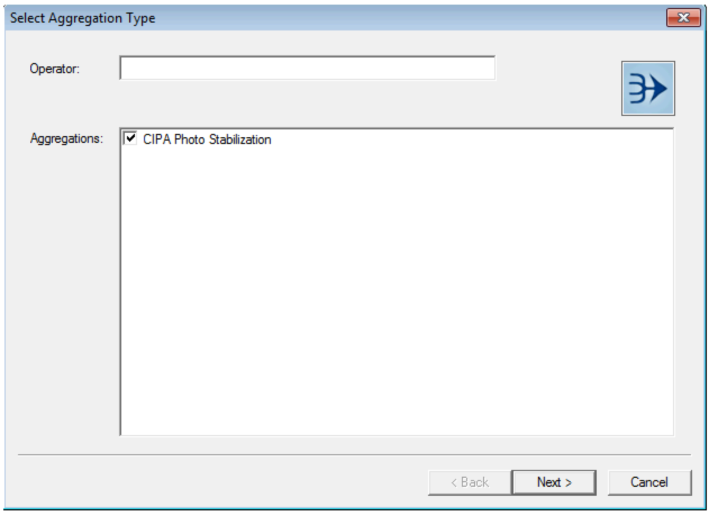
If it is not possible to set the shutter speed on the tested camera (on smartphones, for example), use a lighting setup with variable illuminance capability.

It is possible to launch the measurement with only the reference series and either the associated “stabilization off”or “stabilization on” series. The stabilization performance graph will be generated, but Analyzer will display a warning and will not compute a gain.

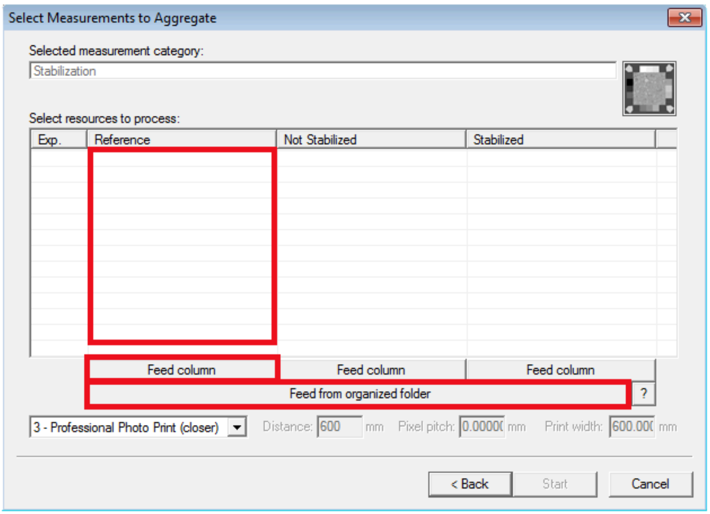
23.6 Launching the Analyzer CIPA Photo Stabilization measurement

- Select the aggregation button to the right of the Analyzer chart menu.

- Click “next” on the following window (CIPA Photo Stabilization is the only aggregation process currently available).



- To select the images or results you want to use for the measurement, you can either double-click in a column, or click on the “Feed column” button, or click on the “Feed from organized folder” button.



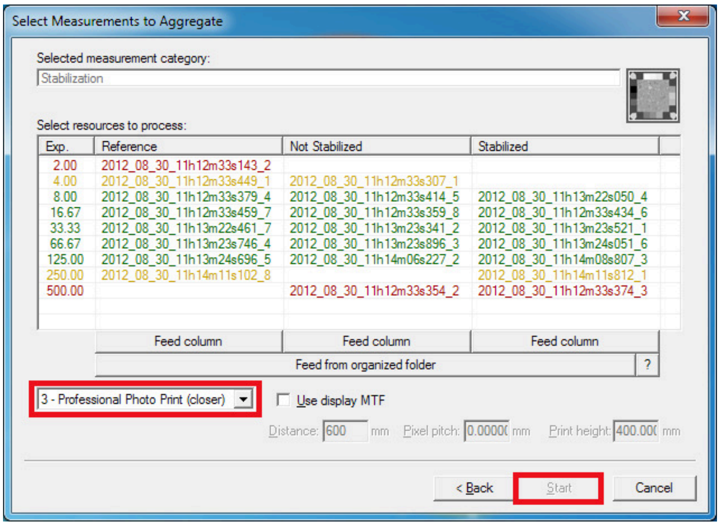
Double-clicking on just one column item, or clicking on the “Feed column” button, opens a new window where all the photo stabilization results available in the Analyzer browser are displayed and can be selected for the measurement.

Clicking on the “Feed from organized folder” button opens a browser that allows you to select a folder containing either images or photo stabilization results.

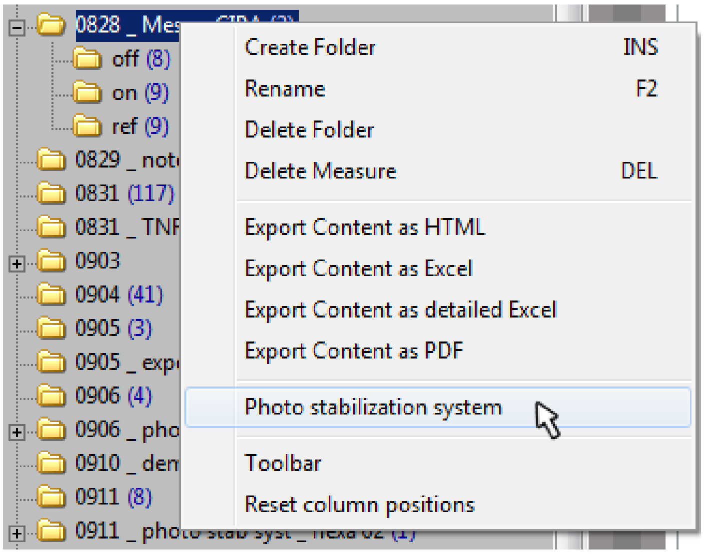
In any case, the results or series of images are sorted by exposure time. If the exposure time is not found in the EXIF data, you will need to enter the exposure time in (milliseconds) manually for each line.

- Once the selection is completed, a line appears in green if all of its fields are filled. When the reference and only one of the two other fields is filled, the line will appear yellow colored.

  If a reference is not filled or is the only field set, the line will appear in red and you will not be allowed to start the measurement unless one of the two other fields is set.



- Select a use case and click "Start".
- If a correctly-organized folder containing either images or results is available in the Analyzer browser, you can launch an aggregation directly by right-clicking on the folder.



[1] CIPA Standard DC-X011-2012, Measurement and Description Method for Image Stabilization Performance of Digital Cameras (Optical Method),
http://www.cipa.jp/image-stabilization/documents_e/DC-X011-2012_E.pdf.

24 – DS: Dark Signal

24.1 Introduction

The sensors of a digital camera collect photons and convert them into an electrical current. This current is analogically measured, then converted into a numerical value by an analog/digital converter and quantized, in general on 10 bits for camera phones and 12 bits on DSLRs.

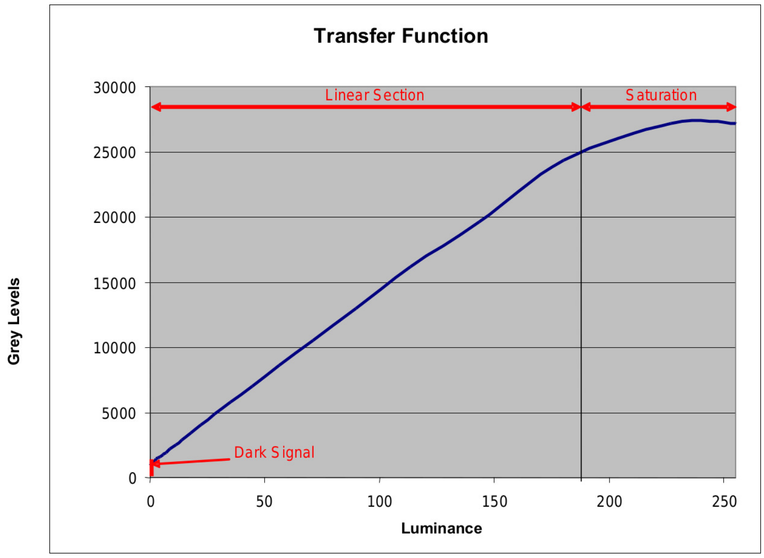
The response of the sensor as a function of luminance has the same shape for all usual sensors, as described in the next section. It is worth noticing that the RGB values after raw conversion are completely different (and measured by the Tone Curve measurement) and take many digital corrections into account. A particular phenomenon is that the current returned by a sensor is not null, even when the sensor is not illuminated at all. Thus, grey levels are defined up to an additive offset, called the dark signal.

24.2 Definitions

The pixel value of a raw image as a function of exposure is approximately a piecewise affine function of the exposure. This sensor response can be characterized by three values:

- The dark signal (or dark current): Even in the absence of any light, a sensor usually returns a non-null value. The main cause of the dark signal is the thermal noise and noise generated by the power supplied to the sensor.
- The saturation value: This is the maximum value the sensor can output. For 12-bit images, this value should be 4095, but occasionally some manufacturers do not use the whole possible dynamic range.
- The gain: The pixel value increases linearly with the luminance value between the dark signal and the saturation value. (This is actually an approximation, and the behavior might vary a little near the saturation value.) Hence, the pixel value is a piecewise affine function of the luminance. The slope of this line is the gain. Thus the gain determines the value of the luminance necessary to saturate the sensor. Determining the gain value depends on the exposure.

The dark signal is usually corrected before or during raw conversion. Indeed, it modifies the values of the RGB image, and uselessly wastes a part of the dynamic of the image, as well as introduces a bias in the vignetting correction, if it is not removed.



Response of a sensor as a function of the luminance

24.3 Influencing factors

The parameters that have an influence on the Dark Signal measurement are:

- ISO Gain,
- Ambient temperature.

24.4 Measurement of dark signal

Analyzer computes the response of the sensor as a function of luminance on the HDR Noise chart. The dark signal is defined as the value for an interpolated luminance value equal to 0. The luminance is normalized so that 100% corresponds to the saturation value.

Analyzer also outputs the whole profile of the pixel value for the R, G and B channels.

24.5 Measurement in raw format

The Dark Signal is measured only in raw format. It is worth noting that the profile of the response of the sensor to the luminance can also be obtained via the Tone Curve measure. However, the Tone Curve measurement aims at describing how a camera renders different lightings in the final RGB images, whereas the Dark Signal measurement is a characteristic of the sensor.

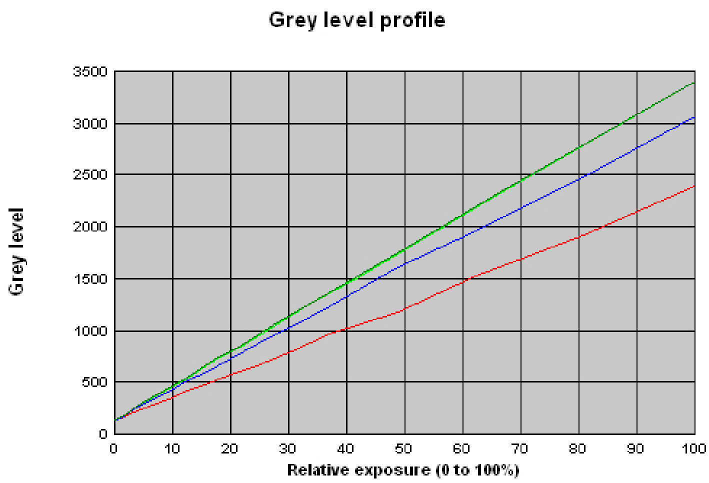
24.6 Analyzer output

Analyzer returns the following measures:

- The values of the dark signal in the R, Gr, Gb, B channels. It should be the same in every channel. It is expressed in grey levels and depends on the encoding of the image. For easier comparison, the result is also expressed in 8 bits equivalent encoding.

		Dark signal	
		(12 bits)	(8 bits eq.)
R	Red channel	128.94	8.06
G	Green channel	129.88	8.12
B	Blue channel	129.28	8.08
G	Green channel	129.89	8.12

- The grey level profile as a function of the relative exposure for the R, Gr, Gb, B. These profiles should be straight lines.



24.7 Measurement accuracy

The DS measurement accuracy is about 1%.

24.8 Shooting

The DS measurement uses the HDR Noise chart.

You will need the following materials to perform the measurement:

- A retro-lighting system producing homogeneous light.
- A tripod.
- A lens with as little vignetting as possible.

Retro-lighting must be the only illumination system during shooting. It must be clean. The target must be clean, particularly with no fingerprints.

The shooting conditions must be as follows:

- You have chosen an aperture that minimizes vignetting (small aperture).
- You have set the ISO speed to minimum to reduce noise as much as possible.
- The white balance is adapted to a retro-lighting illuminant.
- You have chosen an aperture and an exposure time that will saturate the first filter, in order to cover all the dynamic range of the sensor. However, no more than five filters should be saturated so that the dynamic range is covered as thinly as possible.
- The target is centered (to avoid vignetting problems), and must occupy the largest possible area in the image.
- The target is the only lighting source.

- The camera lens is focused on the target so that the image produced appears sharp.
- The target is orthofrontal to the camera.

24.9 Setup parameters influencing the measurement

- Vignetting
- Non-uniform lighting

24.10 Sidecar parameters

For a better Dark Signal measurement, you can indicate patch luminance. Without patch luminance, DS measurement output will not display the grey level profile.

If a Noise chart is used, 16 patch luminances should be given:

```
[DensityChart] // luminance of the HDR Noise chart patches section(cd/m2)
Patch1=1662
Patch2=1300
Patch3=1038
Patch4=773
Patch5=614
Patch6=466
Patch7=400
Patch8=296
Patch9=247
Patch10=188.4
Patch11=140.3
Patch12=52.8
Patch13=14.2
Patch14=1.1
Patch15=0.1
```

If a HDR Noise chart is used, 28 patch luminances should be given:

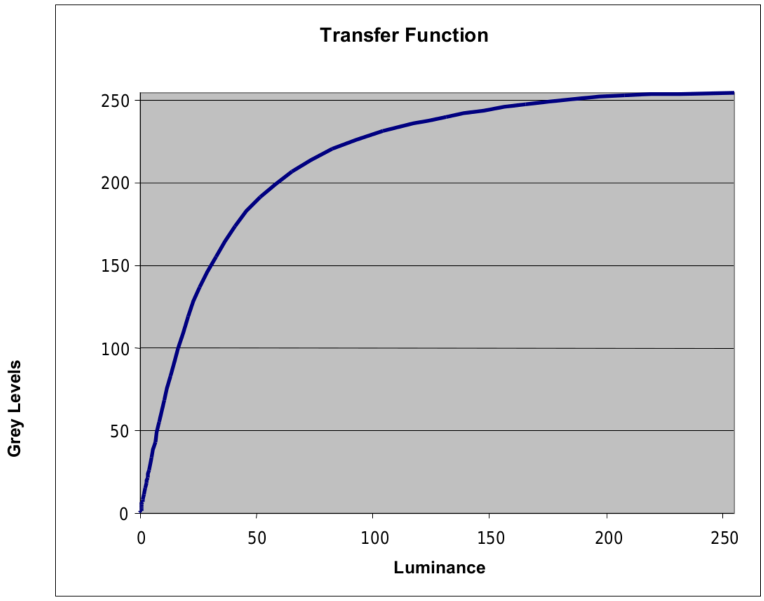
```
[DensityChart] // luminance of the HDR Noise chart patches section(cd/m2)
Patch1 = 5120
Patch2 = 3980
Patch3 = 3180
Patch4 = 2580
Patch5 = 1851
Patch6 = 1476
Patch7 = 1238
Patch8 = 1029
Patch9 = 872
Patch10 = 607
Patch11 = 443
Patch12 = 278
```

```
Patch13 = 176.7
Patch14 = 110
Patch15 = 63
Patch16 = 46.9
Patch17 = 31.8
Patch18 = 17.9
Patch19 = 11.6
Patch20 = 6.8
Patch21 = 3.3
Patch22 = 2.0
Patch23 = 1.6
Patch24 = 0.8
Patch25 = 0.6
Patch26 = 0.3
Patch27 = 0.1
Patch28 = 0.00512
```

25 – TC: Tone Curve

25.1 Introduction

The tone curve is a non-linear function applied to the input luminance values to convert them into grey levels. The digital value returned by a sensor is an approximate linear function of the received light (see Section 19). However, the raw conversion makes this response nonlinear. For the same difference in received charges, the corresponding difference in digital values differs significantly depending on the considered exposure level. The tone curve is also called the transfer function, or the Opto-Electronic Conversion Function (OECF). The ISO standard 14524 describes protocols and charts for measuring the tone curve.



Example of a transfer function (or tone curve)

The tone curve may generally be approximated by a "gamma 2.2" curve, which means that the relative digital value is equal to the number of charges to a power 1/2.2. The original purpose was to compensate the nonlinear response of CRT monitors, whose dark values are badly contrasted. This tone curve is integrated in the sRGB color standard. It is actually slightly different from a gamma curve; more precisely, the behavior of the curve for low values is linear so as to prevent a strong amplification of the noise for these values. Applying a tone curve to an image increases dark values, so that on common displays, digital values will seem to be a linear function of the number of charges.

As changing the tone curve changes the contrast in the resulting image, tone curves in cameras can be slightly different from gamma 2.2 curves depending on the manufacturer's choices. The tone curve can be adapted to fit a target contrast, for example, if a highly-contrasted image is wanted. Some cameras also allow users to choose a tone curve to apply from among a number of preset curves, such as normal, low contrast, high contrast, and so on.

Two RGB images coming from the same raw image; only the tone curves differ

25.2 Definitions

The tone curve is measured on RGB images, since it is a part of the raw conversion. It adapts to the dynamics of the sensor and the output device. Therefore, the values output by the tone curve are grey levels, usually encoded on 8bits (as, for instance, in the sRGB color space). Moreover, on RGB images, the tone curve takes the white balance into account. Thus the tone curves in the different color channels usually coincide or are very close to each other.

The dark signal value is taken into account, so that a null luminance produces a grey level equal to 0. However, the saturation value is not fixed, since it depends on the ISO sensitivity setting of the camera, or possibly on the applied gain for exposure correction. The luminance value necessary to saturate the sensor characterizes the ISO sensitivity of the camera (See Sect. 26), but is not part of the Tone Curve measurement. Only the ratio between the exposure and the saturation exposure is used for the Tone Curve measurement. Changing the sensitivity usually scales the tone curve uniformly, so that the tone curve is generally independent of the sensitivity.

25.3 Influencing factors

The parameters that have an influence on the Tone Curve measurement are:

- Exposure time and aperture: the image must respect the saturation conditions described below.
- Camera body parameters:
  - Curve of contrast: each contrast option (detailer) will correspond to a specific tone curve.
  - Sharpening must be OFF.
- Vignetting.
- Uniformity of illumination.
- White balance must be chosen according to the illuminant.

25.4 Measurement of the tone curve

Analyzer characterizes the tone curve by measuring the grey levels as a function of the number of charges received by the sensor, normalized by the number of charges necessary to saturate the sensor.

This measurement requires the HDR Noise chart, which is a transmission target with a large dynamic range (>13.3 Ev). This target must be set on a retro-lighting device.

The density of each target filter is known, and is used to compute the received number of charges. The density of a filter d, and the number of charges n, can be related by $n = k \cdot 10^{-d}$, k being a normalization constant corresponding to the luminance of the retro-lightning device. Let d_{sat} be the density necessary to saturate the sensor. (It depends on k.) The relative exposure is the ratio between the exposure and the saturation exposure, thus it equals $10^{d_{sat}-d}$ and belongs to the interval $(0, 1)$.

The value of d_{sat} is not exactly known, since it depends on the lighting device and the sensor's sensitivity. It is not possible to exactly measure it either, since it is very unlikely that a saturated patch exactly has a density equal to d_{sat}. Thus, the value of d_{sat} is interpolated.

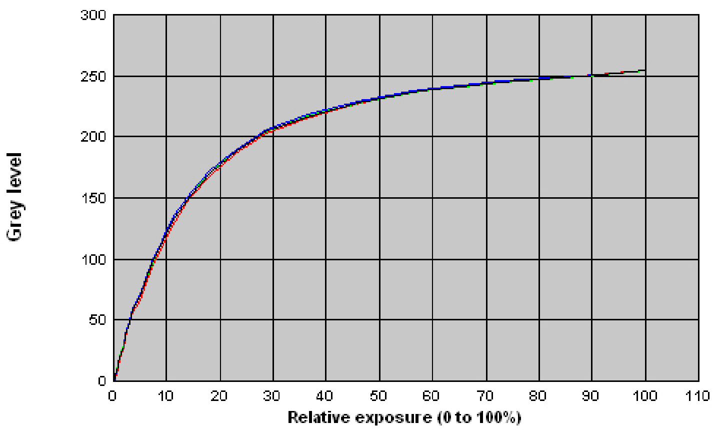
25.5 Measurement in raw format

The application of the tone curve is a part of the raw conversion, thus it makes sense for RGB images only. The response of the sensor to different exposures is given by the dark signal measurement (Sect. 19).

25.6 Analyzer output

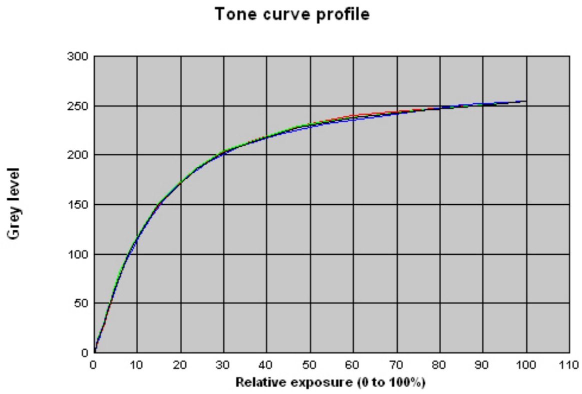
Analyzer returns the following data:

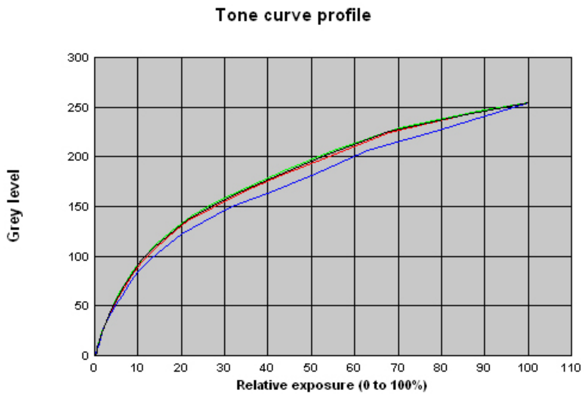
- The tone curve tab contains the response of the sensor in grey levels for the R, G, and B channels as a function of the exposure. The exposure is relative, which means that 0 corresponds to no lighting at all and 100 is the minimum exposure which is necessary to saturate the sensor.



25.7 Examples

The following two examples of tone curve are obtained on a DSLR (Canon EOS30D) and a camera phone. The aperture is f/6.3 and the exposure 40 ms.





The tone curves of the DSLR in the different color channels perfectly coincide, which is not the case for the camera phone. This difference between channels may be due to color vignetting (see Section 15). Moreover, it is worth noticing that the concavity is much stronger for the DSLR. For instance, observe that the exposure to obtain the grey level 150 is about 15% for the DSLR and between 25 and 30% for the camera phone. We can say that the DSLR is more sensitive than the camera phone at this level. (See Section 26 on ISO sensitivity).

25.8 Measurement accuracy

The saturation density value can be determined by interpolation. However, the variation of the grey level near the saturation value is pretty slow, and this interpolated value may differ between two measurements.

The maximum error can be evaluated as follows. Let assume that the tone curve is a gamma 2.2 curve. The grey level GL is obtained from the relative exposure x by the relation $GL = 255x^{1/2.2}$. Hence $\frac{dGL}{GL} = \frac{1}{2.2}\frac{dx}{x}$. At saturation, $x = 1$, by definition. Thus a relative error on the grey level equal to e yields an error on the saturation value of $2.2e$.

This induces possible horizontal scaling in the measured tone curve, but the shape does not change.

Repeatability of the Tone Curve measurement, with same normalization, is ±1.5 grey levels.

25.9 Set up parameters influencing the measurement

The following set-up parameters may influence the measurement of the tone curve:

- The ISO sensitivity setting changes the exposure necessary to saturate the sensor. Although the Tone Curve measurement uses a normalized exposure, different settings may yield different measures.
- Some cameras have different exposure modes, usually named “low contrast”, “normal contrast” or “high contrast”. They act directly on the tone curve.

25.10 Measurement validity

The measurement of the tone curve only makes sense if you give all the influencing parameters. More precisely, you must indicate the value of the exposure and the aperture, as well as the contrast mode (if one is available on the camera).

25.11 Comparing two cameras

Comparing the tone curves of two cameras only makes sense if grey levels are encoded with the same dynamic. This is always the case if the color space of the image is the same (for instance, sRGB). However, it is possible to compute the tone curve at any stage of the raw conversion, in which case the dynamic range of the images may differ.

Tone curves are normalized and it should be possible to compare them directly. However, the difference of two tone curves T_1 and T_2 at a given relative exposure x may not be the best way to compare two tone curves. Indeed, a small normalization error (that is, a small error in the evaluation of the saturation density) may yield a large difference, especially for low grey levels for which the slope of the tone curves are steep.

A better element of comparison is the geometric distance between the two curves. It can be approximated by

$$d(x) = \max\left(\frac{\left|T_1(x) - T_2(x)\right|}{\sqrt{1 + (T'_1(x))^2}}, \frac{\left|T_1(x) - T_2(x)\right|}{\sqrt{1 + (T'_2(x))^2}}\right).$$

The difference of tone curves may be interpreted in terms of sensitivity. (See Section 26).

25.12 Shooting

You will need the following materials to perform the measurement:

- The HDR Noise chart.
- A DMP viewer or any other retro-lighting system producing a homogeneous light.
- A tripod.
- A lens that produces as little vignetting as possible.

Retro-lighting must be the only illumination during shooting. It must be clean. The target must be clean, particularly having no fingerprints.

The shooting conditions must be as follows:

- The aperture is chosen so as to minimize vignetting (small aperture).
- The ISO speed is minimum so as to reduce noise as much as possible.
- The white balance is adapted to retro-lighting.
- You have chosen the aperture and exposure time to saturate the first filter, in order to cover all the dynamic range of the sensor. However, no more than five filters should be saturated so that the dynamic range is covered as thinly as possible.
- The target is centered (to avoid vignetting problems), and must occupy the largest possible area in the image.
- The target is the only lighting source. Use black material to shield any other light that may come from walls, ceiling, floor, etc.
- The camera lens is focused on the target, so that the image produced appears sharp.
- The target is orthofrontal to the camera.
- Lighting is uniform on the target.

25.13 Sidecar parameters

For a better Tone Curve measure, you can indicate patch luminance.

If a Noise chart is used, 16 patch luminances should be given:

```
[DensityChart] // luminance of the Noise chart patches section(cd/m2)
Patch1=1662
Patch2=1300
Patch3=1038
Patch4=773
Patch5=614
Patch6=466
Patch7=400
Patch8=296
Patch9=247
Patch10=188.4
Patch11=140.3
Patch12=52.8
Patch13=14.2
Patch14=1.1
Patch15=0.1
```

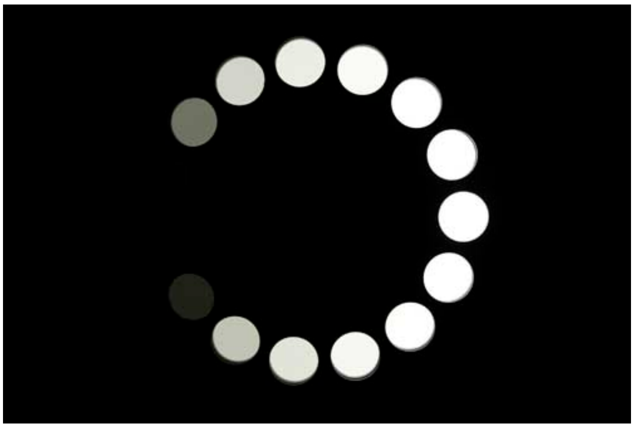
If a HDR Noise chart is used, 28 patch luminances should be given:

```
[DensityChart] // luminance of the HDR Noise chart patches section(cd/m2)
Patch1 = 5120
Patch2 = 3980
Patch3 = 3180
Patch4 = 2580
Patch5 = 1851
Patch6 = 1476
Patch7 = 1238
Patch8 = 1029
Patch9 = 872
Patch10 = 607
Patch11 = 443
Patch12 = 278
Patch13 = 176.7
Patch14 = 110
Patch15 = 63
Patch16 = 46.9
Patch17 = 31.8
Patch18 = 17.9
Patch19 = 11.6
Patch20 = 6.8
Patch21 = 3.3
Patch22 = 2.0
Patch23 = 1.6
Patch24 = 0.8
Patch25 = 0.6
Patch26 = 0.3
Patch27 = 0.1
Patch28 = 0.00512
```

26 – ISO: ISO Sensitivity

26.1 Introduction

ISO sensitivity is the ability of a sensor to provide a defined grey level for a given lighting. This information is used by photographers to determine the nominal exposure conditions. If the ISO sensitivity of the sensor is lower than the sensitivity fixed by the user, the image is underexposed. On the other hand, if the sensitivity is greater, the image is overexposed. Moreover, in order to be easily understood by photographers, the ISO sensitivity of a digital camera has been defined such that it is similar to the ISO sensitivity of photographic film cameras. Lower sensitivities require longer exposure for the same luminance, to produce the same result. On the other hand, very sensitive films were known to be very grainy. A parallel can be drawn for digital cameras, since high sensitivities are usually related to high gain and noise amplification.



Density Chart well exposed

26.2 Definitions

ISO sensitivity (also known as ISO Speed) is a numerical value calculated from the exposure provided at the focal plane of a digital camera to produce specified camera output signal characteristics.

The ISO standard 12232 defines two ways to measure the ISO sensitivity. The first one relates the sensitivity to the exposure necessary to saturate the camera. The second one compares the relative exposures to obtain different signal-to-noise ratios. As Analyzer implements only the saturation-based method, we will focus only on it.

Knowing the scene luminosity, the aperture, the exposure time and the reflectance of a target, we can determine the mean focal plane exposure (H_a) in lux seconds as follows:

$$H_a = \frac{65 \cdot L \cdot t}{100 \cdot A^2}$$

with

L: Luminosity of the scene (cd/m^2)

t: Exposure time (s)

A: Aperture (f-Number)

The saturation luminance H_{sat} is defined as the luminance which is necessary to attain the sensor saturation. This value is computed by interpolation, since the reflectance of patch charts is always more or less quantized (The thinner the quantization, the more accurate the interpolation). The ISO sensitivity is then defined by

$$S_{\mathrm{sat}} = \frac{78}{H_{\mathrm{sat}}}$$

The values reported by manufacturers are not very accurate and are always quantized. The ISO standard 12232 gives the following quantization table. Note that this table allows a relative error between 20% and 25%.

Value of S_{sat}	Reported value
$80 < S_{sat} \leq 100$	100
$100 < S_{sat} \leq 125$	125
$125 < S_{sat} \leq 160$	160
$160 < S_{sat} \leq 200$	200
$200 < S_{sat} \leq 250$	250
$250 < S_{sat} \leq 320$	320
$320 < S_{sat} \leq 400$	400
$400 < S_{sat} \leq 500$	500
$500 < S_{sat} \leq 640$	640

Value of S_{sat}	Reported value
$640 < S_{sat} \leq 800$	800
$800 < S_{sat} \leq 1000$	1000
$1000 < S_{sat} \leq 1250$	1250
$1250 < S_{sat} \leq 1600$	1600
$1600 < S_{sat} \leq 2000$	2000
$2000 < S_{sat} \leq 2500$	2500
$2500 < S_{sat} \leq 3200$	3200
$3200 < S_{sat} \leq 4000$	4000
$4000 < S_{sat} \leq 5000$	5000

26.3 Influencing factors

The primary factors influencing the ISO sensitivity are:

- Exposure time
- Aperture

Moreover, these two parameters are complementary. Indeed, the ISO sensitivity depends only on the amount of light received by the sensor. Doubling the exposure time while reducing the aperture by two (that is, by −1 EV) leads to the same amount of light hitting the sensor.

26.4 Measurement of ISO sensitivity

26.4.1 Saturation based ISO sensitivity

Following the ISO standard 12232, Analyzer provides a measurement of the ISO sensitivity which is an implementation of the saturation-based speed method. It consists in determining the scene luminance that saturates the sensor.

To compute the luminance that reaches saturation, a picture of a chart with several luminances (such as the HDR Noise chart) is acquired by the camera. The luminance of the patches must be measured on the target with a Luminance-meter and entered in a sidecar file (see Section 4.6 for information on sidecar files).

The X-Rite ColorChecker® classic chart can also be used but with less accuracy. In that case, the illumination is measured on the target with a Luxmeter.

From non-saturated patches, it is possible to compute the grey level as a function of luminosity. The luminosity attaining the saturation grey level is interpolated. The calculation described in the previous section gives the saturation ISO sensitivity.

26.4.2 Grey level ISO sensitivity

Analyzer also provides a new measurement called the grey level ISO. For a grey level x, produced by a luminance L, we define ISO(x) as the ISO sensitivity that would be measured if the sensor Tone Curve (see Section 25) were a usual gamma 2.2 curve, passing through the point with coordinates (L, x).

Therefore, if the Tone Curve is actually a gamma 2.2 curve, ISO(x) does not depend upon x and coincides everywhere with the usual ISO speed at saturation.

26.4.3 Interest of the measure

The ISO sensitivity (as given by ISO standard 12232) is proportional to the gain that must be applied to reach the sensor saturation. Thus a high ISO sensitivity usually implies a better luminance recovery, but also larger noise amplification, and a saturation of the sensor for a smaller illumination. Photographers know that films with ISO sensitivity 400 saturate for outdoor scenes with bright daylight.

As suggested in the definition above, the tone curve concept has to be strongly related to the ISO speed. For historical reasons, because of the nonlinearity of CRT monitors, usual tone curves have been close to a gamma 2.2 function, and the sRGB color space integrates this nonlinearity. The saturation luminance of the curve is a free parameter which is precisely related to the nominal ISO speed. By adjusting this parameter, you can choose to saturate or not saturate bright parts of an image (for instance, the sky in outdoor scenes).

However, the most essential parts of a scene do not have a grey level close to the saturation level, but rather closer to a target exposure value (basically the mean value of the image), which is about 50–55%

of the maximum dynamic. If the scene contains a very bright background and a darker subject, the usual gamma 2.2 tone curve may not allow the production of both a non-saturated background and a suitably-contrasted subject.

Hence the manufacturer may choose to bias this tone curve and enhance the subject to make it closer to the target exposure, making the sensitivity different for each grey level. Therefore the value of the sensitivity is more important around those values than those closer to the saturation value.

26.4.4 Relation with the tone curve

We denote the tone curve by $T(L)$, that is the grey level produced by a luminance equal to L, and GL_{sat} the saturation grey level (usually 255). Inversely, $T^{-1}(x)$ denotes the luminance which is necessary to produce a grey level x. The ISO sensitivity at grey level x is related to the ISO (as given by the ISO standard 12232) by the formula

$$\mathrm{ISO}(x) = \mathrm{ISO} \cdot \left(\frac{x}{GL_{sat}}\right)^{2.2} \cdot \frac{T^{-1}(GL_{sat})}{T^{-1}(x)}$$

Notes:

- If the tone curve is indeed a gamma 2.2 curve, then $\mathrm{ISO}(x) = \mathrm{ISO}$ for all grey level value x.
- If $x = GL_{sat}$, then obviously $\mathrm{ISO}(x) = \mathrm{ISO}$.
- For notation simplicity, the argument of T is not normalized with respect to the saturation luminance, as in Section 25. However, this normalization is equivalent to multiply T^{-1} by a constant factor. Hence the expression of $\mathrm{ISO}(x)$ remains unchanged.

26.5 Measurement in raw format

In raw format, the grey level is approximately a piecewise linear function of the luminance. (See the sections on Tone Curve and Dark Signal). Thus it is easier to determine the saturation luminance in raw format, since it is not subject to the flatness problems of the tone curve when close to the saturation value. The grey level ISO is also computed by assuming that the grey level is an affine function of the luminance.

It is worth noting that the ISO sensitivity in raw and RGB formats are usually different. Indeed, grey levels in

RGB images depend on the digital gain, as does the ISO sensitivity. In this case, the raw sensitivity is much smaller in raw than in RGB.

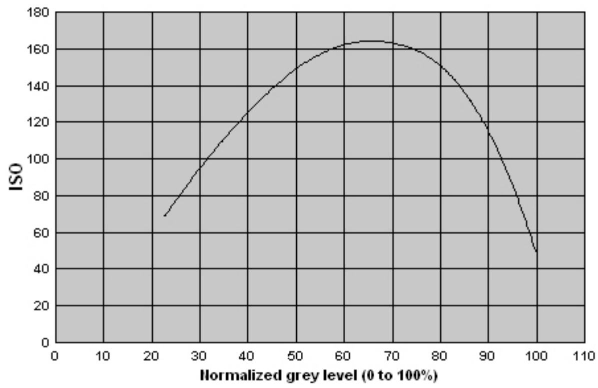
26.6 Analyzer output

Analyzer returns the following values:

- The Summary tab reports the saturation ISO sensitivity (as specified by the ISO standard 12233), the maximum ISO grey level sensitivity, and the grey level sensitivity at relative exposure 50%.

Saturation ISO sensitivity	48.3
Maximal ISO sensitivity	164.1
Saturation at 50%	148.9

- The ISO sensitivity tab displays the grey level ISO sensitivity.



26.7 Measurement accuracy

The repeatability of the measurement is ±2% for the same aperture, exposure time, and ISO.

The error is greater (±10%) for images taken with the same aperture but with a different exposure time. It also turns out that the exposure time written in the image EXIF file is not the precise exposure time.

Changing the exposure time and the aperture may lead to an error up to 20%, due to the inaccuracy of the aperture.

26.8 Measurement scale

The ISO sensitivity at the saturation value is not a quality factor of a digital camera in itself. However, it allows you to determine the gain or the luminance to apply, so that the brightest parts in the image attain the saturation level. Shooting an indoor image at low sensitivity requires a long exposure, a static scene, and a stabilizer to avoid motion blur. On the other hand, high sensitivity requires shorter exposure but produces more noise.

26.9 Setup parameters influencing the measurement

The measurement can be influenced by the variation of the lighting due to the frequency (50/60 Hz) of the power supply. This effect can be almost cancelled out with exposures longer than a few multiples of the current period.

26.10 Measurement validity

An isolated value of ISO sensitivity is not meaningful, since it is necessary to associate it with the influencing parameters. For example, claiming that the ISO sensitivity of a camera is 100 is meaningless. On the other hand, it is meaningful to indicate that a camera has an ISO sensitivity of 200 under a 700 lux lighting, with an aperture of f/6 and an exposure of 1/100 s.

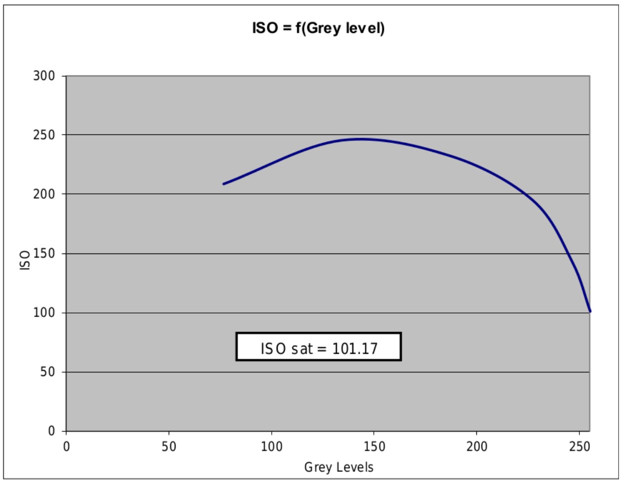
Moreover, if the reference grey level is not the saturation level, then you should also indicate the grey level and the ISO sensitivity at the saturation grey level.

26.11 Comparing two cameras

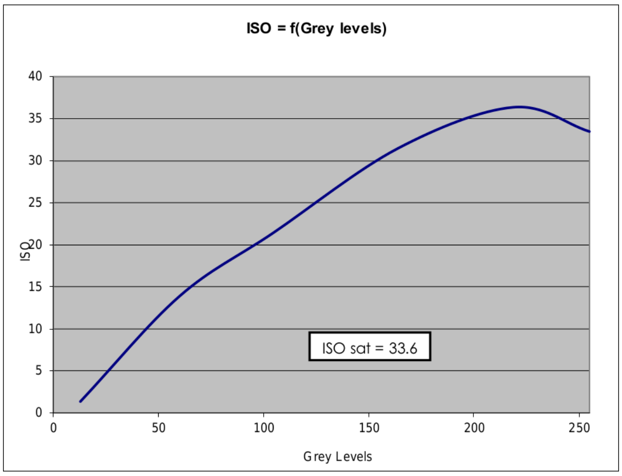
Classically, the ISO value at saturation of two different cameras tells which camera saturates first when luminance increases.

Now, assume that two cameras have the same saturation ISO sensitivity. Obviously, they may not have the same contrast rendering, due to different tone curves. This can be interpreted in terms of grey level ISO. Assume that $ISO_1(x) \geq ISO_2(x)$ for all grey levels around the target exposure. Then, the first camera is more sensitive and keeps a higher exposure in mid-grey levels areas. Noise amplification is also higher than for the second camera. However, since cameras are often evaluated on the SNR, this also usually means that the manufacturer sufficiently trusts the sensor and can have a better exposure.

Consider for example, the ISO curves of the following figures:



Canon EOS 30D - Sigma 70–200 mm f2.8 - EX HSM
ISO 100 Luminosity = 2970
Aperture = f/11.0 Exposure Time = 1/1.7 s



Camera Module 2 Mpix on MI2010 sensor
ISO: 50 Luminosity: 736 lux
Aperture: 2.8 Exposure time: 175 ms

The graph on the left corresponds to a dSLR camera and the graph on the right to a camera phone.

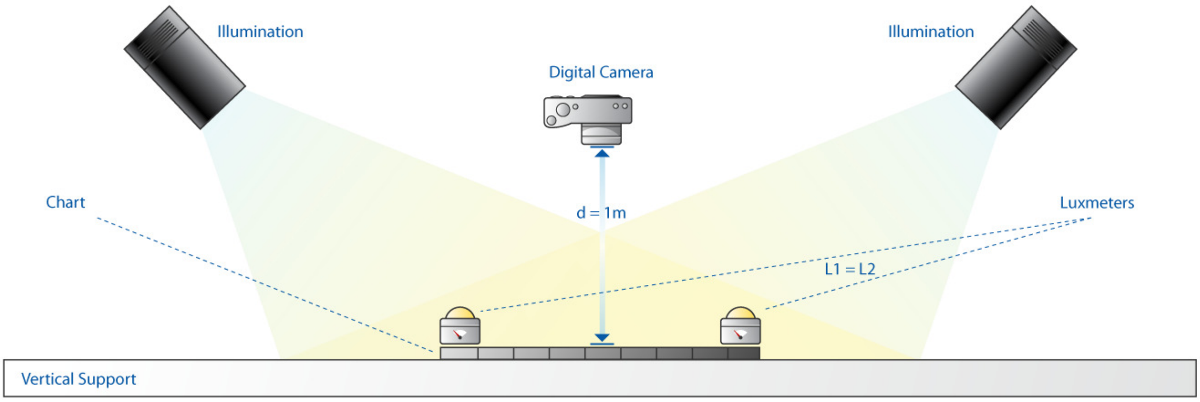
The DSLR has a nominal ISO 100. Thus the exposure time and the aperture necessary to saturate the sensor correspond to an ISO speed of 100. Typical outdoor scenes do not saturate the sensor. However, the ISO speed around the target exposure is close to 250. This means that this camera can avoid saturating a bright background while also keeping good contrast in the foreground. The price to pay is the amplification of noise in the mid-grey levels, since the noise intensity is higher than it should be with a standard gamma 2.2 tone curve. However, noise is generally not the most important problems for a DSLR (especially for bright outdoor scenes), so this curve clearly shows a deliberate choice by the manufacturer.

On the other hand (as shown on the right), the camera phone ISO speed is everywhere lower than the nominal ISO value of 33, meaning that in order to tightly control the noise level at ISO 33, the manufacturer underexposes the images.

26.12 Shooting

You need the following hardware to perform the ISO measurement:

- A tripod for a stable shooting.
- The HDR Noise chart.
- A luxmeter.
- A lightmeter.



Measuring the luminance of the X-Rite ColorChecker® Classic

Follow these steps to set up your equipment for ISO Sensitivity measurement on a X-Rite ColorChecker® classic chart:

1. Set the camera on the tripod.
2. Set the uniformly-lit chart 1 m away from the camera.
3. Measure the luminosity on the white patch and on the black patch. The two values should be as close as possible.
4. Set the ISO sensitivity or gain.
5. Set the aperture of the lens.
6. With a lightmeter, determine a suitable exposure time.

7. Set the exposure time and check that the Ev-bias is equal to 0.
8. Shoot.

You can look at the DS shooting protocol (see Section 24.8) for setting up your equipment for a measurement on the HDR Noise chart. Measurements on this chart will be more accurate.

If the white patch of the chart is not saturated, increase the exposure time and shoot gain until saturation.

26.13 Sidecar parameters

These two parts are necessary for a good ISO measurement. If you do not provide them, Analyzer generates an error.

If a Noise chart is used, 16 patch luminances should be given:

```
[Iso]              // ISO sensitivity section
Aperture=...       // Aperture to compute ISO sensitivity
ShutterSpeedMs=... // Shutter speed in ms to compute ISO sensitivity

[DensityChart] // luminance of the HDR Noise chart patches section(cd/m2)
Patch1=1662
Patch2=1300
Patch3=1038
Patch4=773
Patch5=614
Patch6=466
Patch7=400
Patch8=296
Patch9=247
Patch10=188.4
Patch11=140.3
Patch12=52.8
Patch13=14.2
Patch14=1.1
Patch15=0.1
```

If a HDR Noise chart is used, 28 patch luminances should be given:

```
[Iso]              // ISO sensitivity section
Aperture=...       // Aperture to compute ISO sensitivity
ShutterSpeedMs=... // Shutter speed in ms to compute ISO sensitivity

[DensityChart]     // luminance of the HDR Noise chart patches section(cd/m2)
Patch1 = 5120
Patch2 = 3980
Patch3 = 3180
Patch4 = 2580
Patch5 = 1851
Patch6 = 1476
Patch7 = 1238
Patch8 = 1029
```

```
Patch9 = 872
Patch10 = 607
Patch11 = 443
Patch12 = 278
Patch13 = 176.7
Patch14 = 110
Patch15 = 63
Patch16 = 46.9
Patch17 = 31.8
Patch18 = 17.9
Patch19 = 11.6
Patch20 = 6.8
Patch21 = 3.3
Patch22 = 2.0
Patch23 = 1.6
Patch24 = 0.8
Patch25 = 0.6
Patch26 = 0.3
Patch27 = 0.1
Patch28 = 0.00512
```

27 – HDR: High Dynamic Range

27.1 Introduction

The aim of high dynamic range (HDR) photos is to capture, store, and represent scenes with higher dynamic range than a camera's sensors, printing, and screening devices are capable of supporting.

The first step is to capture the whole dynamic of the scene. To do so, most HDR techniques use a multi-image fusion algorithm, which can be either temporal (meaning that we fuse photos taken at different times) or spatial (meaning that the original photos are taken using sensors placed in different locations). But image fusion can create many artifacts in the image, such as ghosting and noise inconsistencies.

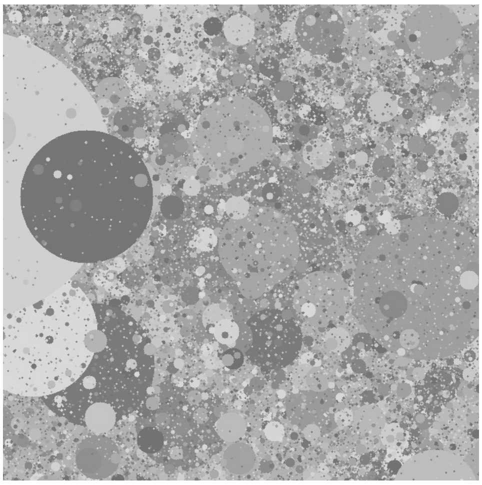
Example of noise inconsistency. Notice how the noise in the sweater is much bigger than in the surrounding areas

The next step after capturing a HDR image is to map it onto a low-dynamic range space in order to print or display it on-screen. While it's not hard to find natural scenes with a dynamic range of more than 13 stops, classic supports (computer screens, domestic printers) can represent scenes with contrast of only about

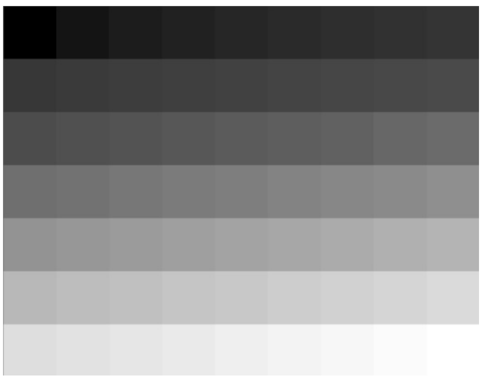
1:100 (6.6 stops). Adapting to this limitation is done by **tone mapping** techniques, which can act on a local scale, changing important aspects of the image across its dynamic range, such as the colors, the texture, and the contrast.

The HDR measure computes different metrics from high-dynamic scenes to determine the quality of the image processing used by the camera to generate HDR images. These metrics are:

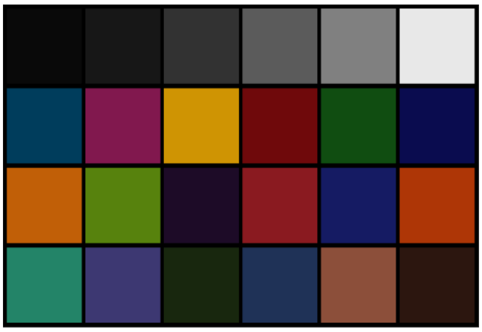
Texture: Texture Preservation is an important measure for HDR photos. A good camera should be able to preserve texture in every region of a high-dynamic scene. We use a dead leaves target to analyze texture, following a procedure similar to that explained in Section 10 (TEX: Texture Preservation and Visual Noise).



Local contrast preservation: Preserving contrast is one of the main challenges of tone mapping techniques. Good tone mapping should be able to preserve the contrast in all regions of a scene. The local contrast preservation is then computed for several areas of the high-dynamic scene, using greyscales composed of 63 grey patches:



Color metrics: In a high-dynamic scene, a camera can represent colors differently depending on if they are located in the bright or in the dark portion of the image. We use a chart similar to the X-Rite ColorChecker® classic to check the color consistency:



27.2 Definitions

27.2.1 HDR texture acutance

For this HDR measurement, we compute an acutance using a transmission chart. We compute this acutance, hereafter called *HDR texture acutance*, similarly to the way we measure Texture acutance (as presented in Section 10 (TEX: Texture Preservation and Visual Noise); however, some important differences exist.

First, the HDR texture acutance is computed using a different chart that is printed using different technologies, and illuminated with different lighting systems. This alone is enough to result in difference to the values of the HDR texture and Texture acutance measurements. However, the most important difference comes from one hypothesis pertaining to the Texture measurement that no longer holds true under these testing conditions.

For texture acutance, we've assumed that the camera applied the same tone curve across all of the image, meaning that we could make an estimation of the inverse tone curve. This inverse tone curve was essential for the computation of the texture acutance because we needed to pass the image into a linear space.

Now, however, the camera won't simply apply a unique tone curve across all of the image, but will use complex local tone mapping algorithms. This means that even after linearizing the image using our estimation of the tone curve, the texture area won't necessarily be linearized. This in turn means that the HDR texture acutance can't be directly compared as in the case of the Texture measure, but rather needs to be put in a larger context to allow correct interpretation.

For example, if two cameras (A and B) apply exactly the same tone curve to the non-texture areas, but camera B applies a more contrasted tone curve in the texture area than camera A, then camera B will have a higher HDR texture acutance. This means that the HDR Texture acutance measurement does not just measure Texture Preservation as such, but also measures Texture Preservation within its surrounding context.

27.2.2 Entropy

Entropy is a single-value metric computed from the HDR chart that measures the local contrast preservation in a given part of the scene, and represents the quantity of information contained in it. Large values for entropy mean that the given part of the scene has a good contrast.

The value for entropy is given in bits, and the maximum possible value for an 8-bit JPEG is 8 bits. The entropy of a given crop of an image is given by computing its histogram and using the formula:

$$\mathrm{Entropy}_{gs} = \sum_{K} \mathrm{hist}_{gs}(K) \log \frac{1}{\mathrm{hist}_{gs}(K)}$$

Where hist_{gs} is the histogram of the grey levels and K the grey level (from 0 to 255)

In the context of the HDR measure, entropy is computed using a greyscale of 63 grey patches.

27.2.3 Color Consistency

Color consistency is a single-value metric related to the device's capability of reproducing the same color between two photos, especially between a low-dynamic scene and a high-dynamic scene. In order to compare colors between images with different contrast, this measurement performs an exposure compensation processing so as to compare only the color of the patches.

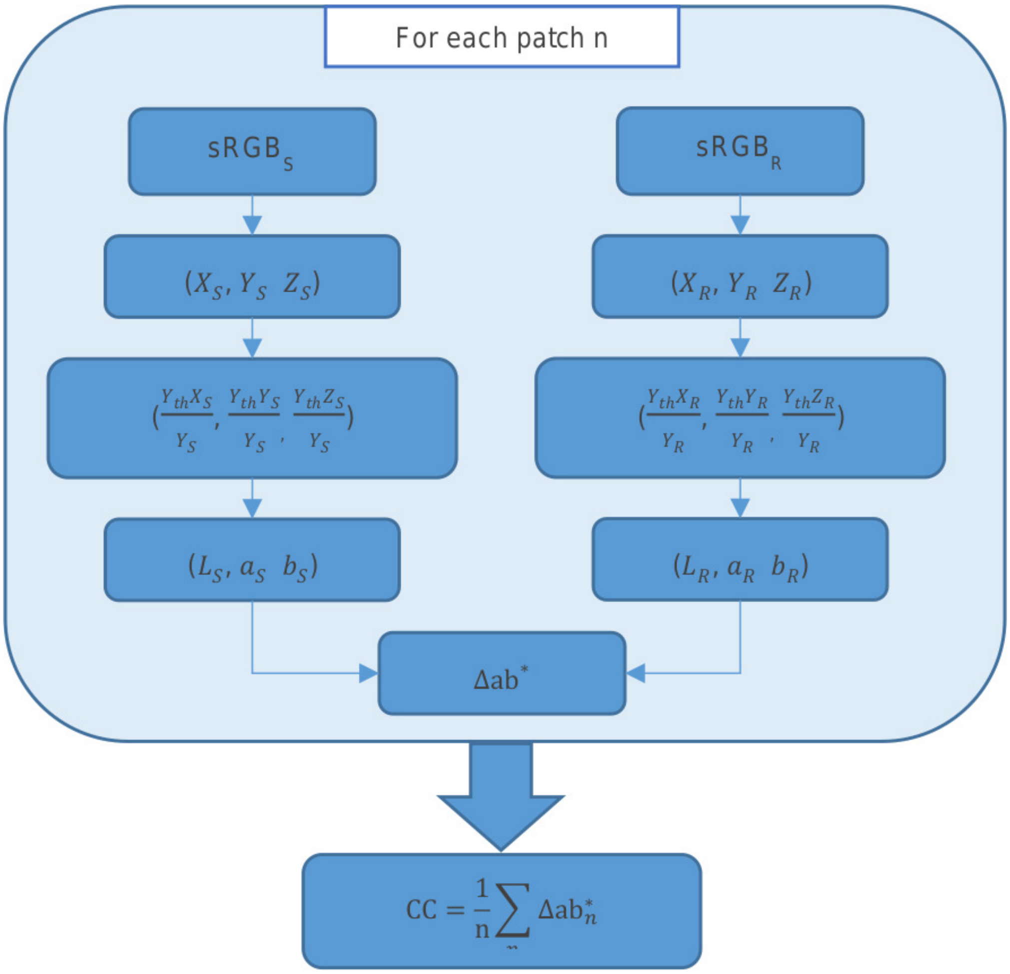
Suppose we want to compute the color consistency between two photos, a sample S and a reference R. In each photo, we have a set of n uniform patches. We also know the theoretical value of those patches. The first step is to convert the photos from whichever color space they use into the *CIE 1931 XYZ color space*. We then compute the mean value of each patch in this color space. For each photo and for each patch, we compute the ratio between the patch luminance (Y) and the theoretical patch luminance (Y). We perform the exposure correction by multiplying all three channels from the *XYZ color space* by the computed ratio. For example, for each patch in our two photos S and R, using the *sRGB color space*, we have:

Original patch	sRGB$_S$	sRGB$_R$
Patch in XYZ colorspace	(X_S, Y_S, Z_S)	(X_R, Y_R, Z_R)
Patch after exposure correction	$\left(\frac{Y_{th}X_S}{Y_S}, \frac{Y_{th}Y_S}{Y_S}, \frac{Y_{th}Z_S}{Y_S}\right)$	$\left(\frac{Y_{th}X_R}{Y_R}, \frac{Y_{th}Y_R}{Y_R}, \frac{Y_{th}Z_R}{Y_R}\right)$

After this exposure correction, we convert the value into the *CIE L*a*b* color space*. For each patch we then compute the *Δab** as given using the following formula:

$$\Delta ab^* = \sqrt{(a_R^* - a_S^*)^2 + (b_R^* - b_S^*)^2}$$

The color consistency is then defined as the mean *Δab** for all the *n* patches present.



27.3 Influencing factors

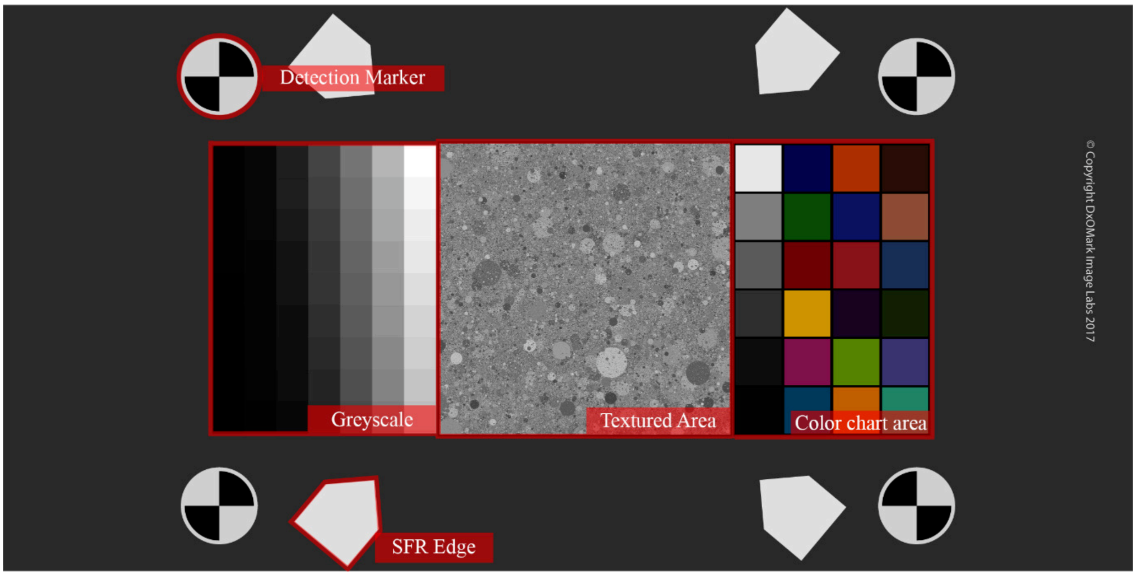
Several parameters influence the HDR measurement:

- The focal length of the lens
- The aperture
- The focus (an inaccurate autofocus will influence the accuracy of the Texture Preservation measurement)
- The ISO setting

- The focusing distance (may impact the measurement for some lenses, especially at short distances — in macro mode, for example)
- The shooting distance for some fixed-focal-length lenses
- Noise reduction settings
- The HDR mode
- The color space used to produce the image

27.4 Measurement of HDR

The HDR chart is designed as follows:



It contains five elements:

- The textured area for measuring the HDR texture MTF
- Four detection markers for automatic target detection
- Four patches with slanted edges for computing an SFR to compare with the HDR texture MTF
- Sixty-three grey patches to compute the entropy of the image, the noise, and for inverting the camera's tone curve (or OECF) for computing the HDR texture MTF in a linear color space

- Twenty-four color patches similar to the X-Rite ColorChecker® classic to perform color-related measurements

For each measurement, we need two photos:

- The sample photo (S): The photo to be studied, consisting of a shot of two charts illuminated by two separated LED panels under different lighting conditions
- The reference photo (R): A photo usually consisting of a shot of two charts equally illuminated. These values will be used as reference for the color, HDR texture, and contrast-related measurements.

The main steps of the measurement:

1. The position of the target is automatically detected. Detection can fail if the image is very noisy or saturated.
2. The histogram of the greyscale is computed and its entropy is calculated.
3. The greyscale is used to estimate the camera's tone curve (or OECF).
4. The estimated tone curve is used to linearize the image before computing the MTFs and the Visual Noise.
5. Horizontal and vertical SFR are computed along the SFR edges.
6. The MTF and Visual Noise are computed as described in Section 10 (TEX: Texture Preservation and Visual Noise). Visual Noise is computed using the grey patches of the color chart area.
7. The color chart area is converted to the CIE 1976 $L^*a^*b^*$ color space with or without exposure compensation, after which the color metrics are computed.

These steps are performed for each chart for both the sample and the reference photos. Below are the metrics that the measurement calculates:

27.4.1 Local contrast preservation – Entropy

The entropy is computed using the histogram of the greyscale before linearization. Its value is given in bits, meaning that a loss of 1 point in entropy means that 50% of the information is lost for that portion of the picture. The difference between the entropy of the sample and the reference is also shown.

27.4.2 Texture Preservation-related measurements

HDR texture acutance, Texture MTF, and Edge SFR are computed. For in-depth explanations about the computation of those metrics, refer to Section 10 (TEX: Texture Preservation and Visual Noise).

The main difference between the calculation used here and the calculation used in Section 10 is that here we do not perform the linearization step by estimating the tone curve the camera uses on the 12 grey patches around the texture, but rather by estimating the tone curve the camera uses on the 63 grey patches of the greyscale.

27.4.3 Noise-related measurements

The Visual Noise is computed in a similar way as described in Section 10 (TEX: Texture Preservation and Visual Noise). The difference here is that we do not use the 12 grey patches around the texture, but rather the 6 grey patches on the color chart area plus the background of the chart.

We also present a graph of the standard deviation for each of the 63 grey patches, which can be an important tool for studying the effects of noise incoherency.

27.4.4 Color-related measurements

Many metrics related to the color are computed for both the sample and reference images.

For the “As Shot” patches, we compute:

- The individual, maximum, and mean of the ΔL and ΔH.
- The individual, mean, and maximum Δab for all patches, and also for only the grey patches.

For the “Exposure Corrected” patches, we compute:

- The individual, maximum, and mean of the ΔC, ΔH, Δa, and Δb.
- The individual, mean, and maximum Δab for all the patches (“color consistency”), and also for only the grey patches (“white balance”).

For in-depth explanations about the computation of these metrics, refer to Section 28 (CF: Color Fidelity).

27.5 Measurement in raw format

The main purpose of this measurement is to qualify the impact of image fusion and other HDR algorithms for the final image available to the user. Thus, it makes sense for RGB images only, so this measurement is not available for raw images.

27.6 Analyzer output

Analyzer returns the following data:

- The shooting conditions tab contains values for the general shooting conditions as well as for the selected viewing conditions:

Image format	RGB
Image depth	8 bits/channel
Width	4032 pixels
Height	3024 pixels
Date	03/11/2017 - 13:53:17
Color space	Display P3
Description	03 - Professional Photo Print (closer)
Distance	600 mm
Print height	400 mm
Use MTF display	Yes
Exposure compensation	Measured OECF – 50%

Brand	Apple
Model	iPhone 8 Plus
Aperture	1.8
Focal length	3.99 mm
Shutter speed	0.27 ms
ISO speed	20
Ev bias	0.00
White balance	Auto white balance

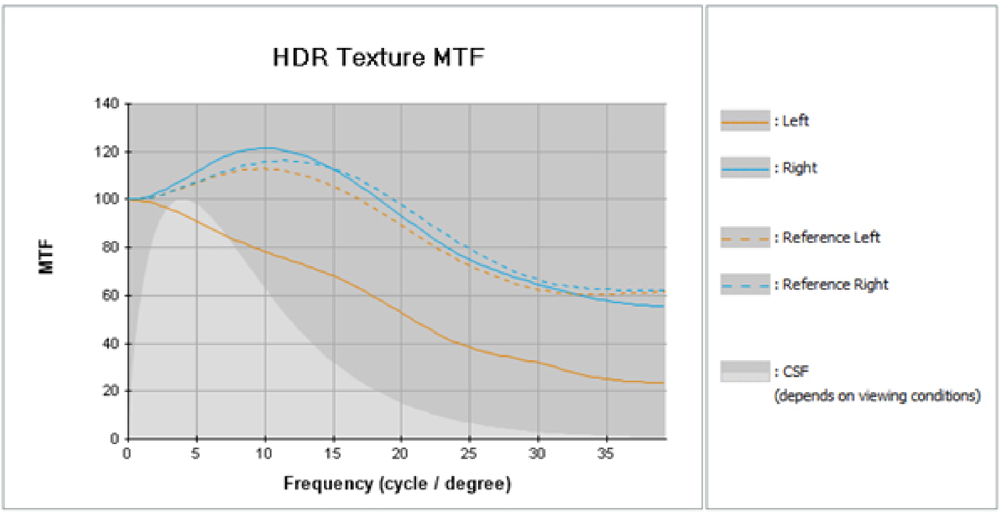
- The summary tab contains the most important metrics for both the sample and the reference images:

	Left			Right		
	Sample	**Reference**	**Difference**	**Sample**	**Reference**	**Difference**
Exposure - Grey level at 18%	92.2	118.5	-26.2	155.3	119.7	+35.7
Texture acutance	0.703	0.891	-0.188	0.934	0.910	+0.024
Local contrast consistency - Entropy (bits)	7.4	7.6	-0.2	7.2	7.5	-0.2
Visual noise at L* 50	1.78	0.69	+1.10	0.88	0.81	+0.06
Color consistency - Mean Δab - Expo. compensated		7.15			6.44	

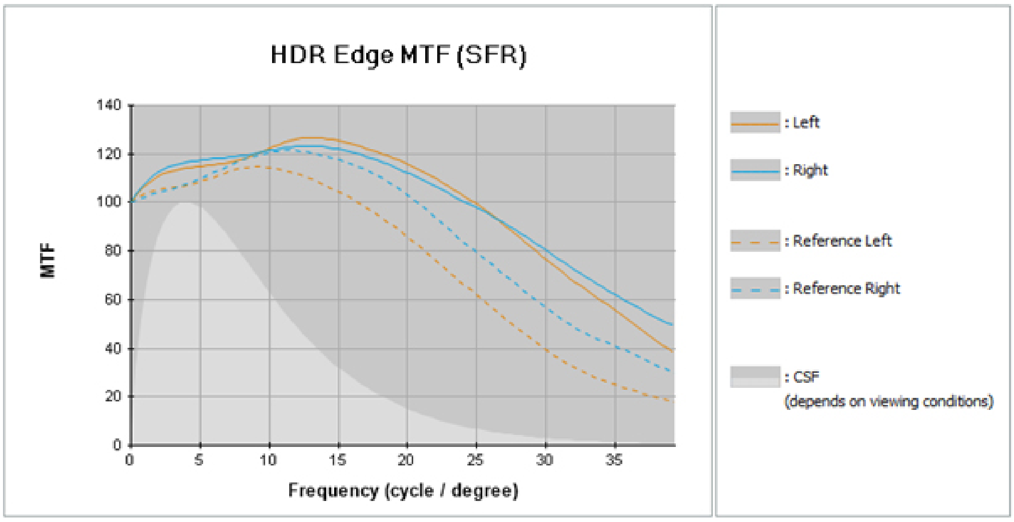
- The MTF tab contains three sections:
  - The pixels-to-degrees factor for both the sample and reference images:

	Sample image	Reference image
Pixels/Degree	79.168	79.482

– The MTF graphs for texture:

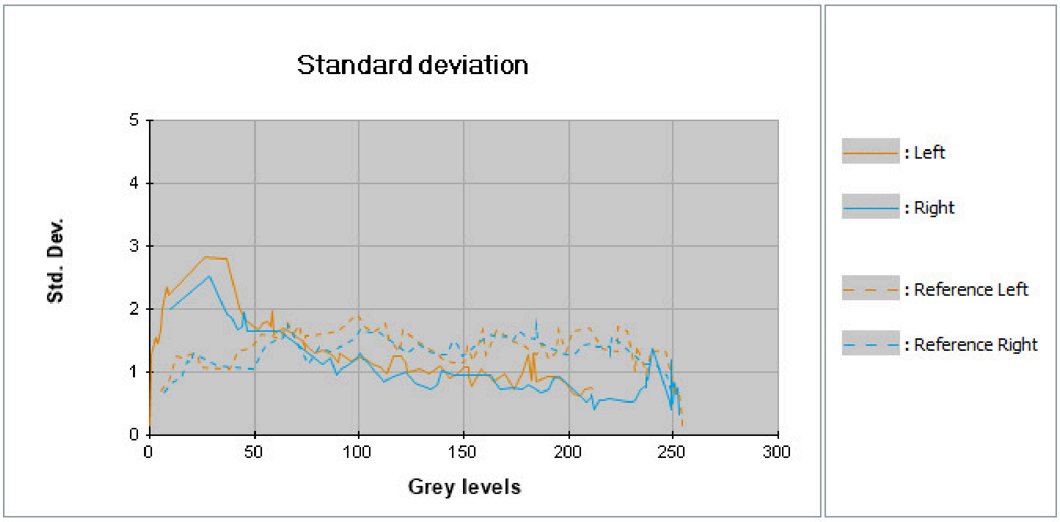


– The graphs for MTF edge:



- The Noise tab shows a table with the average of the minimum and the maximum of the standard deviation for each patch of the greyscale, and a graph with all its values:

	Left		Right	
	Sample	Reference	Sample	Reference
Std. Dev. - average	1.29	1.33	0.96	1.32
Std. Dev. - minimum	0.15	0.06	0.32	0.66
Std. Dev. - maximum	2.83	1.93	2.53	1.76



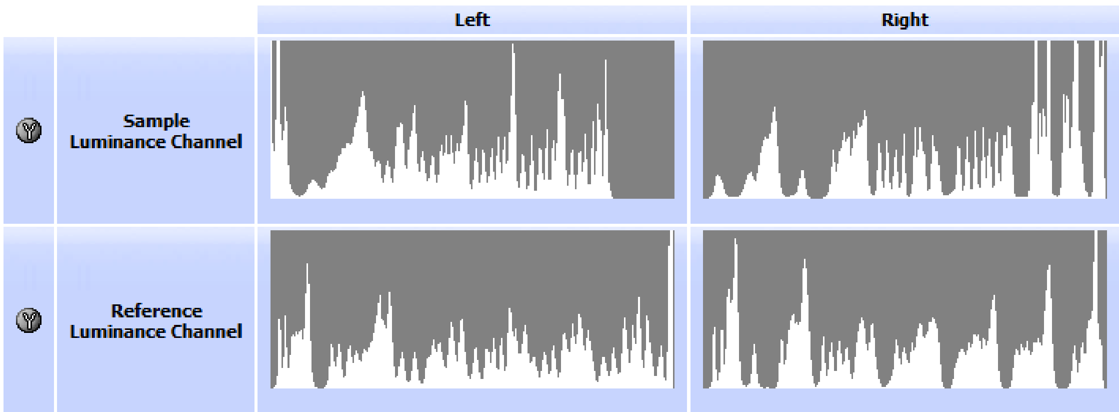
- The Visual Noise tab shows the estimated visual noise for a CIELab L^* value at 50, obtained by linear interpolation:

	Left						
	Visual noise	Variance			Covariance		
		L*	a*	b*	L*a*	L*b*	a*b*
Sample image	1.8	0.1	0.6	0.0	-0.1	0.0	-0.1
Reference image	0.7	0.1	0.1	0.1	0.0	0.0	0.0

	Right						
	Visual noise	Variance			Covariance		
		L*	a*	b*	L*a*	L*b*	a*b*
Sample image	0.9	0.0	0.1	0.2	0.0	0.0	-0.1
Reference image	0.8	0.1	0.1	0.1	0.0	0.0	-0.1

- The Contrast tab has three sections:
  - The crops of the greyscales:

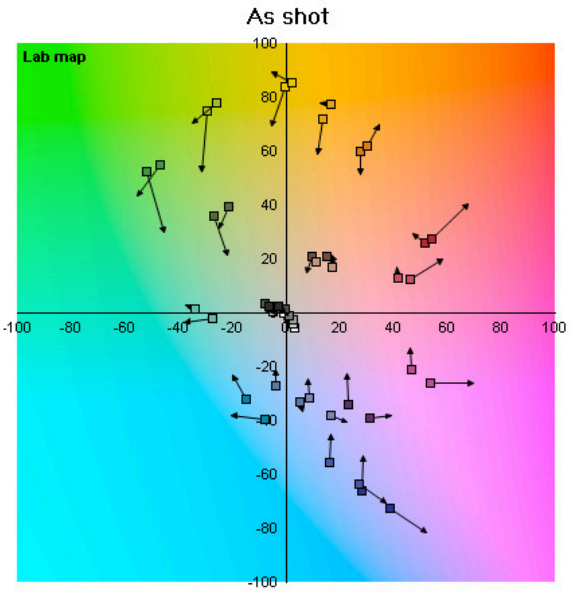
– The histograms of the greyscales:



– The entropy of the greyscales, computed for each channel:

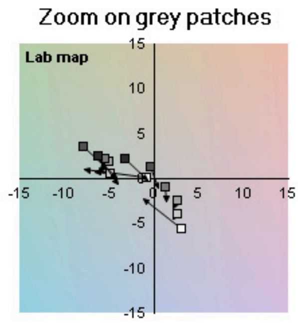
		Left			Right		
		Sample	Reference	Difference	Sample	Reference	Difference
R	Red Channel	7.4	7.7	-0.3	7.2	7.5	-0.2
G	Green Channel	7.5	7.6	-0.1	7.2	7.5	-0.3
B	Blue Channel	7.4	7.7	-0.2	7.1	7.4	-0.3
Y	Luminance Channel	7.4	7.6	-0.2	7.2	7.5	-0.2

- The 2D tab has two sections:
  - An "As shot" section with the 2D map of the color chart area patches and the corresponding color metrics (always computed relative to the reference image):

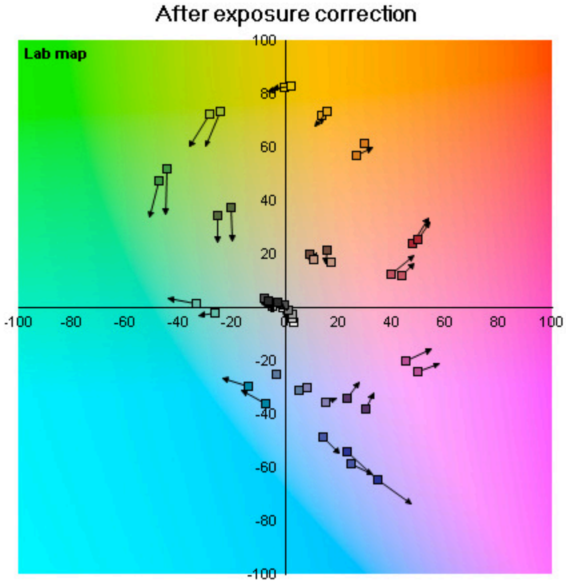


	Mean		Max.	
	Left	Right	Left	Right
Δ L	-13.52	9.18	18.35	13.12
Δ E	16.72	13.44	27.73	20.73

	Mean Δ ab		Max. Δ ab		SMI	
	Left	Right	Left	Right	Left	Right
Color consistency	8.59	8.23	23.23	18.48	8.03	26.08
White balance	2.44	1.51	5.11	2.55	86.57	91.72

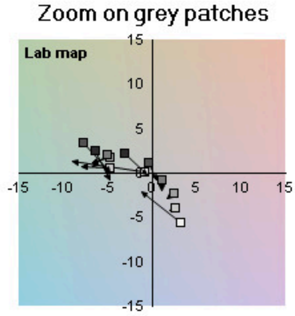


  - An "After exposure correction" section with the 2D map of the color chart area patches and the corresponding color metrics after correction:

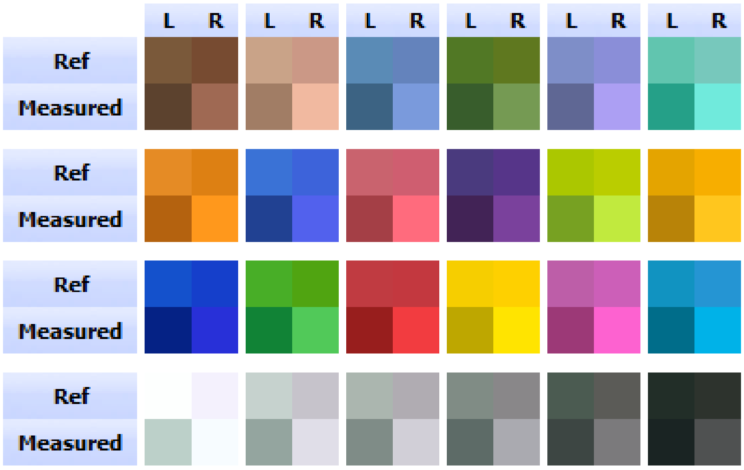


	Mean		Max.	
	Left	Right	Left	Right
Δ C	5.07	4.33	14.63	13.98
Δ H	4.13	4.17	12.91	12.40

	Mean Δ ab		Max. Δ ab		SMI	
	Left	Right	Left	Right	Left	Right
Color consistency	7.15	6.44	15.78	16.70	60.65	64.58
White balance	2.94	1.23	4.47	2.21	83.83	93.22



- The “Color – As Shot” and “Color – exp. Corrected” tabs each contain two sections:
  - The means and maximums of the main metrics for the patch colors, computed relative to the reference image:



	Mean values		Max. values	
	Left	Right	Left	Right
Δ L	-13.52	9.18	18.35	13.12
Δ E	16.72	13.44	27.73	20.73
Δ ab	8.59	8.23	23.23	18.48

– The metrics calculated for each individual patch:

	L	R	L	R	L	R	L	R	L	R	L	R
Ref												
Measured												
Δ L	-9.63	12.84	-14.37	12.29	-15.09	8.96	-10.08	12.40	-14.91	8.38	-13.79	10.49
Δ E	11.54	13.31	14.46	12.76	16.30	9.83	18.47	15.29	16.46	10.84	14.33	14.84
Δ ab	6.36	3.50	1.58	3.43	6.16	4.04	15.48	8.95	6.98	6.88	3.91	10.50

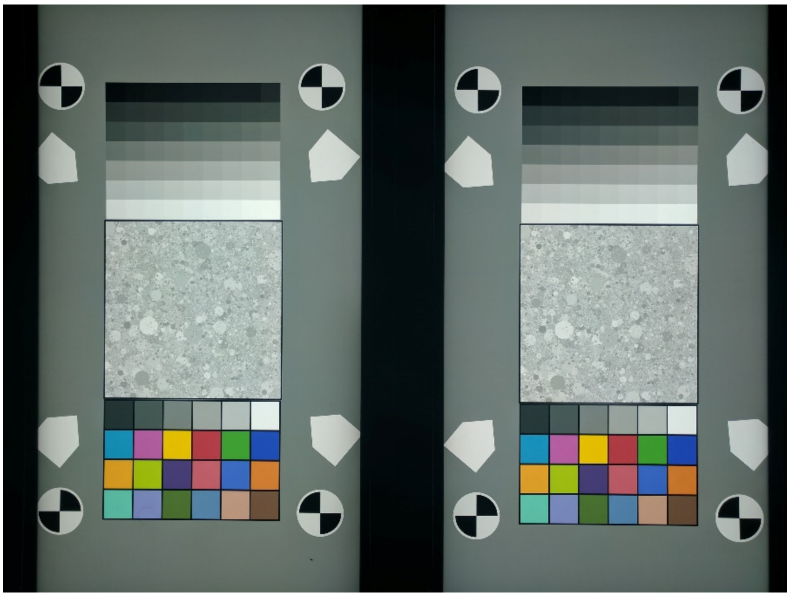
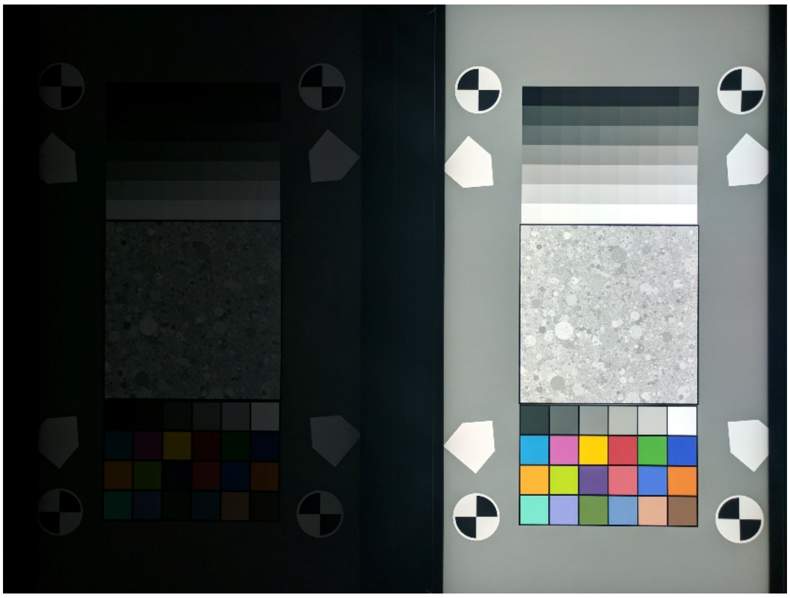
	L	R	L	R	L	R	L	R	L	R	L	R
Ref												
Measured												
Δ L	-15.68	10.12	-18.25	2.02	-13.13	10.13	-8.52	7.65	-14.40	9.04	-12.85	7.64
Δ E	18.04	13.60	21.05	12.36	13.67	17.36	13.99	11.21	26.55	14.58	18.44	8.68
Δ ab	8.91	9.09	10.48	12.19	3.82	14.09	11.10	8.19	22.31	11.44	13.22	4.11

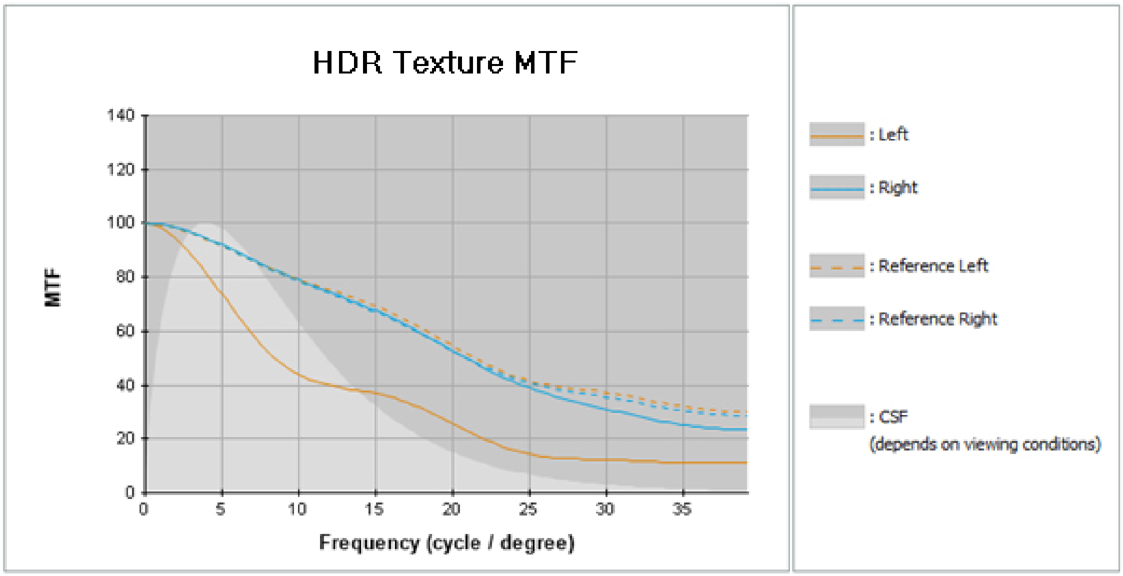
	L	R	L	R	L	R	L	R	L	R	L	R
Ref												
Measured												
Δ L	-18.02	-0.71	-15.14	12.19	-11.64	9.39	-15.55	5.95	-13.27	8.68	-14.87	8.75
Δ E	22.12	15.89	27.73	18.80	12.97	20.73	21.68	10.58	15.48	18.37	18.14	15.30
Δ ab	12.82	15.87	23.23	14.32	5.72	18.48	15.12	8.74	7.96	16.18	10.39	12.55

	L	R	L	R	L	R	L	R	L	R	L	R
Ref												
Measured												
Δ L	-18.35	3.04	-17.19	9.78	-15.41	12.88	-12.70	13.12	-7.66	12.62	-3.97	12.76
Δ E	19.62	6.20	17.29	9.81	15.46	12.93	12.81	13.23	9.21	12.87	5.55	13.22
Δ ab	6.92	5.41	1.77	0.74	1.19	1.07	1.69	1.66	5.11	2.55	3.88	3.46

27.7 Examples

The following graph is an HDR Texture MTF computed under the following conditions:

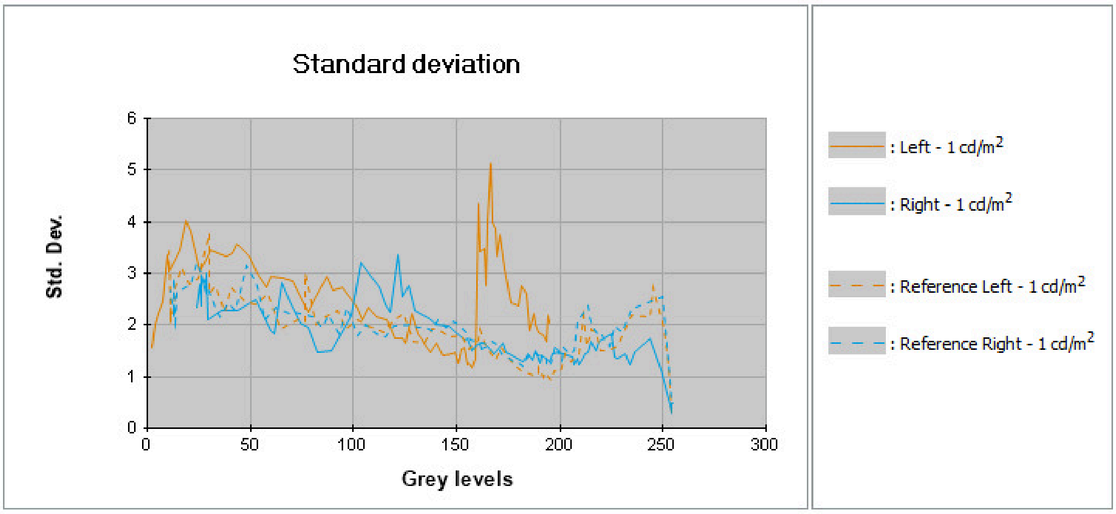
• The reference photo (both LED panels are well and equally lit)	
• The sample photo is as well-lit as the reference photo by the right panel, but poorly lit by the left LED panel	



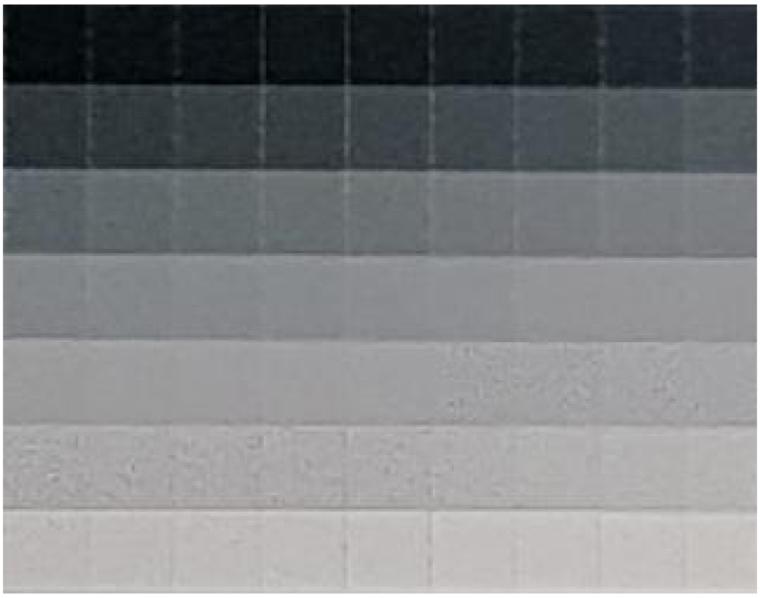
We can see that the MTF from the left sample chart decreased for all frequencies, meaning that the camera was not as good at Texture Preservation for this portion of the photo as it was when shooting the well-lit chart.

The Noise tab displays the following graph:

	Left - 1 cd/m²		Right - 1 cd/m²	
	Sample	Reference	Sample	Reference
Std. Dev. - average	2.48	1.79	1.65	1.82
Std. Dev. - minimum	1.18	0.27	0.31	0.43
Std. Dev. - maximum	5.13	3.78	3.36	3.22

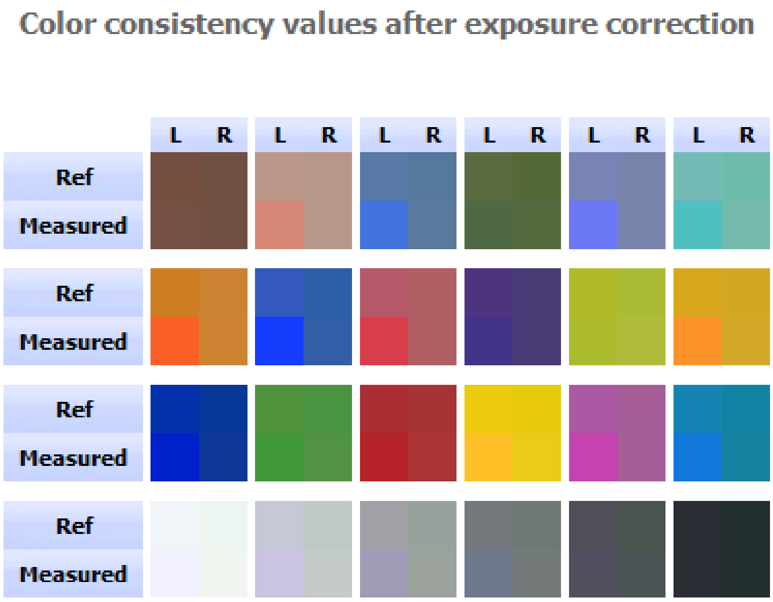


We can see that the left side of the sample image not only has high levels of noise, but also has discontinuities. This presence of noise incoherency can be visually seen between the fifth and sixth lines of the greyscale that originated the curve:



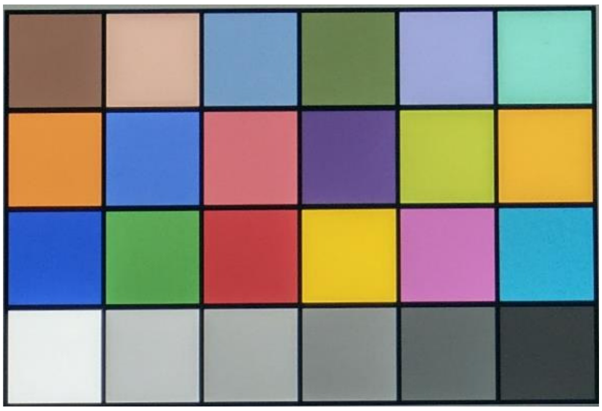
This can happen when the camera's multi-image fusion algorithm changes the images it stitched together in that portion of the image. This noise artifact is important to study because this incoherency can be interpreted as the presence of texture. Notice as well that the whitest patch of the greyscale is not completely white, which is why its curve on the noise graph does not end at 255.

The following image is an example of the content in the "Color – exp. Corrected" tab of the measurement:



	Mean values		Max. values	
	Left	Right	Left	Right
Δ a	10.44	1.48	35.99	2.66
Δ b	-7.47	-0.62	39.06	1.29
Δ ab	17.32	1.64	53.11	2.87
Δ C	14.25	1.15	51.03	2.83
Δ H	7.06	0.90	25.95	1.80

We can see that the mean value of Δab^* is 17.32, which implies a big difference in color between the images. If we visually compare the color chart areas, we can see that the camera oversaturated some color patches to compensate for the low exposure level of the underexposed image:

Sample image	Reference image
	

The color differences are most visible on the second line for the orange, blue, and salmon patches. These differences can also be individually seen in the table in the same tab:

	L	R	L	R	L	R	L	R	L	R	L	R
Ref												
Measured												
Δ a	-1.15	1.96	18.23	1.72	16.40	1.44	-2.81	1.92	21.24	1.59	-6.73	1.56
Δ b	-1.40	-0.32	8.90	-0.62	-29.98	-0.45	-3.00	-1.29	-36.25	0.00	-5.61	-0.52
Δ ab	1.81	1.98	20.29	1.83	34.17	1.51	4.11	2.31	42.02	1.59	8.76	1.64
Δ C	1.79	0.83	19.50	0.32	32.96	0.22	0.67	2.18	41.74	0.37	7.91	1.57
Δ H	0.27	1.80	5.62	1.80	9.01	1.49	4.06	0.76	4.80	1.55	3.76	0.48

	L	R	L	R	L	R	L	R	L	R	L	R
Ref												
Measured												
Δ a	31.72	1.73	35.99	1.10	22.13	1.31	0.02	1.26	-2.94	1.50	26.82	0.35
Δ b	0.50	-0.23	-39.06	-0.16	16.47	-0.44	-5.26	-0.27	-0.87	-1.04	-1.39	-0.89
Δ ab	31.73	1.75	53.11	1.11	27.59	1.38	5.26	1.29	3.06	1.82	26.85	0.95
Δ C	18.26	0.45	51.03	0.40	26.44	1.09	4.35	0.95	0.13	1.47	6.92	0.85
Δ H	25.94	1.69	14.72	1.03	7.86	0.85	2.96	0.87	3.06	1.08	25.95	0.44

	L	R	L	R	L	R	L	R	L	R	L	R
Ref												
Measured												
Δ a	18.55	0.36	-7.23	2.02	6.22	0.93	16.02	1.38	20.22	0.47	20.54	0.58
Δ b	-17.97	0.11	3.67	-1.19	6.32	-0.37	-2.98	-0.47	-6.59	-0.17	-24.23	-0.11
Δ ab	25.83	0.38	8.10	2.35	8.87	1.00	16.30	1.46	21.26	0.50	31.76	0.59
Δ C	24.86	0.04	7.81	2.31	8.51	0.65	1.69	0.52	20.93	0.50	22.48	0.27
Δ H	6.99	0.38	2.17	0.42	2.50	0.76	16.21	1.37	3.74	0.06	22.43	0.53

	L	R	L	R	L	R	L	R	L	R	L	R
Ref												
Measured												
Δ a	3.85	2.60	6.24	2.66	4.83	2.38	0.73	1.93	1.16	1.40	0.61	1.39
Δ b	-9.10	-1.20	-9.69	-1.09	-8.74	-1.12	-7.77	-1.02	-3.36	-1.00	-1.95	-0.95
Δ ab	9.88	2.86	11.52	2.87	9.98	2.63	7.80	2.18	3.56	1.72	2.05	1.68
Δ C	9.73	2.80	11.23	2.83	9.90	2.63	7.80	2.10	3.45	1.33	1.91	0.87
Δ H	1.72	0.62	2.59	0.49	1.32	0.11	0.23	0.59	0.86	1.08	0.73	1.44

27.8 Measurement accuracy

For a discussion about the accuracy of the Texture- and Visual Noise-related measurements, see Section 10 (TEX: Texture Preservation and Visual Noise). For color-related measurements, see Section 28 (CF: Color Fidelity). The accuracy of the entropy measurement is ±0.2.

Note that the repeatability of the measurement is dependent on the repeatability of many of the algorithms that the camera uses, including auto-exposure, auto-white balance and auto-focus. If these are not stable, taking a series of photos and selecting the best one may increase the accuracy of the measurement.

27.9 Measurement scale

27.9.1 HDR Texture Acutance

As explained in Section 10 (TEX: Texture Preservation and Visual Noise), the acutance is not simply just a measurement of sharpness anymore, but also of the contrast of the texture when compared with the rest of the scene. This means that we can expect to find acutance values above 1.0 for cameras which are not only good at preserving texture, but which also do a good job of increasing the contrast of the dead leaves portion of the HDR chart.

Acutance	Level of sharpness
Above 0.95	The image is very sharp. This may be the result of using sharpness enhancement algorithms and/or different tone mapping leading to local increased contrast in the texture.
Between 0.85 and 0.95	The image is sharp.
Between 0.70 and 0.85	The image is slightly blurry.
Between 0.60 and 0.70	The image is blurry. Many fine details are lost.
Below 0.60	Most fine details are lost, and the texture may be saturated.

27.9.2 Entropy

The following table gives a subjective scale of entropy results. Please note that a loss of 1 point in entropy means that 50% of the information is lost for that portion of the photo.

Entropy	Level of contrast consistency
Above 7	The camera does an excellent job of preserving the contrast in this area of the scene. The difference between the contrasts of two images with such high entropy is not visible.
Between 6.5 and 7	The camera does a good job at preserving the contrast in this area of the scene.
Between 6 and 6.5	The photo is not well-exposed in this area of the image. Saturation is expected.
Below 6	Strong saturation is expected.

27.9.3 Color consistency

The table below presents a subjective scale of the color consistency metrics. Note that color consistency is always done as a comparison between the chosen photo and the reference photo.

Color consistency (mean Δab^*)	Qualitative effect
$x < 8$	Almost no difference between the reference image and the sample image.
$8 < x < 15$	Little difference between the photos.
$x > 15$	Clear differences between photos. There might be a problem with saturation or white balance.

27.10 Setup parameters influencing the measurement

The following setup parameters may change the results of the HDR measurement:

- You must normally deactivate the digital zoom function, unless it is the subject of the test.
- Set the resolution to the highest available value to obtain accurate measurements.
- Framing of the image in 4:3, 16:9, etc.: Maximize the use of the sensor when taking the photograph, unless it is the subject of the measurement.
- Disable special camera settings such as noise reduction filter, saturation filter, contrast enhancer, and so on.
- Deactivate the exposure correction (you must set the EV to zero).
- Make sure the compression ratio is as low as possible (TIFF format is preferred to JPEG).
- Activate or set the HDR mode to automatic mode, unless you want non-HDR photos for comparison reasons.

27.11 Validity of the measurement

The HDR measurement (as with the Texture measurement) is meaningful only if you mention all the information about focal length, aperture, ISO speed, exposure correction, noise reduction filter, saturation, and contrast for both the sample image and the reference image. You must also mention the selected viewing conditions for the acutance value. Moreover, the measurements are valid only if you include the values for the power and white balance of both LED panels.

Giving any metric by itself with no further information is not meaningful. You should provide all the values of any influencing parameters. This said, a measurement can be meaningful if you say that, for example:

- The device is a 6-Mpixel camera, with a 24 mm focal length, at f/2.8 and ISO 400.
- The image was taken for a 40×60 cm print viewed at 60 cm.
- No sharpening filter, exposure correction, noise reduction filter, or other in-camera processing was used.
- Both LED panels were at 6500 K.
- The reference image was taken with both LED panels at 100% of their power.
- The sample image was taken with the right LED panel at 100% and the left LED panel at 12.5%.

27.12 Comparing two cameras

Many shooting protocols can be defined to study different scenarios. We propose a protocol to use to compare the performance of cameras shooting scenes in which the important subject is in the low-light part of the image, but also in which a bright light object is on the field of view — in other words, the classic case of an **indoor photo with a window in the background on a sunny day**.

To simulate such scene, we chose a protocol in which one LED panel is constantly set at a bright-light level and the other LED panel is progressively less and less bright. We set the device to auto-exposure and auto-HDR modes, giving it full control of the scene.

We start the series with both LED panels at the same intensity, and for each successive photo, we increase the difference between panels by decreasing the intensity of one of them. With both panels set to the same color temperature, and one of them at 100% intensity, the intensity of the second panel should be set to:

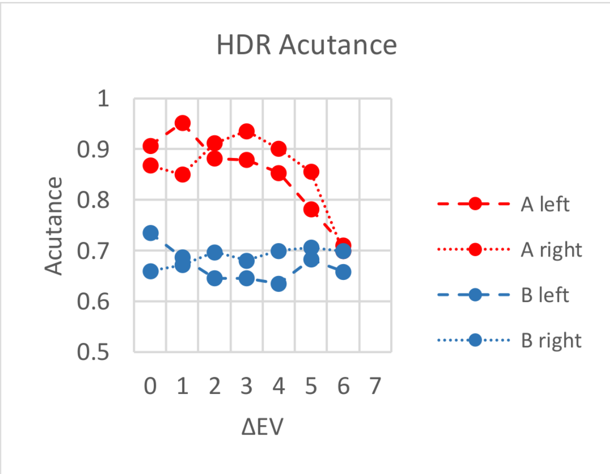
	30 kHz	250 kHz			
ΔEV between the LED panels	Any color temperature	2700 K	3200 K	5000 K	6500 K
0	100%	100%	100%	100%	100%
1	50%	57%	59%	63%	56%
2	25%	33%	36%	44%	33%
3	12.5%	23%	26%	34%	24%
4	6.3%	18%	20%	27%	19%
5	3.1%	15%	17%	23%	15%
6	1.6%	13%	15%	20%	13%
7	0.8%	11%	13%	18%	12%

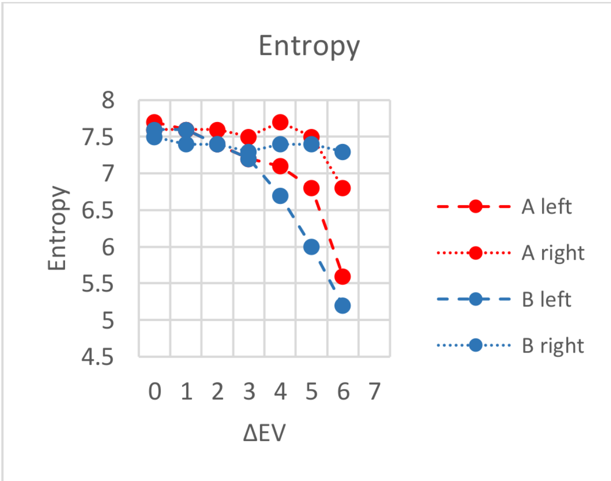
Note: The KinoFlo Celeb 250 panels operate at a specific frequency which can be changed in units sold by DXOMARK IMAGE LABS. Visible flickering artifacts can appear in pictures with frequencies under 250 kHz, which is why **we recommend you operate at 250 kHz**. The default setting is 30 kHz.

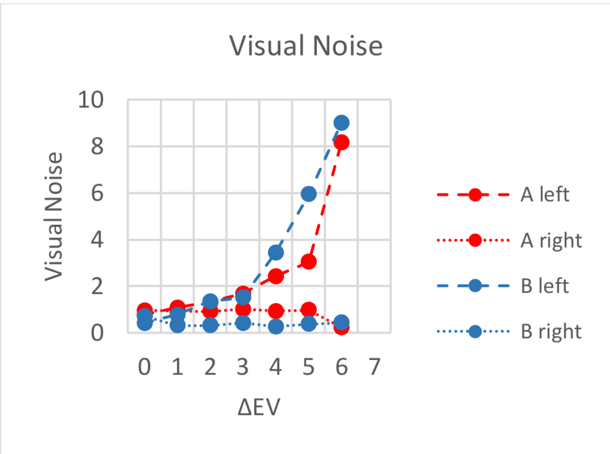
An important input of the HDR measure is the reference image, which is used mostly for computing the color metrics. In this protocol, the proposed reference image is taken with the device on HDR-off mode, with both LED panels lit at full intensity. This means that we can study how the HDR algorithms change the colors for difference exposures. However, other options are possible, such choosing an image taken with another device, for example.

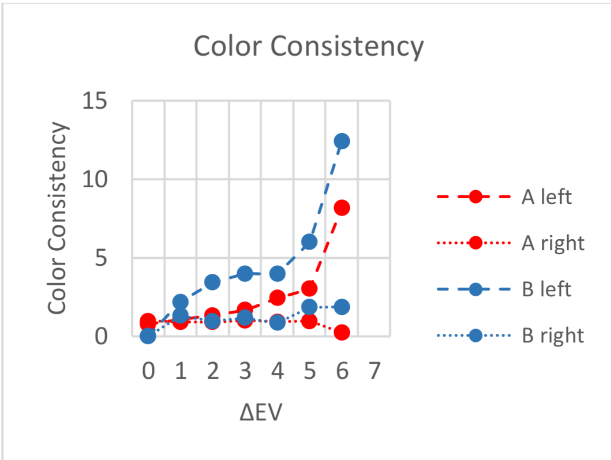
We present as an example of this protocol a comparison between two devices, A and B. We performed these measurements using “Professional Photo Print (closer)” viewing conditions.

Neither device was able to detect the left chart (low light) for *ΔEV* = 7, which indicates that they could do better in terms exposing the low-light portions of high-dynamic scenes. Below are the graphs of some of the most important metrics computed by the HDR measurement for this example:

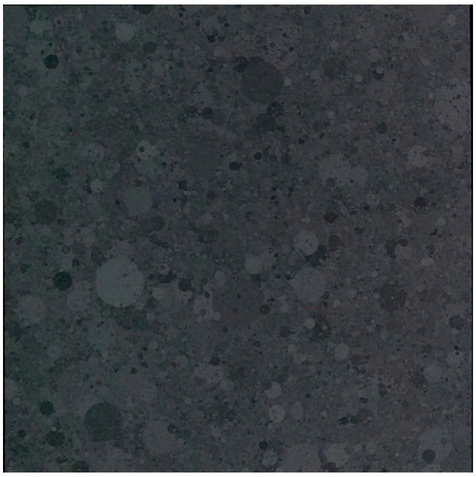
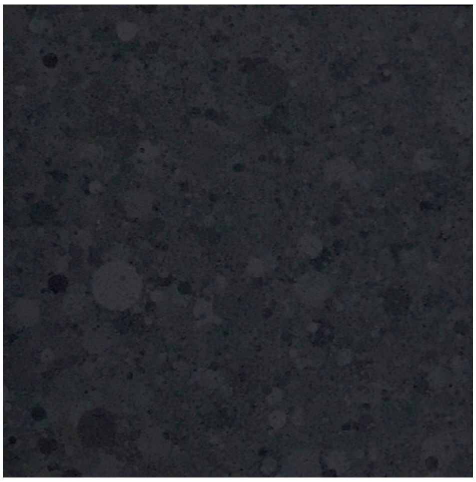








In terms of Texture Preservation, the acutance graph shows that device A does a better job of preserving texture and details for all the tested cases. For example, the following images are of the left (low-light) side of the chart, taken by both smartphones at ΔEV = 6. We can see that while both devices have similar exposure levels, device A not only has captured a more contrasted picture overall, as shown by its higher entropy, but also has better Texture Preservation, shown by the higher acutance.

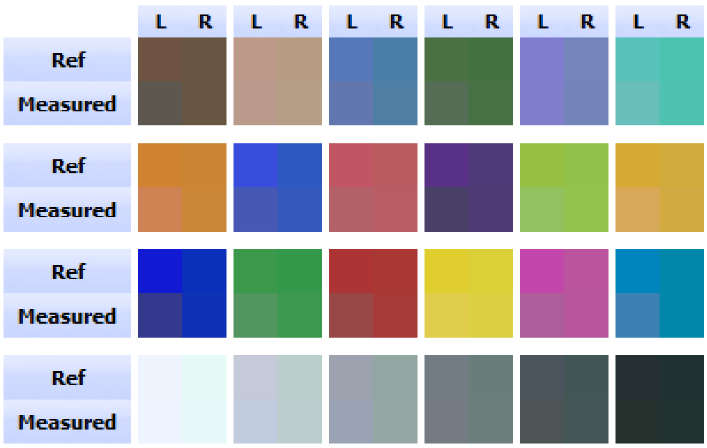
Devices	A	B
Texture		
Exposure Grey Level at 18%	11.3	9.0
HDR Acutance	0.711	0.659
Entropy	5.6	5.2

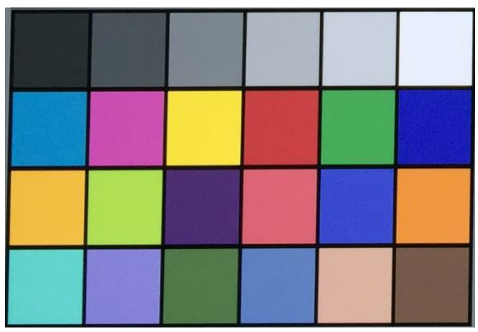
One might be tempted to think that device B's poor Texture Preservation could be explained by a preference for stronger noise reduction, but the Visual Noise graph shows that device B also performs worse in that category, though the difference is not huge.

In terms of contrast, the entropy graph tells us that device A is better than device B at preserving contrast in most of the scenes. The only exception is found for the right chart at ΔEV = 6, for which device A does a worse job. This might indicate a strategy of clipping bright tones in order to preserve the contrast in darker areas.

The Color Consistency graph shows us that device B's colors change drastically for large ΔEVs. A more in-depth analysis of the photos using the "Color – exp. Corrected" tab shows that this difference comes mostly from the blue and red patches on the low-light chart, for which the colors appear slightly desaturated. We show an example of the photo with ΔEV = 6.

Color consistency values after exposure correction



Sample image	Reference image
	

In summary, this study shows that for backlit photos, device A does a better job at preserving texture, color, and contrast than device B.

27.13 Shooting

The HDR measurement uses the HDR chart.

Decide on the protocol to use: Section 27.12 (Comparing two cameras) describes a shooting protocol created to measure a camera's performance in backlit scenarios. However, we encourage users to develop and test new protocols aimed at studying different scenarios.

Decide on the important parameters: Focal length, aperture, focusing, resolution, ISO, sharpness, digital zoom, etc.

Special shooting conditions (see also Section 5: Shooting the test target)

- The smartphone must be as close as possible to the charts without cutting off important areas of the chart. It is not a problem if the uniform grey areas on the top and bottom of the chart are not entirely visible, but the markers must not be too close to the top and bottom borders of the image.
- As a general rule, keep a vertical space of approximately half the marker size between the markers and the top/bottom image borders.
- The visible background behind the target must be black.
- Borders of the target must be parallel to the borders of the image.
- The table on which the LED panels are set must be black or been covered by a black cloth.
- The target must be the only source of light.
- The target should be as orthofrontal as possible. Use the mirror method to suitably position the camera (see the protocol on page 90).
- Be careful when focusing: a bad or unrepeatable focus will change the results.

Below are examples of correct and incorrect chart framing:

Correctly framed chart	Incorrectly framed chart
	

Note: It is important to keep a record of all the parameters and settings associated with each shot. Depending on the model, not all cameras record all the EXIF data, and if the measurement is to be used to compare two cameras, the shooting conditions for the image files must be strictly identical.

28 – CF: Color Fidelity

28.1 Introduction

Color fidelity can be described as the ability of a camera to accurately reproduce colors in comparison with an objective reference. However, the notions of color of an object as well as an objective reference are not obvious to define.

Indeed, the color of an object changes under different lighting conditions. This can be measured by using a spectrometer decomposing the light reflected by the object. On the other hand, a constant characteristic of the object is its albedo, which can be expressed as the amount of incident light the object scatters back for each wavelength. A common simplifying hypothesis is that objects are Lambertian, meaning that they reflect light the same way in all directions. Knowing the spectral decomposition of a light source and the albedo of an object theoretically permits computation of its color (with this particular illuminant) — that is, the spectrum of the light it reflects. Representing the albedo in each point of an image is not achievable in practice. Indeed, the space of albedos is infinitely dimensional because wavelengths are a continuum (up to quantum effects).

Actually, such a computation may not prove really useful, either. The human eye cannot distinguish every single color. There are basically two different kinds of photosensitive cells in the eye, cones and rods. Rods are sensitive to low levels of light, while cones are responsible for color perception. There are three different types of cones, characterized by three different spectral responses denoted by S (for short length), M (for medium) and L (for long), centered respectively in blue, green, and red.

This is the reason that usual color spaces are usually described by three components. A finite dimensional space cannot intrinsically represent any arbitrary color, and has a more limited span (called the gamut). However, it is possible to approximate the set of colors which are perceived by the human eye, which is also more or less three-dimensional. The first successful modeling attempt was the CIE XYZ space, invented in 1931. A more commonly-used space is the sRGB space created by Hewlett-Packard and Microsoft Corporation in 1996 for use on the Internet. Each channel of this space is characterized by a spectral response. It turns out that the gamut of the sRGB space is very incomplete. Nonetheless, it is the most widely-used color representation. Another commonly-used color space is the Adobe RGB (1998) color space, whose gamut is slightly larger than the sRGB gamut.

Most digital cameras sensors use Color Filter Arrays (CFA), and thus also have three different types of photosites. However, the spectral responses of the photosite do not coincide with the sRGB standard and are different for each sensor. Hence the color space generated by the sensor is not the sRGB color space. The Color Fidelity measurement aims to quantify this discrepancy. It is a function of:

- The ability of a sensor to distinguish different colors (related to spectral responses)
- How colors are corrected (determined by the raw conversion)
- A number of aesthetic choices made by the manufacturer.

The same scene picture with a camera phone, and a dSLR. The sky turns to purple with the camera phone. Greens contain more yellow with the dSLR

Color rendering contains at least two steps: white balance correction and color mapping. The white balance makes spectrally-neutral objects appear grey by applying different scales on the R, G, and B channels. These scales depend on the spectral response of the color filters and on the illuminant. The illuminant is often characterized by its temperature, which is the temperature of the "black body" whose spectral distribution is the closest to that of the illuminant.

The same picture taken with two different white balances. Left is 2850 K (tungsten) and right is 3550 K (as shot)

Color mapping is usually a linear transformation of the sensor color space so as to fit a standard color space (as sRGB or Adobe RGB). Theoretically speaking, perfect fidelity can be achieved only if the three primary colors of the sensor span the same gamut as the primary colors of the color space. This may not be easy or even possible. Indeed, attaining good color fidelity might require stretching the color space of the sensor a lot. This may create very disturbing color noise, and manufacturers may choose to reduce noise by rendering less-saturated colors.

28.2 Definitions

The sRGB color space, it is not perceptually uniform for the Euclidean norm.

By this, we mean that given a color (R_0, G_0, B_0), the colors satisfying $(R - R_0)^2 + (G - G_0)^2 + (B - B_0)^2 = d^2$ for a given d, do not seem perceptually equally different from (R_0, G_0, B_0). Actually, no usual norm has this property in the sRGB space, and more complex non-uniform metrics should be used. This makes color comparison pretty tedious computationally speaking and not very intuitive.

Instead of designing such a metric, it is also possible to deform the color space such that the final color space is uniform. This idea leads to the CIELAB (also called $L^*a^*b^*$) color space, created in 1976. This space is approximately perceptually uniform for the Euclidean norm. Hence, it is a better space for color comparison. A color is described by three components (L^*, a^*, b^*). The L component is the lightness, while (a, b) describe the hue and the saturation of the color.

The conversion from color space RGB to CIELAB is performed in three steps:

- RGB to XYZ

  Given an RGB color whose components are in the nominal range $[0, 255]$ and the tone curve function TC:

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_{color} = \begin{bmatrix} M \end{bmatrix} \times \begin{bmatrix} TC(R_{color}/255) \\ TC(G_{color}/255) \\ TC(B_{color}/255) \end{bmatrix}$$

  where M is a 3×3 matrix depending on the reference white point of the RGB color system and X, Y, Z are the color coordinates in the CIE XYZ (1931) system.

  In case of the sRGB color space, the tone curve function is almost a gamma function ($TC(c) \approx c^{2.2}$) and

$$M = \begin{bmatrix} 0.4124 & 0.3576 & 0.1805 \\ 0.2126 & 0.7152 & 0.0722 \\ 0.0193 & 0.1192 & 0.9505 \end{bmatrix}$$

- Chromatic adaptation

  The definition of a RGB color space includes a reference white point (For instance, the reference white point of sRGB is D65).

  So, for $R = G = B$, the output XYZ values will correspond to the RGB color space reference white point $(X_{\mathrm{WS}}, Y_{\mathrm{WS}}, Z_{\mathrm{WS}})$.

  By definition The $L^*a^*b^*$ values are computed using a white point which can be different from the white point reference of the RGB color space.

  To compare the $L^*a^*b^*$ target values (computed with a destination white point $(X_{\mathrm{WD}}, Y_{\mathrm{WD}}, Z_{\mathrm{WD}})$), a chromatic adaptation will be performed to transform $(X_{\mathrm{WS}}, Y_{\mathrm{WS}}, Z_{\mathrm{WS}})$ to $(X_{\mathrm{WD}}, Y_{\mathrm{WD}}, Z_{\mathrm{WD}})$.

  This chromatic adaptation is a linear transformation of a source color $(X_{\mathrm{S}}, Y_{\mathrm{S}}, Z_{\mathrm{S}})$ into a destination color $(X_{\mathrm{D}}, Y_{\mathrm{D}}, Z_{\mathrm{D}})$ by applying a matrix M which depends on $(X_{\mathrm{WS}}, Y_{\mathrm{WS}}, Z_{\mathrm{WS}})$ and $(X_{\mathrm{WD}}, Y_{\mathrm{WD}}, Z_{\mathrm{WD}})$ destination reference white:

$$(X_W D, Y_W D, Z_W D) = (X_W S, Y_W S, Z_W S) \times M$$

where

$$M = \left[M_A\right] \times \begin{bmatrix} \rho_D/\rho_S & & \\ & \gamma_D/\gamma_S & \\ & & \beta_D/\beta_S \end{bmatrix} \times \left[M_A\right]^{-1}$$

$$\begin{pmatrix} \rho_D \\ \gamma_D \\ \beta_D \end{pmatrix} = M_A \begin{pmatrix} X_{\mathrm{WD}} \\ Y_{\mathrm{WD}} \\ Z_{\mathrm{WD}} \end{pmatrix} \qquad \begin{pmatrix} \rho_S \\ \gamma_S \\ \beta_S \end{pmatrix} = M_A \begin{pmatrix} X_{\mathrm{WS}} \\ Y_{\mathrm{WS}} \\ Z_{\mathrm{WS}} \end{pmatrix}$$

Where $\left[M_A\right]$ is the Bradford Matrix:

$$\left[M_A\right] = \begin{bmatrix} 0.8951 & -0.7502 & 0.0389 \\ 0.2664 & 1.7135 & -0.0685 \\ -0.1614 & 0.0367 & 1.0296 \end{bmatrix}$$

White point destination ($X_{WD}Y_{WD}Z_{WD}$) can be provided in the sidecar file:

1. Illuminant: Analyzer provides different white points defined by default, in this case $L^*a^*b^*$ reference values are also defined for each white point
2. White point: the user can provide his own white point by given xyY coordinates (Y is assumed to be equal to 1). In this case, $L^*a^*b^*$ target values are required in the sidecar.

Conversion for xyY to XYZ is performed as below:

$$X = \frac{xY}{y}$$
$$Y = Y$$
$$Z = \frac{(1 - x - y)Y}{y}$$

- XYZ to CIELAB

$$L^* = 116 \times f(Y/Y_{WD}) - 16$$
$$a^* = 500 \times \left[f(X/X_{WD}) - f(Y/Y_{WD})\right]$$
$$b^* = 200 \times \left[f(Y/Y_{WD}) - f(Z/Z_{WD})\right]$$

where

$$f(t) = \begin{cases} t^{\frac{1}{3}} & \text{for } t > 0.008856 \\ 7.787 \times t + \frac{16}{116} & \text{otherwise} \end{cases}$$

Here ($X_{WD}Y_{WD}Z_{WD}$) are the CIE XYZ tristimulus values of the destination reference white point, X, Y, Z are the color coordinates in the CIE XYZ (1931) system; L^*, a^*, b^* the color coordinates in the CIELAB (1976) system.

28.3 Influencing factors

Many parameters influence the Color Fidelity measurement:

- The light source.
- Exposure correction (exposure time, aperture).
- ISO setting (to reduce the colored noise, colors are usually less saturated for high ISO speeds).
- White balance settings.
- Color space.

The white balance correction depends essentially on two parameters:

- The light source.
- The color vignetting.

Depending on the camera body, other secondary parameters may influence the color fidelity in an image:

- The sharpening filter applied to the image.
- Activation of a noise reduction filter.
- Compression ratio.
- Resolution.
- Brightness/saturation/contrast and any other color setting.

28.4 Measurement of color fidelity

The X-Rite ColorChecker® classic chart provides a set of 24 representative colors with their theoretical values expressed in the CIE 1976 $L^*a^*b^*$ coordinates system.

Analyzer automatically detects the color patches within the test target image. Measurement of color fidelity error is performed for each uniformly-colored patch.

The color coordinates of each patch are measured in RGB values, and then converted to CIELAB coordinates. Any valid ICC profile is supported to define input RGB color space, notably sRGB, AdobeRGB and DCIP3. The ICC profile is read from Exif metadata of input image. If no such profile is defined, sRGB is used by default.

Analyzer offers detailed colorimetric information, mostly based on the standard defined in 1976 by CIE (CIE Draft Standard DS 014-4.2/E:2006: "Colorimetry - Part 4: CIE 1976 *L***a***b** Color Space").

28.4.1 Distances between colors

Considering two colors expressed in Lab coordinates:

$$\mathrm{Color}_1 = (L^*{}_1, a^*{}_1, b^*{}_1)$$
$$\mathrm{Color}_2 = (L^*{}_2, a^*{}_2, b^*{}_2)$$

let

$$\Delta L^* = L^*{}_1 - L^*{}_2$$
$$\Delta a^* = a^*{}_1 - a^*{}_2$$
$$\Delta b^* = b^*{}_1 - b^*{}_2$$

be the elementary errors. From those differences, CIE defines several color errors:

- The Euclidian distance CIE 1976

  $$\Delta E = \sqrt{\Delta L^{*2} + \Delta a^{*2} + \Delta b^{*2}}$$

  represents the difference between two colors.

  $\Delta E > 3$ reflects a noticeable color difference.

- SMI: Sensitivity Metamerism Index

  SMI is defined in ISO standard 17321 and describes the ability of a camera to reproduce accurate colors.

  SMI is an index quantifying this property, and is represented by a number lower than 100 (negative values are possible). A value equal to 100 is perfect color accuracy. A value of 50 is the difference in color between a daylight illuminant and an illuminant generated by fluorescent tubes, which is considered a moderate error.

  More precisely, SMI is defined as

$$\mathrm{SMI} = 100 - 5.5 \times \overline{\Delta E}$$

where $\overline{\Delta E}$ is the average CIELAB error observed on the X-Rite ColorChecker® classic patches.

- Absolute Chroma error (absolute value of the ΔC^* CIE 1976)

$$\Delta C = \sqrt{a^{*2}_1 + b^{*2}_1} - \sqrt{a^{*2}_2 + b^{*2}_2}$$

Absolute Chroma = $|\Delta C|$

- Hue error CIE 1976

$$\Delta H = \sqrt{\Delta E^2 - \Delta L^{*2} - \Delta C^2}$$

Geometrical meaning:

Let θ be the angle on the (a^*, b^*) plane “between the two colors”:

$$\cos(\theta) = \frac{1}{2}\left[\frac{C^*_1}{C^*_2} + \frac{C^*_2}{C^*_1} - \frac{\Delta a^{*2} + \Delta b^{*2}}{C^*_1 \cdot C^*_2}\right]$$

Assuming θ is small:

$$\theta = \frac{\Delta H}{\sqrt{C^*_1 \cdot C^*_2}}$$

- Color difference that omits exposure

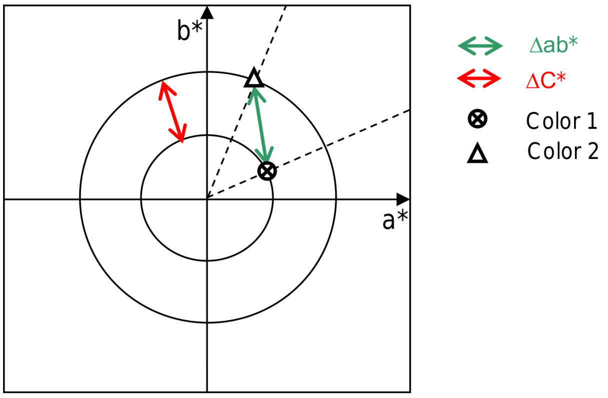
$$\Delta ab^* = \sqrt{\Delta a^{*2} + \Delta b^{*2}}$$

This formula does not entirely remove the exposure effect, but reduces it to an acceptable level and is therefore a lot more stable.

- SMI (White balance)

$$\mathrm{SMI}_{\mathrm{WB}} = 100 - 5.5 \times \Delta ab^*$$

is an index quantifying the white balance bias.



28.4.2 White balance

As a by-product of color fidelity, Analyzer offers a white balance measurement. The white balance error is evaluated using the average and the maximum of color fidelity error (precisely, the *Δab* error) on grey patches, excluding black and white.

28.4.3 White balance and exposure correction

The dependence of color fidelity on the exposure parameters and the white balance settings can be reduced. Indeed, Analyzer provides exposure and white balance corrections, which dramatically stabilize the measurement.

Exposure and White balance corrections are computed using the RGB coordinates of the target's grey 36% square (grey 6.5 using the Munsell notation).

- Exposure correction:

  When the exposure of the evaluated chart is not close enough to the theoretical chart exposure, the Color Fidelity measurement can be biased. This can be corrected by applying an *a posteriori* exposure correction that multiplies each color channel of the evaluated chart by the same scale, computed on a reference square:

$$\text{scale} = \frac{\text{Theoretical green level on the reference square}}{\text{Measured green level of the reference square}}$$

The reference square is the 21st square on the chart, representing neutral grey at 36% reflectance (or grey 6.5 using the Munsell notation).

- White balance correction:

  In case the white balance correction on the chart is unsatisfactory, an automatic *a posteriori* white balance correction can be achieved by scaling the red and blue channels, which means that red and blue scales are evaluated using a reference patch on the chart:

$$\text{red scale} = \frac{\text{Measured green level on the reference square}}{\text{Measured red level of the reference square}} \quad \text{for the red channel,}$$
$$\text{blue scale} = \frac{\text{Measured green level on the reference square}}{\text{Measured blue level of the reference square}} \quad \text{for the blue channel.}$$

  The reference square is the 21^{st} square on the chart representing neutral grey at 36% reflectance (or grey 6.5 using the Munsell notation).

28.5 Measurement in raw format

Because color rendering is achieved in the raw conversion process, the Color Fidelity measure only makes sense for RGB images.

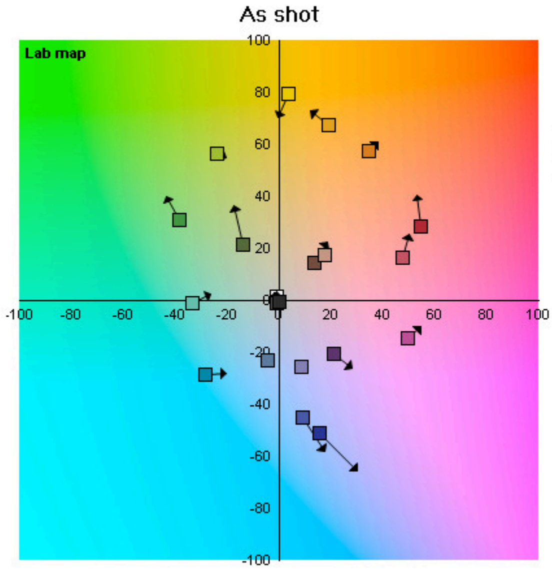
28.6 Analyzer output

Analyzer returns the following results:

- The Summary tab presents the color fidelity and white balance as-shot measurement.
- The 2D maps tab graphically illustrate the color fidelity in the (a, b) plane of the CIELAB (1976) color space. Four series of maps are given:
  - The results directly computed from the RGB image.
  - With a posterior white balance correction.
  - With a posterior exposure correction.
  - With both balance and exposure correction.

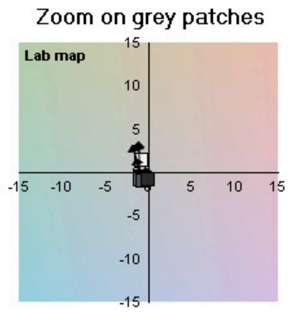
  Each series has the following results:

- Each square represents a patch on the X-Rite ColorChecker® classic chart. Because the CIELAB color space takes the illumination into account, the positions of the squares are independent of the illumination. An arrow starts from each square. The end of the arrow gives the measured value of the color.
- A zoomed crop of the map around the origin is displayed on the right side. It contains all the grey patches and gives insight about the white balance accuracy.
- A summary of the numerical values are also displayed, including the mean and maximum values for different distances, as well as the mean and maximum *Δab* value measured for only the grey patches, excluding black and white (white balance).



	Mean	Max.
Δ C	5.75	18.59
Δ H	3.66	11.02

	Mean Δ ab	Max. Δ ab	SMI
Color Fidelity	7.25	20.47	49.73
White Balance	3.68	4.30	79.79



- Analyzer's second type of data output is the table of color difference values for each patch and for different color distances. The patches are presented in the same order as on the X-Rite ColorChecker® classic chart, with grey patches on the bottom row. The values are given under the same conditions as the 2D maps: as-shot (RGB image from the camera), with an *a posteriori* white balance correction, or/and exposure correction.

	Mean values	Max. values
Δ L	0.94	11.78
Δ a	1.73	14.66
Δ b	1.92	14.98
Δ ab	7.25	20.47
Δ E	9.14	20.93
Δ C	5.75	18.59
Δ H	3.66	11.02

Δ L	-5.79	3.03	1.66	-1.17	3.32	5.28
Δ a	5.18	1.67	-0.82	-3.75	1.84	6.64
Δ b	8.34	1.19	-0.77	14.98	1.67	3.31
Δ ab	9.82	2.05	1.12	15.44	2.49	7.42
Δ E	11.40	3.65	2.00	15.49	4.15	9.10
Δ C	9.69	2.02	0.92	14.93	0.90	6.54
Δ H	1.61	0.32	0.63	3.94	2.32	3.50

Δ L	3.56	0.33	4.07	-5.94	5.80	4.45
Δ a	3.23	8.30	2.89	7.03	3.33	-6.84
Δ b	3.06	-13.15	8.94	-5.37	-1.64	5.33
Δ ab	4.45	15.55	9.39	8.85	3.71	8.67
Δ E	5.70	15.56	10.23	10.66	6.89	9.74
Δ C	4.30	14.80	6.16	8.79	2.75	3.71
Δ H	1.16	4.77	7.09	1.00	2.49	7.83

Δ L	-4.37	6.92	3.25	2.01	4.77	6.29
Δ a	14.66	-5.16	-1.56	-4.23	4.87	7.63
Δ b	-14.28	8.60	12.08	-9.15	4.61	0.92
Δ ab	20.47	10.03	12.18	10.08	6.71	7.68
Δ E	20.93	12.18	12.61	10.28	8.23	9.93
Δ C	18.59	9.53	5.20	9.23	3.69	5.67
Δ H	8.57	3.13	11.02	4.06	5.60	5.18

Δ L	-5.09	2.58	5.39	1.21	-7.14	-11.78
Δ a	-0.31	-0.71	-1.14	-0.17	-0.69	-0.32
Δ b	1.78	3.69	3.86	4.29	2.53	1.34
Δ ab	1.80	3.76	4.02	4.30	2.62	1.37
Δ E	5.40	4.56	6.73	4.46	7.61	11.86
Δ C	1.73	2.47	2.68	2.47	1.09	0.06
Δ H	0.52	2.84	3.00	3.51	2.38	1.37

28.7 Measurement accuracy

The repeatability of the **Color Fidelity** error measurement is not guaranteed when the exposure correction and the white balance correction algorithms are not stable (they often depend on the image content). The accuracy of the Color Fidelity error measurement has been estimated on images under the same illumination and with corresponding exposure and white balance.

The accuracy of the color fidelity error computed on *Δab** is ±5%.

Example:

	Measure	Range
*Δab** mean	5.60	[5.32, 5.88]
*Δab** max	16.70	[15.87, 17.54]
ΔE mean	6.00	[5.70, 6.30]
ΔE max	21.2	[20.13, 22.26]

The repeatability of the **white balance** error measurement is not guaranteed when the exposure correction and the white balance correction algorithms are not stable (they often depend on the image content). The accuracy of the white balance error measurement has been estimated on images under same illumination and corresponding exposure and white balance.

The accuracy of the white balance error computed on delta ab is ±5%.

Example:

	Measure	Range
Grey *Δab** mean	5.60	[5.32, 5.88]
Grey *Δab** max	9.70	[9.125, 10.185]

28.8 Measurement scale

28.8.1 Color fidelity

Δab^* mean	Qualitative effect
$x < 8$	Chart colors are similar to theoretical colors.
$8 < x < 15$	Chart color are different from the theoretical colors, but it could be the camera manufacturer's choice.
$x > 15$	Colors are bad, or there may be a problem with exposure or white balance.

28.8.2 White balance

White balance measure (mean grey Δab^*)	Qualitative effect
$x < 5$	Very accurate white balance.
$5 < x < 8$	Correct white balance.
$8 < x < 11$	Perceptible error, but acceptable.
$x > 11$	Bad white balance.

28.9 Setup parameters influencing the measurement

Carefully check the following parameters:

- No dust on either the lens or the sensor.
- The position of the test target is correct in relation to the camera/photographer's eye axis.

- Lighting is uniform on the test chart.
- Lens choice.
- Size of the test target in the image (shooting distance).

28.10 Measurement validity

Camera manufacturers frequently make decisions to aim for more contrasted and saturated colors than the theoretical ones, which often appear a bit dull. Moreover, an isolated measurement of color fidelity is meaningless, as it should always be given with the following parameters:

- Contrast, saturation, brightness and/or hue (and any other color setting).
- Color mode, if needed.
- Choice of ISO to be measured.
- Color space.

28.11 Comparing two cameras

You can compare measurements at identical exposures if ISO and illumination are identical. Ideally, white balance and exposure correction must be equivalent; but the exposure and white balance corrections allow more flexibility. In such cases, grey level dynamics and neutralization of the photographs are identical on images to be compared. Measurement accuracy is then compatible between images.

28.11.1 Comparison example

The two following pictures have been shot under illuminant D50, with an ISO sensitivity 200.

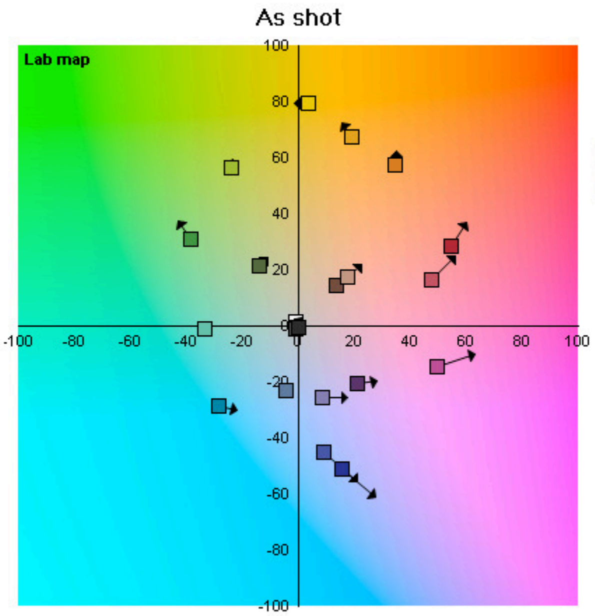
Camera phone (iPhone5S)

DSLR (Nikon D810)

We observe that:

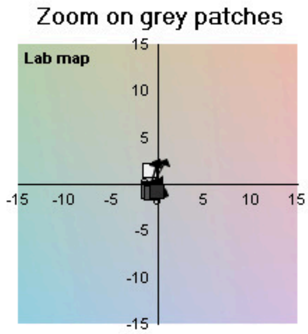
- The white balance tends slightly to green on the Nikon D810.
- Magenta is slightly oversaturated on the iPhone5S (3rd line, 5th column).
- Blue flower (1st line, 5th column) are quite similar.

These trends can also be observed on the color fidelity 2D maps below.

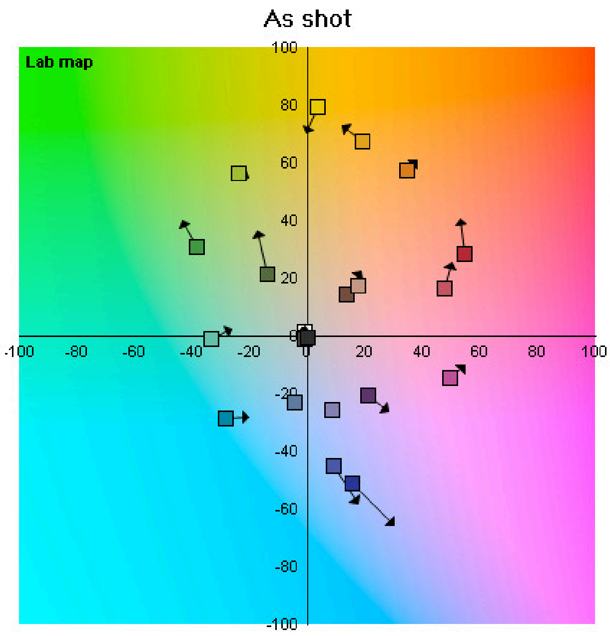


	Mean	Max.
Δ C	4.89	13.51
Δ H	3.77	8.35

	Mean Δ ab	Max. Δ ab	SMI
Color Fidelity	6.58	15.84	45.91
White Balance	3.11	3.97	82.87

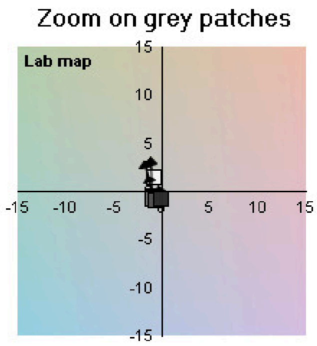


Color fidelity map for a camera phone (iPhone5S)



	Mean	Max.
Δ C	5.75	18.59
Δ H	3.66	11.02

	Mean Δ ab	Max. Δ ab	SMI
Color Fidelity	7.25	20.47	49.73
White Balance	3.68	4.30	79.79



Color fidelity map for a DSLR (Nikon d810)

The measurements prove that the two devices have a close behavior on color representation. The DSLR globally reproduces colors that are slightly closer to the reference, while its white balance is slightly less accurate than that of the camera phone.

The measurements prove that the DSLR globally reproduces colors that are closer to the reference, though there are noticeable deviations from the reference for red and blue tones. However, in this case, this may reflect the subjective choices of the manufacturer about producing more saturated reds and blues. Sensors in the camera phone are of lower quality; the usual difficulty is obtaining colors close to the reference while controlling noise.

28.12 Shooting

a) **Install the appropriate X-Rite ColorChecker® Classic (see Section 4.12).** We strongly recommend using the frame with markers that allows automatic detection even in a scene.

b) **Decide on the important parameters, if applicable:**

- Minimum level of sharpness, or sharpening filter inactive.
- Activation of a noise reduction filter.
- Contrast, saturation, brightness and/or hue = 0 or are inactive (along with any other color setting).
- Maximum resolution.
- Maximum image quality (best compression ratio).
- Choice of ISO to be measured, otherwise ISO = 200 is recommended.
- Color space.

c) **Special conditions for framing the photograph (see also Section 4).**

To correctly detect the test target in the image and thus achieve a reliable measurement, take care about the following points:

- There is no dust on either the lens or the sensor.
- The test target is correctly oriented — that is, the text is at the bottom of the shot image.
- The edges of the test target are parallel to the edges of the image.
- The test target is correctly exposed and uniformly lit.
- The white balance is correct (lower than 8 using Analyzer White Balance measurement).
- The distortion in the image is lower than 1% (Analyzer TV distortion metric) if possible.
- Each patch has at least 64×64 pixels visible in the digital image.

- The test target covers 75% of the framing; the background color should differ from the colors of the patches in the test target, and the test target should be centered.
- If possible, make sure there is no vignetting or at least less than 45% attenuation on each channel (Analyzer measurement).

Take all necessary precautions to avoid shaking the camera when shooting. You may want to use a cable release or trigger the shot from a computer connected to the camera.

28.13 Sidecar parameters

Use the `[Common]` section for measuring noise on the X-Rite ColorChecker® classic for raw and RGB formats. Coordinates are the positioning coordinates on the chart, not the markers of the frame.

```
[Common]
// Manual X-Rite ColorChecker\textregistered\ classic chart position
X1=... // x coordinate of the top-left corner
Y1=... // y coordinate of the top-left corner
X2=... // x coordinate of the top-right corner
Y2=... // y coordinate of the top-right corner
X3=... // x coordinate of the bottom-left corner
Y3=... // y coordinate of the bottom-left corner
X4=... // x coordinate of the bottom-right corner
Y4=... // y coordinate of the bottom-right corner
```

The color section allows you to use different illuminants. The default illuminant is D65

Illuminant, and in this case, white points and $L^*a^*b^*$ reference values are also provided by default.

You can provide the white reference point in the sidecar (x, y coordinates; Y is supposed to be equal to 1). In this case, the lab reference values are required and a chromatic adaptation will be applied.

Providing $L^*a^*b^*$ overrides the Illuminant defaults values.

Providing the xy white point overrides the illuminant white point, and implies provided $L^*a^*b^*$ values, too.

You can also define the Lab reference values as described below. The index given after L, a, or b should correspond to the patch as described on the image below.


```
[Color]         // Color section
Illuminant=... // A, B, C, D50, D55, D65 or D75
x_whitepoint=
y_whitepoint=
L1=
a1=
b1=
...
L24=
a24=
b24=
```

Note that you must provide values for the 24 patches, otherwise the default Lab values will be used.

29 – FL: Flash

29.1 Introduction

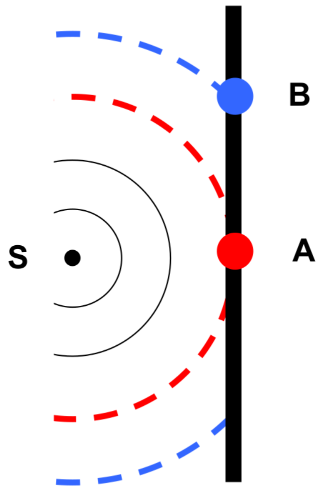
A flash is a physical lighting unit mounted on or embedded into a camera. Its typical use is to illuminate a scene when light is too low to adequately expose the image. A flash can also serve as an additional light source for the scene, with the mixed lights illuminating the shadows on the side facing the camera.

Typical use of a flash for scene illuminating. Left: without flash. Right: with flash

As with any light source, the light of a flash has intrinsic characteristics: power, direction, and spectral distribution. Analyzer can characterize the three typical flash effects presented in the following sections.

29.1.1 Non uniformity

At first approximation, the light emitted by the flash can be considered a pointwise light source. The light then follows the inverse-square propagation law: its amplitude decreases with the square of the distance from the light source (Bouguer Law). Therefore the effect of the flash on an image is not uniform. The non-uniformity depends on two factors: the distance between the flash and the exposed object, and the area being exposed. The following figure illustrates this phenomenon.



S is the light source and considered as being the flash. It illuminates the thick black panel.
Each propagating front is represented as a circle around S. From the propagation law and because the distance from S is equal for all points on the same front, the power of the light is the same for all points on the same front.
The point A in the panel receives more light than the point B, since the distance between S and B is higher than the distance between S and A.

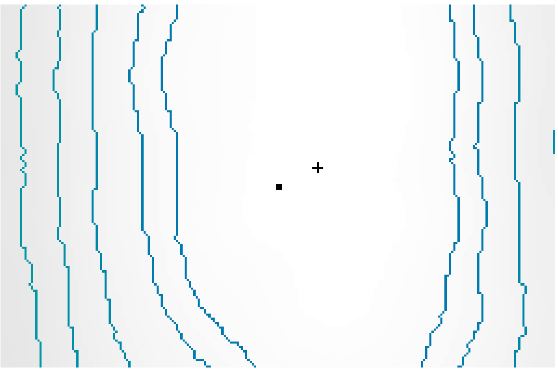
In scenes where the distances between two points within the image become non-negligible, this physical effect is visually perceptible. In the previous example, the greater the distance between A and B, the greater the difference of light power they receive.

On the other hand, the radius of the propagating fronts increases with the distance between the light source and the exposed object. When this distance becomes very large, the propagating fronts are almost planar and the light is considered “diffuse.” In the previous example, the light reaching points A and B has the same power if S is infinitely far from the plane, and the lighting becomes uniform.

While sometimes desirable, non-uniformity of the light source may expose some parts of the photograph more than others. This leads to different exposure values on some parts of the image.

As with the Vignetting measurement, the decay of the luminance from the center to the edges of the chart images provides valuable information.

Finally, in the preceding examples, the light source was assumed to be pointwise. However, this hypothesis is not always verified and depends both on the shape of the flash body and the distance between the flash body and the chart. This explains why sometimes the shape of the flash body becomes visible in the image. The influence of the flash body decreases with the distance from the chart, as illustrated in the figure below.



The image on the left was taken with a *Canon EOS 30D* DSLR with a mounted *Canon Speedlite 420EX* flash unit. The shot of the chart was taken at a distance of 1.5 m. Since the flash is rectangular-shaped and the distance from the chart was particularly low, the pointwise hypothesis is not verified. The image shows fall-off lines that are not circular. This indirectly shows that the reflectors of such a flash diffuse the light differently toward vertical or horizontal axes.

29.1.2 Overall illumination off-centering

Mounting an external flash device to a camera body naturally induces a translation of the overall illumination in the scene. The shifting of the center may sometimes lead to some undesirable effects, all the more so as the phenomenon is hardly foreseeable. As mentioned above, whether the flash unit in particular (and of the whole system in general) is pointwise is not guaranteed when the distance between the flash unit and the object is small.

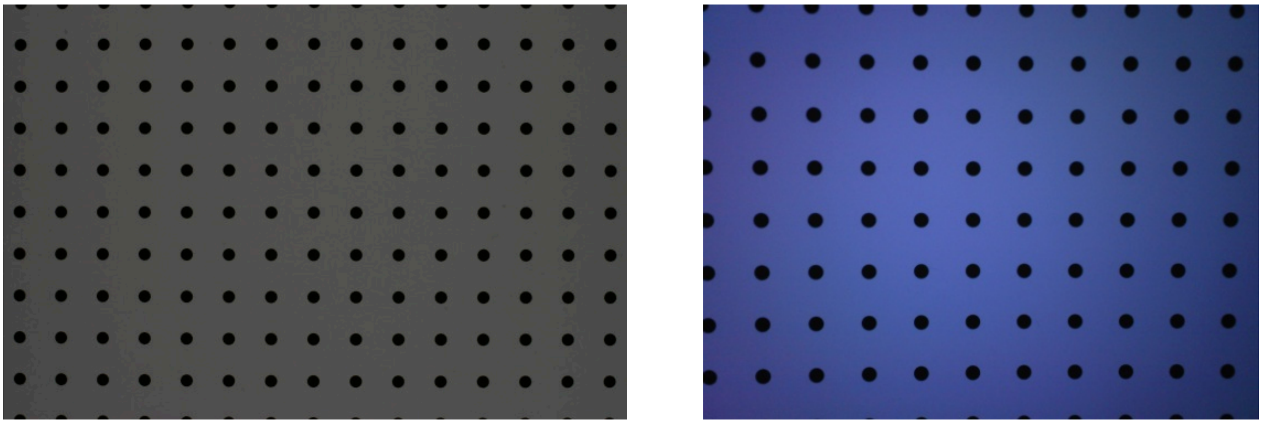
Hence, the "*overall illumination off-centering*" measurement provides relevant information about the distance below which the system cannot be considered pointwise.

29.1.3 White balancing

An acquisition system has to compensate for the illuminant so that the produced image has no color cast. A neutral grey chart should be grey on the digital image; however, this behavior can rarely be achieved for the following reasons:

A flash is often considered as a light source equivalent to a black body radiator with a temperature in the 5500 K–6500 K range (daylight). This parameter can fluctuate. In Analyzer and for the scope of the Flash measurement, the content of the images is assumed not to introduce any chromatic content (in other words, a grey chart is the subject of the shot).

If the camera is in Auto White Balance mode (AWB), the imaging system has to compensate for the flash illuminant when the flash is on or for the illuminant if it is off. The camera may have a "Flash White Balance" (FWB) mode, too, and in that case the compensation takes into account the flash.



Different results for white balancing. Left: Canon EOS 30D with the internal flash unit and AWB. Right: "Samsung D900" camera phone with the internal flash unit and AWB

These color balancing features depend on the camera body and are not commonly available. It is assumed in the following analysis that the camera body is set to AWB mode.

Analyzer's FL measurement can quantify the camera's ability to correct the white balance. The measurement is thus performed on the full imaging system of both camera and flash, and is not a characteristic of the flash alone.

29.2 Definitions

Non-uniformity is mainly characterized by light intensity fall-off from the center to the edges of the resulting images. To that extent, the non-uniformity measurement is similar to the Vignetting measurement described in Section 15.4. As with the Vignetting measurement, the fall-off is expressed in density, EV, and percent.

The computation of the fall-off profile needs a center point. This point is not necessarily at the center of the image, but is rather a point called the "*center of flash*," which identifies the location in the image where the light received by the object is maximal. Indeed, as mentioned in the introduction, flash use induces an overall illumination off-centering. The center of flash provides a means of accurately coping with this shifting.

- Uniformity: a light source is considered as uniform when the exposure is equal at any point on the exposed object. For purposes of the FL measurement, the mentioned object is planar.
- Center of flash: identifies the locus of the point that receives the most light during a shot. It is a

physical coordinate (pixel) in the image.

- Off-centering is a value quantifying the overall illumination of the off-centering phenomenon. It is independent of the image size and has no unit. The higher this value, the further the flash center is from the image center.

- Chromatic deviation is defined as the average color of the center of the flash. Its value is expressed as a "*Δab*" color difference (refer to part 28.4 for more information). The higher this value, the further the flash center color is from grey.

29.3 Influencing factors

Since the FL measurement is similar to the Vignetting measurement, the influencing factors are also similar. However, the FL measurement is intended for qualifying flash characteristics. In order to quantify a flash alone, it is necessary to reduce camera vignetting by choosing an appropriate aperture. If it is not possible to change the aperture, the measurement qualifies the whole camera + flash system.

Assuming the absence of vignetting, the following factors are of particular concern for measuring FL:

- Distance from the chart: as mentioned, the light emitted by the flash follows the inverse-square law. Obviously, the distance of the chart from the flash is an important influencing factor on the power of light received by the chart. Besides the power of light, the greater the distance, the greater the radius of the waves arriving on the chart, and consequently, the better the uniformity of the light. Moreover, the greater the distance, the less influence the flash body shape has on the resulting image.

- Aperture: the aperture of the lens reduces the quantity of light reaching the capture module inside the body. The quantity of light emitted by the flash is too high for a small f-number to be used. Moreover, a small aperture reduces the influence of the vignetting on the measurement.

- Charge delay: the internal capacitors of the flash need a delay to charge up fully. Hence, the amount of time should be observed between two consecutive flashes. One minute is recommended between shots.

- Charge level of the flash battery: the lower the charge of the battery, the longer the time needed to charge the internal capacitors. It is assumed that the battery is fully charged when testing.

- Exposure time: the exposure time is generally longer than the overall flash lighting time. When possible, a long exposure time should be used (1/30 s or 1/15 s, for instance) in order to capture all the light power.

29.4 The measurement of FL

Here are the different measurements related to flash characteristics:

29.4.1 Uniformity

As mentioned, the FL measurement is similar to the Vignetting measurement. In that sense, almost all the information about the Vignetting measurement are applicable here.

The maximum fall-off provides information about how the light is distributed on the exposed object. If the fall-off remains low, the light of the flash is considered as uniform.

Maximum fall-off is provided in the following units:

- Percent
- EV (see Section 15.4)
- Density

29.4.2 Off-centering

The center of the flash provides the geometrical center of the most exposed points. Off-centering is expressed in percent. It represents the ratio between the distances from the image to the flash center, and the length of the half-diagonal of the image:

$$d_{\text{off-}C} = \frac{||CL - CI||}{||\text{corner} - CI||}$$

where CL, CI and "corner" are respectively the center of flash, the center of the image, and one of the image corners. This measurement is independent of the size of the image.

29.4.3 Chromatic deviation

This quantity is measured on color RGB images only and is discarded for grey level or raw images. Two different phenomena are in play in the detection of chromatic neutrality: The first is the spectral distribution of the light emitted by the flash itself; the second is the ability of the camera body to compensate for the chromatic deviation.

However, the measurement treats these two phenomena as one unique system. The main assumption about this measurement is that the chart being shot is chromatically neutral, and thus the resulting image's chromatic content should also be neutral.

The locus of points where the light is the most powerful defines a particular subset of points. The chromatic deviation is computed within this subset in the CIELAB color space as a color difference with the grey, without accounting for the exposure. (See Section 28.4 for further details.) The chromatic deviation is defined as:

$$\Delta c = \sqrt{\bar{a}^2 + \bar{b}^2}$$

where $\bar{a}$ and $\bar{b}$ are respectively the mean of CIELAB a^* and b^* (from the chromatic plane in the CIELAB color space) within the subset. Subsetting the points for this computation limits the effect of the color vignetting.

29.5 Measurement in raw format

Analyzer measures FL on RAW-format images, as raw images are not subject to any type of prior digital processing. The maximal fall-off value on raw images provides information on the intrinsic characteristics of the flash, while the same measurement on RGB images provides information on the system of flash and camera.

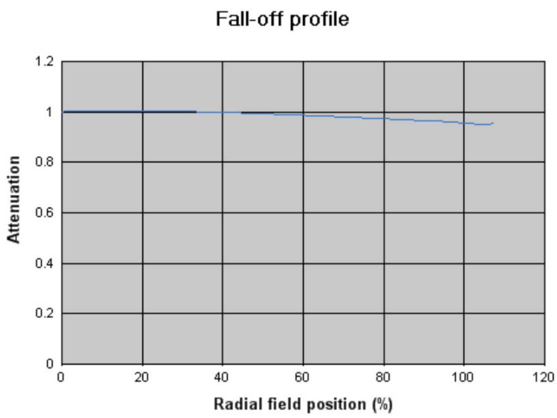
For the scope of the flash, the FL measurement on raw images does not take into account the tone curve correction. Since this correction is not linear, there is no trivial correspondence between the measurements on raw and on RGB images.

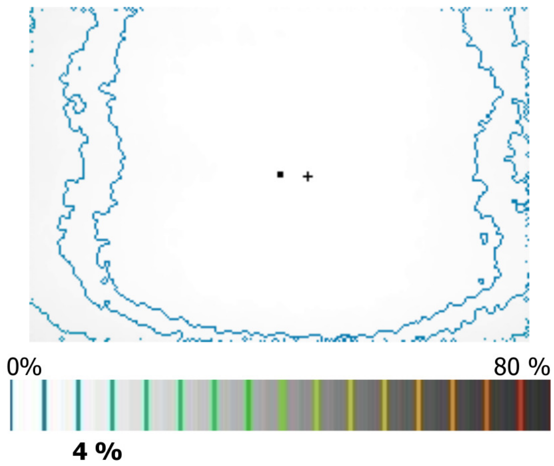
You can define the following two parameters using a sidecar file:

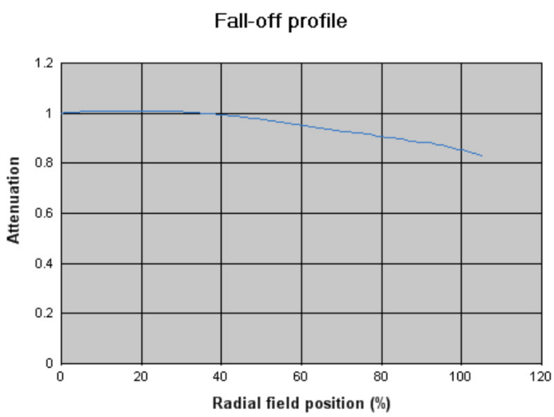
- Dark signal
- Crop area

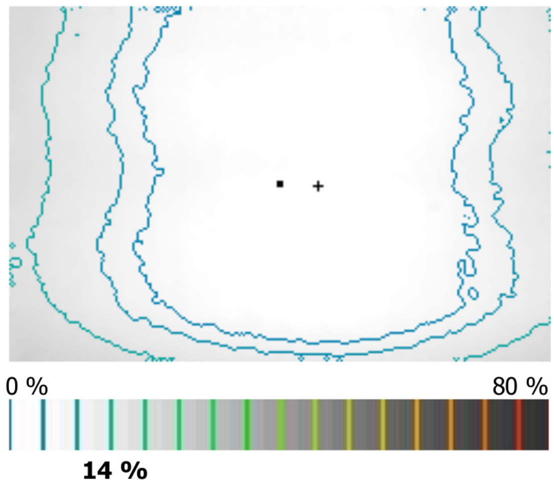
The crop area does not influence the measurements. An inappropriate setting may lead to a truncated fall-off graph, as shown in the figure below (first row, left graph), but has no impact on the measurements. Indeed, the maximal fall-off value does not take this artifact into account.

As mentioned, there is no trivial correspondence for a unique shot between measurements performed on the raw or the RGB image file. The following figure shows the results for the same shot saved both in raw and RGB format.









29.6 Analyzer outputs

Analyzer outputs are organized by tabs. The Summary tab provides most of the relevant measurement results, while the Fall-off Profile tab provides a graphical interpretation of those results. These outputs are detailed below.

- The Summary tab contains the maximal fall-off value in the image, expressed in different units (Ev, percent of the image dynamic, and density).

  The chromatic deviation is also provided for RGB images only. This value is expressed as a "*Δab*" color difference.

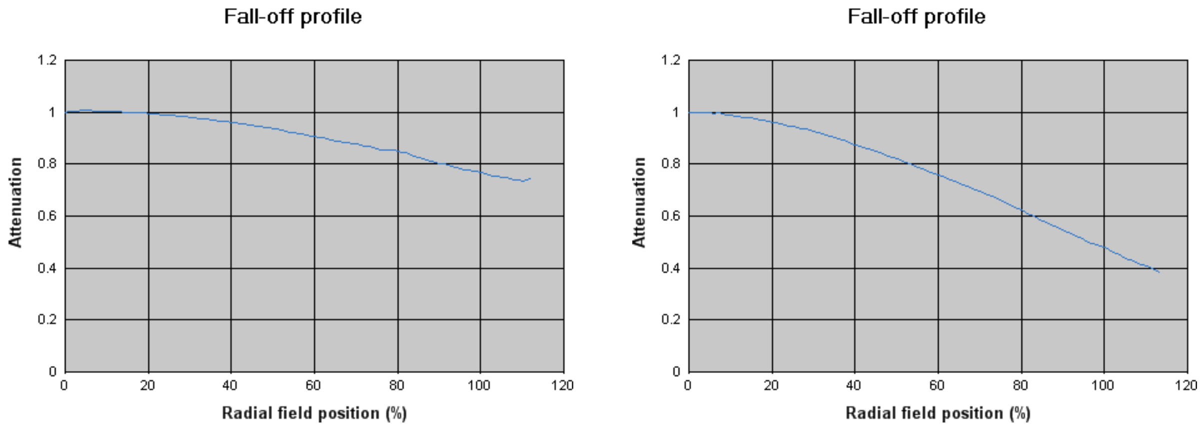
  Other measurements of interest are the off-centering expressed in percent (see Section 29.4), and the grey level at flash center. This latter value is intended to measure exposure level control.

	in Ev	in %	in density
Max. Attenuation	1.05	51.6	0.32
Chromatic deviation	47.46		
Off-centering (in %)	14.63		
Grey level at lightning center	94.25		

Summary for the Samsung D900 with its internal flash unit, fired at 50 cm

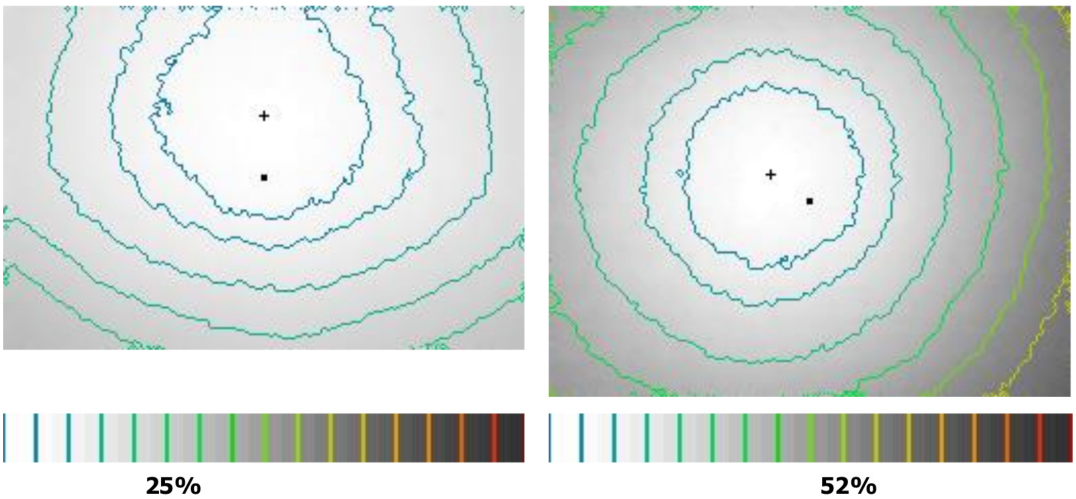
- The Fall-off Profile tab shows two graphics: a one-dimensional fall-off map and a thumbnail image.

  The 1D map (figure below) shows the average fall-off profile. As explained, this profile maps the isodistances to the mean grey levels observed in the image. The origin of the map is the center of lighting.



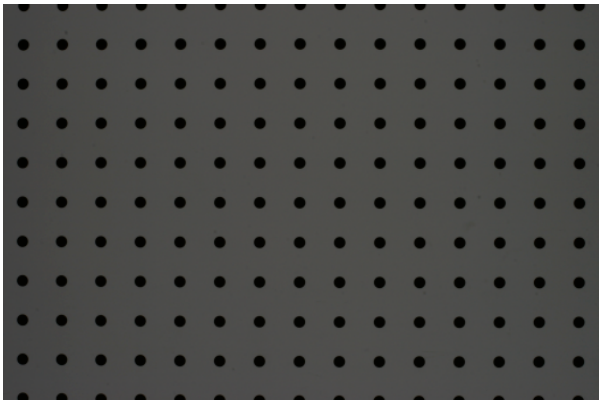
Left: Canon EOS 30D with a Canon Speedlite 420EX flash unit, fired at 1.5 m.
Right: Samsung D900 with its internal flash unit (at 50 cm)

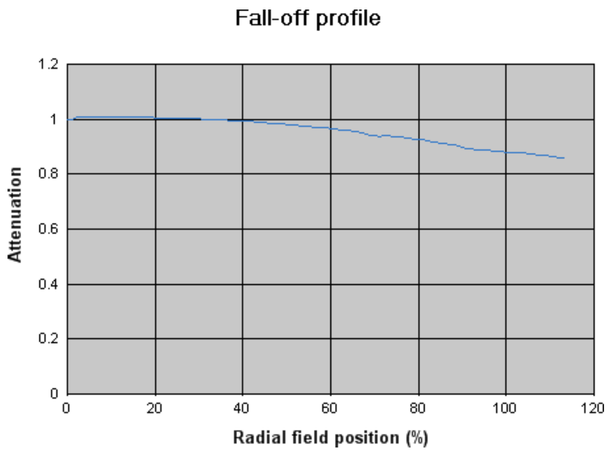
A thumbnail image highlights the fall-off of the flash, and helps you see the effects of non-uniformity. The flash center is drawn as a cross, while the image center is represented by a dot. The lines show the decay of the light from the flash center. Their colors indicate the fall-off value expressed in percent. These colors are reported in the legend that appears below the thumbnail image. Finally, the maximal fall-off expressed in percent is reported below the legend. The following figure shows the thumbnails corresponding to the results above.



29.7 Examples

The following figures show the results for a *Canon EOS 30D* with a *Canon EF50mm f/1.4 USM* lens. The focal length is 50 mm, ISO 100, and the f-number is 22. The flash unit is embedded in the body. The distance between the chart and the camera is 1.5 m. The measurements are performed on the RGB image below left.

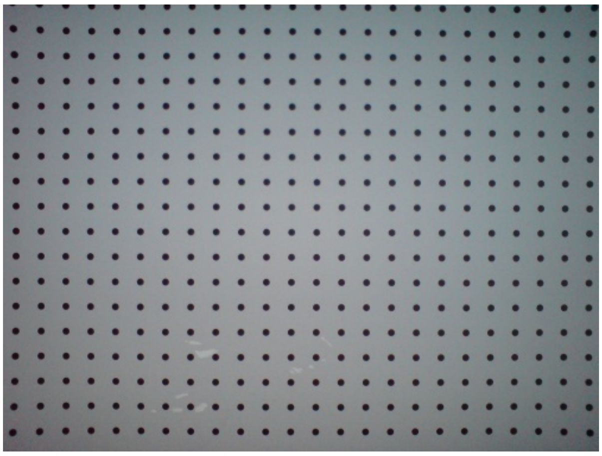


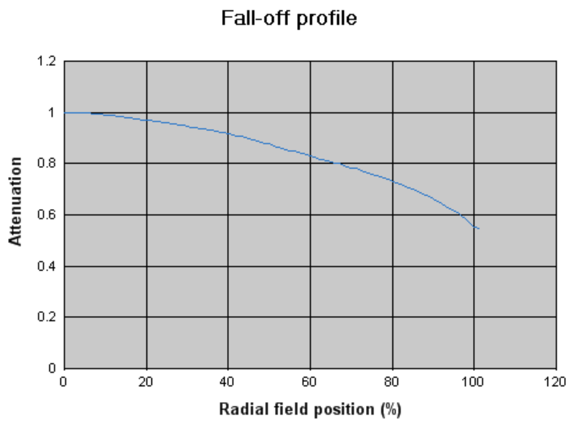


In the left-hand example above, the fall-off is hardly perceptible visually. However, the fall-off graph on the right shows the decay of the light near the corners. The computations provide a maximum fall-off of 12%, which is particularly low. The embedded flash unit has good uniformity at 1.5 m.

The maximal fall-off value is 12% (1 – 0.88), while the graph shows a more important decay at abscises over 100. This is explained by the fact that values over 100 are not taken into account for the maximal fall-off value. (Values over 100 are provided for information).

The following figures show the results for a Sony-Ericsson K800 camera phone. The image was taken at 1 m from the chart. The results are very different from those of the DSLR.





The maximum fall-off is 46%. However, for the camera phone, the vignetting correction has a non-negligible impact on this measurement.

Since the chart is assumed to be white, it is possible to deduce the chromatic deviation of the overall system (flash color and AWB mode). However, for camera phones, the color vignetting is quite high. As mentioned, the computation of the chromatic deviation is restricted to a particular subset of the image (for example, as in Section 29.4). In the above image, the points near the center are rather grey, and the computed chromatic deviation is “only” 2.25, even if the color vignetting suggests a higher chromatic deviation.

29.8 Measurement accuracy

As with vignetting, the dark signal may shift the overall fall-off profile. The fall-off difference is given by the following formula:

$$\Delta F = \frac{F \cdot DS}{VN_{\text{center}} - DS}$$

where VN_{center} is the exposure at the center of flash, DS is the dark signal, and F is the measured maximal fall-off with dark signal (all expressed in percent). The equation above shows that the difference between the theoretical maximal fall-off and the measured fall-off is proportional both to the dark signal and to the fall-off value itself. On the other hand, if the image is under-exposed, the term for the denominator may become non-negligible. It is straightforward to deduce that accuracy is better with high exposure.

The power of the light emitted by the flash unit is also dependent on the battery charge level and the time between two consecutive shots. There is no way to retrieve these parameters accurately.

29.9 Measurement scale

A flash is considered good if the three following conditions are met:

1. The center of flash remains close to the center of the image.
2. The chromatic deviation remains low, which guarantees the ability of the paired flash and camera body to properly manage the white balance.
3. The maximum fall-off remains low, which signifies that the light emitted by the flash is uniform for the subject surface.

The following tables provide qualitative information about the values provided by Analyzer. These results were based on a wide array of reference hardware.

29.9.1 Luminance fall-off

Maximum lessening value (EV)	Maximum lessening value (%)	Qualitative level
Between 0 and 0.16 EV	Between 0 and 10%	Excellent
Between 0.17 and 0.33 EV	Between 11% and 20%	Very good
Between 0.34 and 0.4 EV	Between 21% and 24%	Good
Between 0.4 and 0.7 EV	Between 25% and 39%	Fair
Between 0.8 and 1.2 EV	Between 40% and 55%	Bad
Over 1.3 EV	Over 56%	Very bad

29.9.2 Chromatic deviation

Δc	Qualitative level
Between 0 and 2	Excellent
Between 3 and 6	Very good
Between 7 and 9	Fair
Between 10 and 30	Bad
Over 30	Very bad

29.9.3 Off-centering

As previously mentioned, the *off-centering* measurement provides quantitative information on the centering of the flash's light. A value close to 0 indicates good centering of the light.

The accuracy of this measurement is tightly correlated to the measurement of the maximal fall-off. If the fall-off remains low, thus indicating a rather uniform light, the influence of the off-centering also remains low. Conversely, if the fall-off is high, then the off-centering is relevant.

Value (%)	Qualitative level
Between 0 and 3%	Excellent
Between 4 and 9%	Very good
Between 10 and 17%	Good
Between 18 and 25%	Fair
Between 26 and 40%	Bad
Over 41%	Very bad

29.10 Setup parameters influencing the measurement

The parameters that influence the Flash measurement are:

- The part of the transfer curve that is involved, which depends on:
  - The ISO sensitivity.
  - Auto White Balance is ON.
- Any digital zoom is OFF.
- Image aspect ratio 4:3, 16:9, etc. (normally the shot should make use of the sensor field as much as possible, unless the sensor field is the object of the measurement).
- The compression ratio, which should be as low as possible (the TIFF format is preferred to JPEG, and if JPEG is used, choose a compression ratio that is less than 10).
- Specific modes of the camera such as saturation, contrast, color modes, etc., which should be turned OFF.

29.11 Validity of the measurement

The fall-off depends on the overall exposure of the image. Hence the measure can be neither relevant nor accurate for highly under-exposed or over-exposed images.

29.12 Comparing two flashes

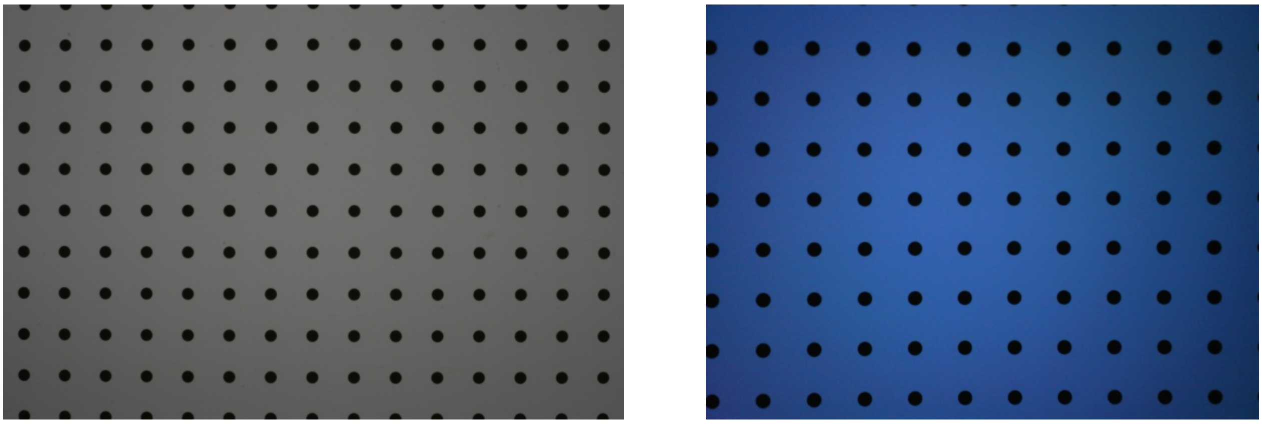
As with the Vignetting measurement, the fall-off measurement is independent of the image resolution. In addition, the measurements for off-centering as well as for chromatic deviation are also independent of the image dimensions, as mentioned in the Section 29.4. It is thus possible to compare two different flash-equipped systems.

In this section, the two following systems are compared:

1. *Canon EOS 30D* with a *Canon EF50mm f/1.4 USM* lens and a *Canon Speedlite 420EX* flash unit. The images were taken at 1.5 m from the chart. The lens is set to its smallest aperture.

2. *Samsung D900* camera phone with a fixed lens and built-in LED flash. The shots were taken at 50 cm from the chart. The lens aperture is not changeable.

Sample images for these two systems are shown on the figure below.



Sample shots. Left: Canon EOS 30D dSRL. Right: Samsung D900 camera phone

29.12.1 Measurements

The summary screens for the *Canon* and the *Samsung D900*, respectively, are shown below.

	in Ev	in %	in density
Max. Attenuation	0.40	24.3	0.12
Chromatic deviation	0.97		
Off-centering (in %)	20.81		
Grey level at lightning center	110.35		

	in Ev	in %	in density
Max. Attenuation	0.99	49.8	0.30
Chromatic deviation	45.08		
Off-centering (in %)	12.32		
Grey level at lightning center	90.42		

Analyzer outputs of the summary pane. Left: Canon EOS 30D dSRL. Right: Samsung D900 camera phone

- Maximal fall-off: The results show a very different result, as expected. The maximal fall-off is 24.3% for the Canon, while it reaches nearly 50% for the Samsung. The fall-off is thus non-negligible for the DSLR, but is particularly important for the camera phone. According to the tables provided in Section 29.9, the DSLR has quite good uniformity.

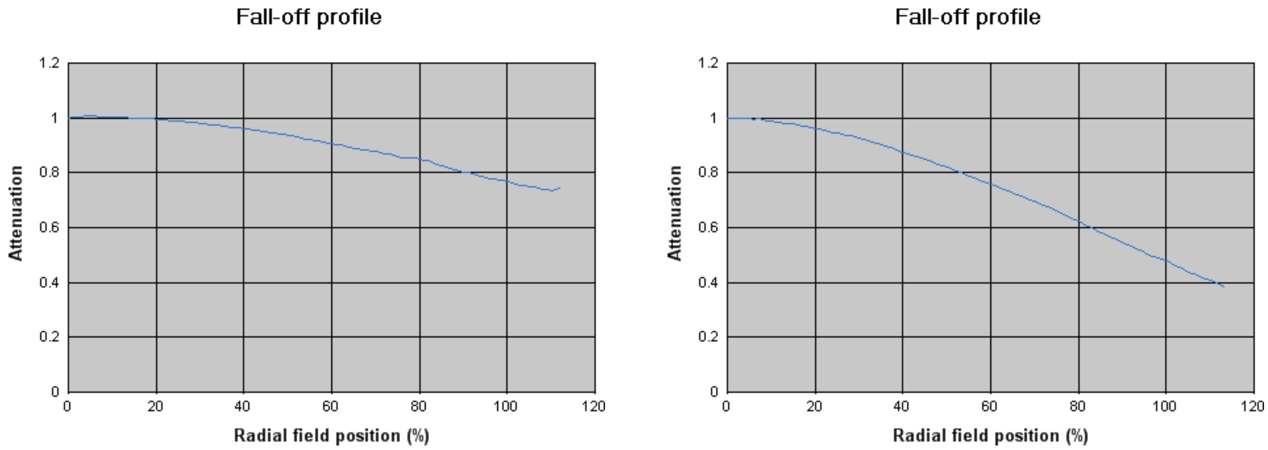
On the contrary, the uniformity of the camera phone is quite bad. However, the camera phone is used with its built-in lens, and shows a vignetting of 10% approximately under normal exposure conditions. It is worth noticing also that the distance of the camera phone from the chart is lower than for the DSLR. As mentioned, the uniformity measure is sensitive to the distance between the flash and the chart.

- Chromatic deviation: the results are in very different ranges. The results are 0.97 for the Canon and 45.08 for the Samsung. The chromatic deviation of the Canon is negligible, which means has good white balancing. This is not the case for the Samsung, which fails to balance the chart correctly. Its chromatic deviation is particularly high. This measurement is independent of the distance between the chart and the system.
- Off-centering: the results are close but reveal a very different flash system. The Samsung has good centering (i.e., low off-centering value) while the DSLR performance is only fair. Moreover, the distance of the camera phone from the chart is one-third that of the DSLR. These results are natural, since the flash is very close to the lens on the camera phone, while the flash is mounted (that is, it is an external unit) on the DSLR (figure below).

Left: Canon EOS 30D dSRL with a mounted Canon Speedlite flash unit.
Right: Samsung D900 camera phone with its built-in flash unit.
The flash and the lens are very close on the camera phone, which led to a good centering performance.

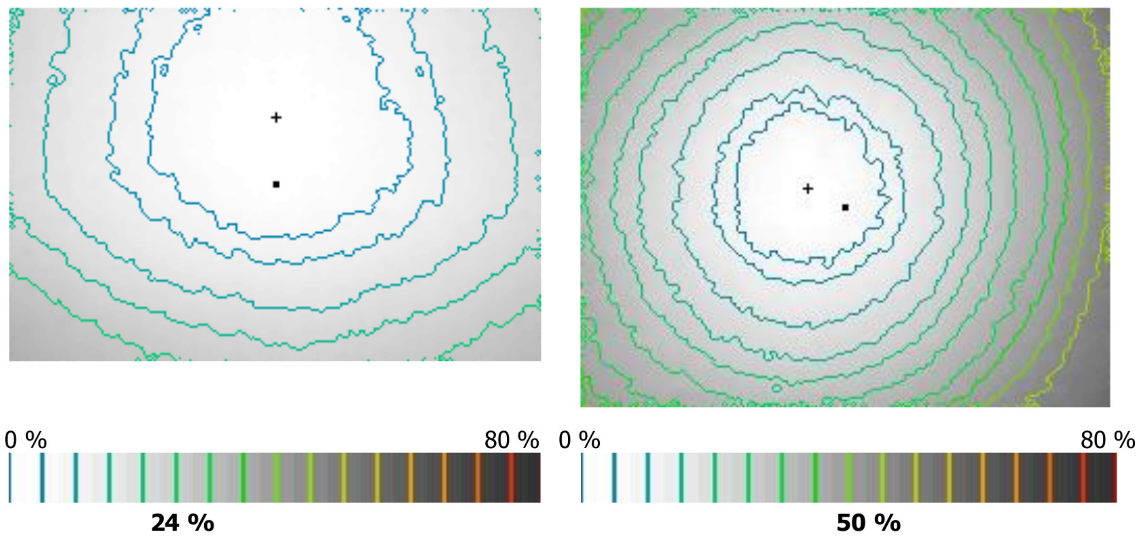
29.12.2 Fall-off graphs

The fall-off graph tends to reinforce the observations made above. The figure below shows the profiles for the two tested systems.



Fall-off profiles. Left: Canon EOS 30D DSRL. Right: Samsung D900 camera phone

The profiles show a more important fall-off for the Samsung camera phone than for the Canon DSLR. Some other elements are noticeable from the shape of the graphs. Even though it is hardly visible, the Canon DSLR performs a correction that triggers off a small amplification near the light center. The decay is parabolic-shaped for the DSLR, while it seems more linear for the camera phone (i.e., parabolic near the flash center). The 20% fall-off is reached at 90% of the lighting center for the Canon DSLR, while this fall-off level is reached at nearly 50% for the camera phone (50% corresponds to the half-distance between the flash center and the corner).



Thumbnail images and fall-off levels. Left: Canon EOS 30D dSRL. Right: Samsung D900 cameraphone

Finally, the fall-off levels (figures above) emphasize the shapes of the fall-offs. The results for the Canon

DSLR show the impact of mounting an external flash unit on the body. The overall levels are shifted vertically upward. Moreover, the shapes are not radial around the center of flash (marked as a cross): this phenomenon is a consequence of the shape of the flash unit, and also the fact that the optical center and physical flash center are remote.

On the other hand, the camera phone fall-off levels are particularly radial around the flash center. The LED used as a flash can thus be considered a point in space, even at short distances.

29.13 Shooting

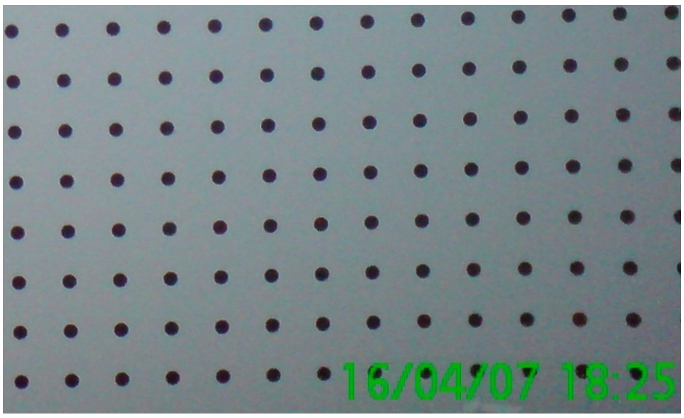
The FL measurement uses either a Dots chart or a Uniform White chart. For mounted flash units, it is preferable to use a wide chart, such as the *D0001_200*, in order to perform a measurement that is still accurate at more than 2 meters from the chart. However, it is still possible to perform the measurements with a smaller dot chart, so long as no other element than the chart is visible in the image.

There is no particular constraint for the use of a Bright chart. Its surface should preferably be planar in order to avoid any shadows, and again, no element other than the chart should be visible in the image.

a) ***Determine the influencing parameters*** focal length, aperture, focus distance, ISO setting, EV, digital zoom, aspect ratio.

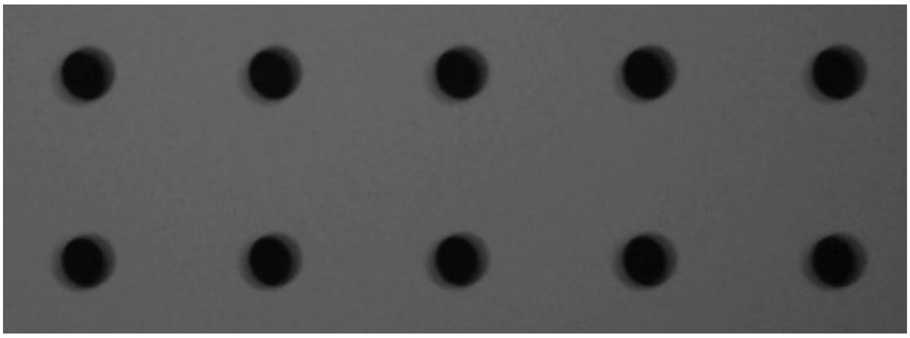
b) ***Specific shooting conditions*** (see also Section 5); the framing should be such that:

- There is no fixed requirement for the number of spots visible in the image, but the image should preferably be sharp.
- No element external to the test target should appear in the shot. This also means that overlay information should be avoided, as shown in the figure below.



Example of a bad sample image

- Orthofrontality does not need to be precise, but should be correct.
- No other light source should influence the measurement. Hence the room should be totally dark before each shot, unless the purpose is to measure the camera's ability in a mixed environment (low-light combined with flash, for example).
- The measurement is not sensitive to the orientation of the camera. It is thus possible to shoot the images in landscape (horizontal) or portrait (vertical) orientation; the latter is often the default orientation for camera phones.
- For camera phones, the battery's charge level may vary between consecutive shots. To keep this from influencing the measurement, wait approximately one minute between two consecutive shots.
- Since the room should be completely dark, camera bodies equipped with an AF lens might fail to focus correctly. To avoid this undesirable behavior, focus with the lights on and then lock the autofocus.
- Take all necessary precautions to avoid shaking the camera while shooting. The figure below shows an example of shaking during the shot.



Example of shaking during the shot

Note: It is important to keep a record of all the parameters and settings associated with each shot. This information is all the more so important in that the EXIF data, when available, does not contain the flash configuration details. This parameter becomes crucial when comparing different flashes.

Note: It is often impossible to take the shot with a wide aperture. In fact, we recommend (when possible) to reduce the aperture to its minimum. This will first of all minimize the amount of vignetting, but will also adequately expose the chart. Indeed, the FL measurement will provide incorrect values or will fail if applied to burned images.

29.14 Sidecar parameters

The sidecar parameters are the same as for the vignetting. They correspond basically to a crop area (useful for raw images) or a black value.

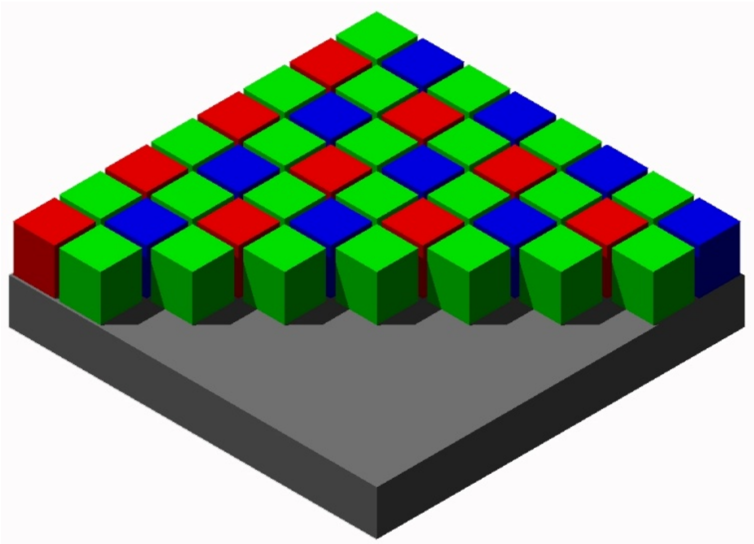
```
[Crop]       // analysis area section
Left= ...    // left position
Right= ...   // right position
Top= ...     // top position
Bottom= ... // bottom position

[Black]         // Black value section
BlackValue= ... // value to subtract to have 0 black (must be in 15b for raw images)
```

30 – CS: Color Sensitivity

30.1 Introduction

Color sensors usually have three different types of photosites that are sensitive to light in different bands of wavelengths. Although there are other (marginally-used) technologies, most color sensors use a Bayer color filter array. Each block of 4 contiguous photosites contains one photosite sensitive to low wavelengths (blue), one to high wavelengths (red), and 2 identical photosites sensitive to medium wavelengths (green).



Typical Bayer arrangement on a RGB sensor

After analog-to-digital conversion, the signal is stored on each channel on a certain number of bits. This number is usually 12 for a reflex camera, and 10 for a camera phone.

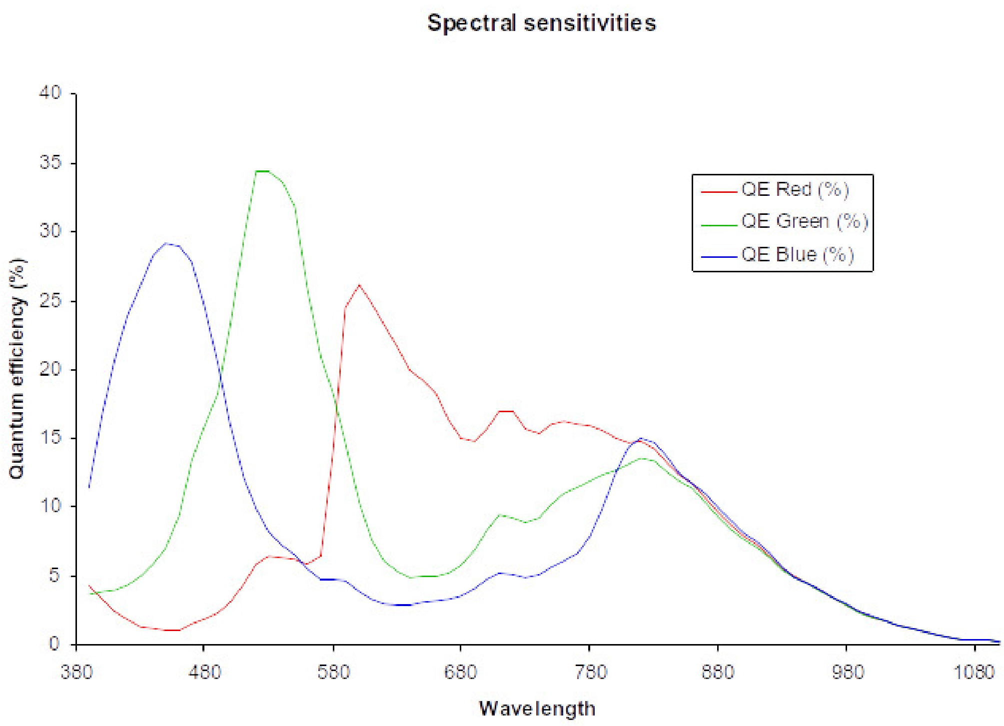
Hence the chip can encode colors on 36 bits or 30 bits in raw format. However, RGB images are usually encoded on 24 bits (8 bits for each channel), so the number of colors that can be represented by the camera is actually less than 16.77 Million (~ 24 bits). However, the limitation of 24 bits is still theoretical. In practice, the sensor introduces some noise, and a perfectly uniform area yields some deviation around the expected value. Two colors differing by a standard deviation of noise can be considered as not distinguishable.

The transformation between raw format (36 bits) and RGB format (24 bits) is usually computed with the tone curve (see the definition in Section 25). The tone curve is a non-linear transformation, thus it will introduce a noise quantification that Analyzer takes into account.

As in the case of the tonal range for grey levels (see Section 17.2), we can define the useful number of colors of a sensor as the number of colors that it can distinguish up to noise. We call this number *color sensitivity*.

Since each channel has its own noise level, it actually distinguishes far fewer than the theoretical 10 or 12 bits of the raw data. The sum of the tonal range on each channel can give a rough idea of the color sensitivity of a sensor. Experiments show that this sum is already less than 24 bits.

Moreover, the R, G, and B channels of a sensor are not specified by any norm and are a consequence of the sensor design. They are characterized by their spectral sensitivities, giving the proportion of incident photons that eventually reach the sensor for a given wavelength (called *quantum efficiency*). The figure below gives an example of a sensor's spectral sensitivities. Note that the photosites are usually sensitive to near-infrared. Therefore, you must add an infrared filter to the system to filter out these wavelengths. In particular, note that these curves are not the color matching functions X, Y, Z.



Spectral sensitivities of the color filters of a RGB sensor

The raw values in the R, G, and B channels on a uniform surface (neglecting noise for the time being) are not the sRGB values of this surface. In other words, the color space of the sensor is not the sRGB color space nor any usual color space. A first consequence of these spectral sensitivities is that a theoretical constant spectrum (i.e., every wavelength of such a spectrum have the same intensity) would yield three values R, G, and B that are usually different. As silicon is weakly sensitive to low wavelengths, B is often much smaller than G (a factor 2 or more is not unusual).

To obtain the final RGB image, the sensor color space has to be mapped into a normalized color space (as sRGB or Adobe RGB) by a numerical processing. It may vary with the ISP, but it usually contains at least the three following steps:

- A white balance correction (neutral spectrum, then yields R, G, and B equal).
- A chromatic adaptation, modeled by a 3×3 matrix.
- A tone curve.

The first two steps introduce some digital gains on the different channels, to compensate for the sensor's lack of sensitivity to some wavelengths. The overlap of the spectral sensitivities is also a crucial factor. Indeed, a large overlap yields similar responses to colors that are actually different in the sRGB color space, and can even possibly lead to metamerism (that is to say, very different spectra may lead to the same sensor response). If the aim is to obtain color fidelity, the chromatic adaptation matrix must have huge singular values to restore the difference between the different channels. This introduces an anisotropic magnification of noise in the sensor color space and obviously reduces the number of distinguishable colors even further.

The Color Sensitivity measurement takes the noise characteristics of the sensor into account, as well as its spectral sensitivities, to qualify the sensor in terms of color rendering. It does not need to measure the spectral sensitivities of the sensor itself, but rather, only a single shot of the X-Rite ColorChecker® classic and possibly a Noise measurement.

30.2 Definitions

Color sensitivity is the number of reliably distinguishable colors up to noise. Roughly speaking, two colors are considered as distinguishable if their difference is larger than the noise. In this respect, color sensitivity is the generalization to color of the notion of *tonal range* (see Section 17.2).

We extend this idea for color data to define the color sensitivity:

Let $\sum(r, g, b)$ the noise covariance matrix at the value (r, g, b).

For $1 \leq i \leq 3$, let $\sigma_i^2(r, g, b)$ be the eigenvalues of this covariance matrix. We call **Color Sensitivity** the number

$$CS = \int \frac{\mathrm{d}r\,\mathrm{d}g\,\mathrm{d}b}{\prod_{i=1}^{3} \max(1, \sigma_i)}$$

Before going any further, let us explain this formula. The determinant of the noise covariance matrix is the volume of the incertitude ellipsoid in which the difference between two colors is most likely due to noise. However, because digital images are encoded on integer values, the dimensions of the incertitude ellipsoid are quantized. Hence the integrand in the equation above can be seen as the density of distinguishable colors around the point (r, g, b), and takes quantization into account. The integral itself can then be interpreted as the total number of colors that can be distinguished by the sensor.

Note that color sensitivity can be computed at each step of the color rendering process, provided we can compute the noise covariance matrix. Analyzer uses the measurement of the raw noise and computes the noise covariance matrix after white balance, color correction, and tone curve.

- Raw noise: It is empirically observed that noise values at different pixels are independent (except in presence of more complex phenomena, as cross-talk). Hence, for each value (r, g, b), the noise covariance matrix is in general diagonal. Moreover, the noise is approximately Gaussian-, value-, and channel-dependent.
- White balance and color correction: You can numerically evaluate the white balance scales and the chromatic adaptation matrix by mapping the colors observed on a X-Rite ColorChecker® classic with the target values. These values depend on the illuminant. Analyzer can use several reference illuminants to compute the target values. The optimization of the matrix is obtained by the minimization of the mean square error on the patches of the X-Rite ColorChecker® classic, measured in the CIELAB color space, as suggested in the ISO standard 17321. Matrices that are very different from a diagonal matrix usually yield poorer color sensitivities since they are characteristic of sensor spectral sensitivities with important overlap. Moreover, some RGB values given by the sensor are necessarily clipped after this linear transformation. This sensor-used color space also describes the efficiency of the sensor in terms of color rendering.
- Tone curve correction (see Section 25.2): The tone curve is a non-linear transform applied to each channel before reducing the color depth, usually to 24 bits (8 bits per channel). The goal is two-fold:
    1. To map the linear color space onto a non-linear color space such as the sRGB color space. This

non-linearity takes the logarithmic sensitivity of the human eye into account as described by the Weber Law.

2. To better adjust the dynamic of the image to the output dynamic range by, for example, increasing the average luminance of the image.

For our model, we choose to use a usual approximation of the sRGB tone curve: γ of 2.2. (This tone curve is exact for other RGB color spaces such as Adobe RGB). It can be mathematically proven that this transformation has very little influence on the color sensitivity, as defined in the equation above. However, it is necessary to compute the target values on the X-Rite ColorChecker® classic.

This number for sRGB color that the sensor will not reach can be computed, and is called the covered sRGB gamut.

The Sensitivity Metamerism Index (SMI) is defined in the ISO standard 17321 as SMI = 100 – 5.5 · ΔE. It reflects the ability of the sensor to reproduce colors. To this purpose, the white balance and the color correction matrix are computed so as to minimize the CIELAB error between the reference values and the observed values. Although a reference illuminant (D55) is usually chosen, the SMI is also of great interest for other illuminants, such as tungsten.

30.2.1 Key values

The following three values are particularly relevant:

Effective color depth: The logarithm (base 2) of the color sensitivity. This is a number of bits between 0 and 24. (The sRGB maximal depth is 8 bits per channel).

Sensor used color space: The percentage of the sensor color space that is used via color processing.

Covered sRGB gamut: The output volume percentage that the system (sensor + color processing) will not reach.

30.3 Influencing factors

Several parameters influence the Color Sensitivity measurement:

- ISO sensitivity changes noise and thus color sensitivity.

- Illuminant, light source.
- White balance.
- Image compression (RGB measurement).

The white balance correction depends essentially on two parameters:

- The light source.
- The color vignetting.

30.4 Measurement of the Color Sensitivity

The X-Rite ColorChecker® classic 2005 provides a set of 24 representative colors with their theoretical values expressed in the CIE 1976 $L^*a^*b^*$ coordinates system and in the sRGB color space.

Analyzer detects the color patches on the test target image, measures the noise (see Noise Measurement Section 17) and the mean R, G, and B values for each patch. The noise values can either be pre-calculated on the HDR Noise chart, or directly evaluated on the X-Rite ColorChecker® classic. You need to indicate the image coordinates of the four corners of the color chart in a sidecar file (see below).

Analyzer implements the Color Sensitivity measurement as shown:

$$CS = \int \frac{\mathrm{d}r\,\mathrm{d}g\,\mathrm{d}b}{\prod_{i=1}^{3}\max(1,\sigma_i)}$$

where the σ_i are the eigenvalues of the noise covariance matrix.

To make fair comparisons between different sensors, you must apply an exposure correction that brings the X-Rite ColorChecker® classic white patch to 90% of the sensor dynamic.

For an RGB image, the covariance matrix is directly evaluated on the patches of the X-Rite ColorChecker® classic, and linearly interpolated. Note that this value may be biased by a strong image compression that artificially reduces the noise in the chart patches. Therefore RGB color sensitivity not only depends on the sensor characteristics, but also on the possibly complex processing leading to the final image.

For details about applying the measurement on raw images, see Section 30.5 below.

The percentage of represented colors gives the proportion of the sRGB color space that the sensor can see. This should be close to 100%.

The sensor-used color space is the proportion of the sensor color space needed to entirely cover the sRGB color space. It turns out that because of spectral sensitivities with low responses for blue and red, this is usually close to 10%.

Analyzer also measures the SMI (Sensitivity Metamerism Index).

30.5 Measurement in raw format

The Color Sensitivity measurement on raw data uses a more detailed description of the sensor noise generated via a standard color rendering process. More complex algorithms such as demosaicing are not taken into account, because they are highly dependent on the ISP. The raw noise is evaluated on each channel. Spatial noise is considered as white, meaning that the measurement ignores possible correlations introduced by crosstalk, so the covariance matrix of (R,G,B) noise on the sensor is diagonal. The white balance is estimated so as to make the neutral patches of the X-Rite ColorChecker® classic as grey as possible (the values on the R, G, and B channels should be equal). The color matrix is then determined so as to minimize the mean ΔE^* error in the CIELAB color space.

The noise covariance matrix after white balance and color correction is determined by an easy calculation. The color sensitivity as well as all the other measurements are given as described above.

30.6 Analyzer output

	in bits	in %
Color sensitivity	17.96	1.52

Covered sRGB gamut (in %)	100.00
Sensor used color space (in %)	8.64
Mean ΔE	8.41
Mean Δab	5.39
Sensitivity Metamerism Index (DSC/SMI)	53.76

Analyzer returns the followings results:

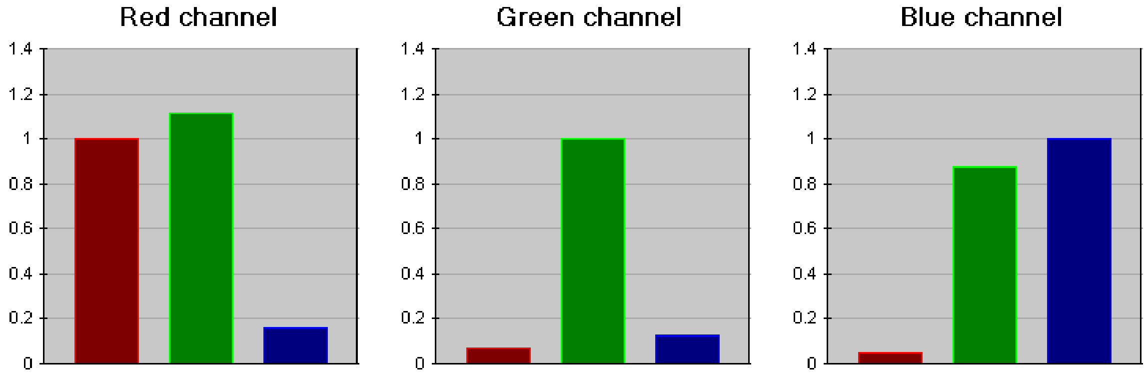
- Color Sensitivity (between 0 and 24 useful bits and between 0 and 100%): This number represents the number of bits that are actually useful for encoding the colors the sensor can distinguish. For a raw measurement, it shows how the sensor represents different colors. For a JPG measurement, it shows how high the noise is after color processing.
- Sensor-used color space (in %): Percentage of raw color clipped by color processing.
- Covered sRGB gamut (in %): Percentage of sRGB color that the system (sensor + color processing) cannot reach.
- Mean *ΔE*: Color Fidelity Error (refer to Section 28.2).
- Sensitivity Metamerism Index (DSC/SMI - ISO 17321): A sensor can theoretically reproduce the sRGB values of all the possible colors if and only if its spectral sensitivities are linear combinations of the color matching functions given by the CIE XYZ color space (Luther-Ives condition). It is never the case in practice, which means that two different spectral distributions can lead to the same tristimulus values (X,Y,Z) but different sensor outputs, and vice-versa.

  DSC/SMIs are designed to provide a measurement for such potential error. DSC/SMI Average provides a measurement of camera metamerism for ordinary reflective objects.
- R,G,B Sensor contribution for each channel JPEG (raw channel decomposition): This measurement is only available in raw. The white balance and the chromatic adaptation matrices map the sensor RGB space onto the sRGB color space (before tone curve). By inverting this transformation, you can determine the decomposition of the raw R, G, and B channels on the sRGB channels. Although less precise than the sensor's spectral sensitivities, this measurement nonetheless provides good insight about

the spectral sensitivities, and particularly of their overlap and relative sensitivity. This decomposition is normalized independently for each channel. More precisely, the R component in the R channel is set to 1, and likewise for the G and B channels. Different sensitivities in the different channels yield large white balance correction coefficients and important overlaps yield a chromatic adaptation matrix with large singular values. Both phenomena decrease the color sensitivity. The color correction matrix is also displayed, without its white balance correction component.

Raw channel decomposition:

These diagrams display the decomposition of the sensor photosites on the color matching functions of the sRGB color space.
The Red channel (resp. Green and Blue) is normalized such that the Red component (resp. Green and Blue) equals 1.



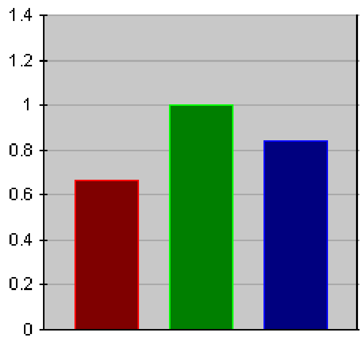
R	G	B
1.00	1.11	0.16

R	G	B
0.07	1.00	0.13

R	G	B
0.05	0.88	1.00

Relative sensitivity:

This diagram displays the sensitivity of the R,G,B channels. The G channel sensitivity is normalized to 1.



R	G	B
0.66	1.00	0.84

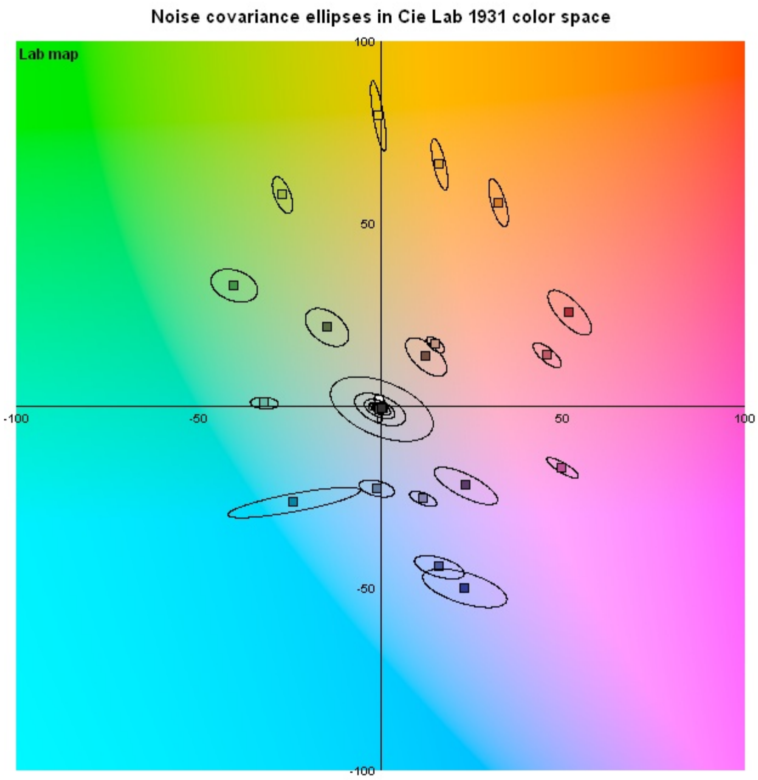
Color matrix:

This array displays the color correction matrix from sensor RGB to sRGB, without the white balance correction. The matrix is calculated as to minimize the mean ΔE* error in the CIELAB color space.

	R	G	B
R	1.55	-0.55	-0.00
G	-0.15	1.58	-0.43
B	0.01	-0.30	1.28

- 2D map of noise in the ab space. For each theoretical value of the X-Rite ColorChecker® classic chart, Analyzer represents the uncertainty ellipse (computed from the noise covariance matrix).

The human eye cannot distinguish two colors that are very close to each other. More precisely, in a 2D representation, the colors that are perceived as identical to a given color lie in an ellipse centered on the reference color. This ellipse is called the MacAdam ellipse. The Lab color space was conceived as a uniform color space. If this were perfectly true, MacAdam ellipses would be circles with an equal radius (theoretically equal to 1). This is not actually the case. However, comparing the uncertainty ellipses with circles gives a rough idea of the color sensitivity of the sensor, compared to the human eye.



30.7 Examples

The first example is a DSLR, with ISO speed 100.

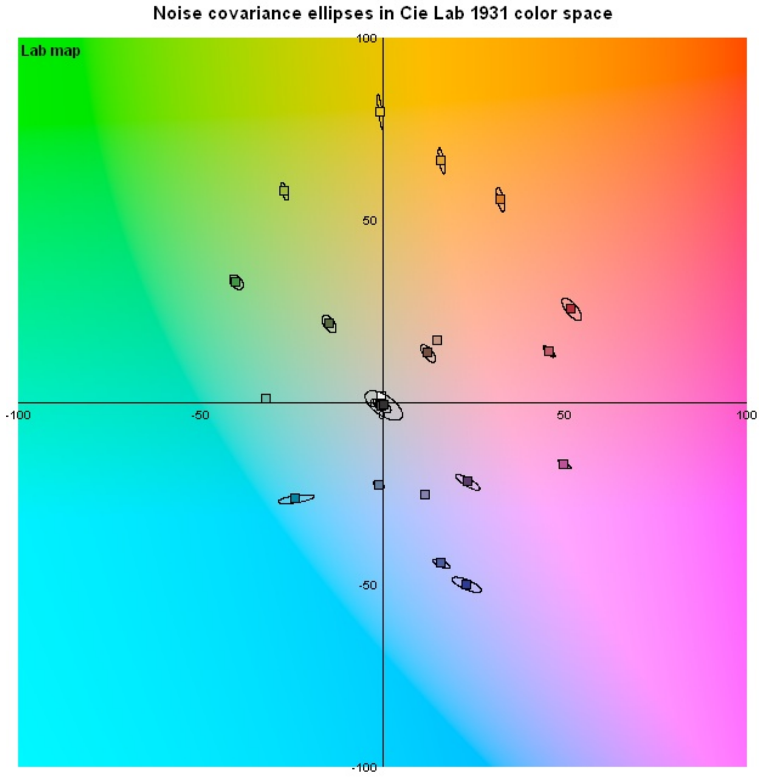
	in bits	in %
Color sensitivity	21.42	16.75

Covered sRGB gamut (in %)	100.00
Sensor used color space (in %)	9.95
Mean ΔE	2.35
Mean Δab	1.75
Sensitivity Metamerism Index (DSC/SMI)	87.10

With this type of sensor, color fidelity is very good: *ΔE* and *Δab* are very low (hence giving a high SMI). Color sensitivity is higher than 20 bits.

The tonal range of the same DSLR is between 7and 8 bits. It is worth noticing that $CS < 3 \times TR$, where *CS* is the color sensitivity and *TR* is the tonal range. Tonal range, as with color sensitivity, measures the number of distinguishable grey levels, but it does not evaluate noise after color correction. Thus the relation above would be true if the chromatic adaptation matrix were the identity matrix. As the color matrix and the white balance increase the noise, the color sensitivity is less than the sum of the tonal ranges in the R, G, and B channels.

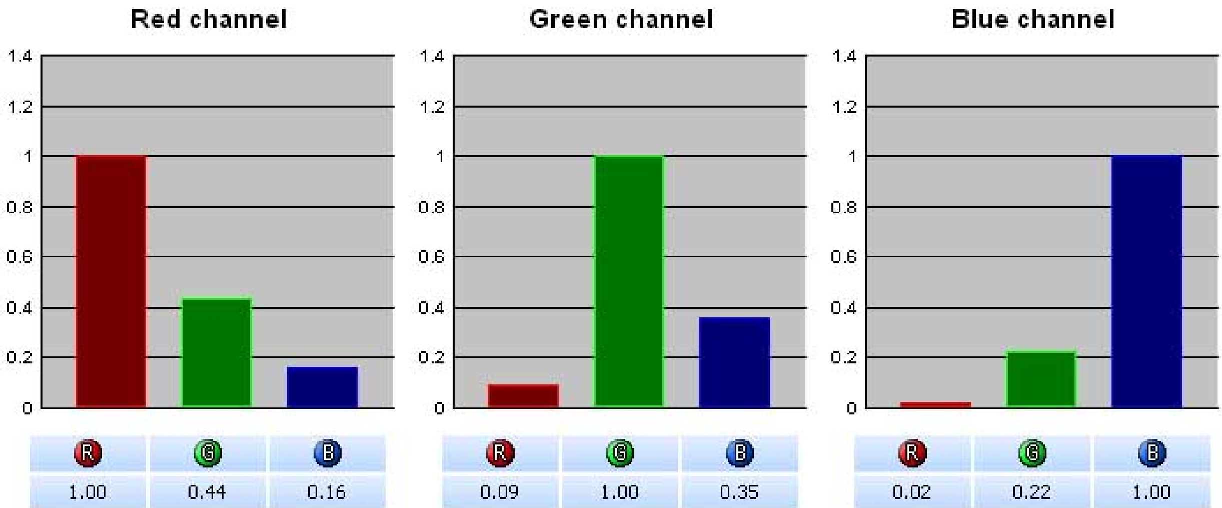
The 2D map of noise in ab space also illustrates the good quality of the sensor.



The noise covariance ellipses of the 24 patches of the X-Rite ColorChecker® classic target are very small. There is no overlap between any of them.

Raw channel decomposition :

These diagrams display the decomposition of the sensor photosites on the color matching functions of the sRGB color space.
The Red channel (resp. Green and Blue) is normalized such that the Red component (resp. Green and Blue) equals 1.



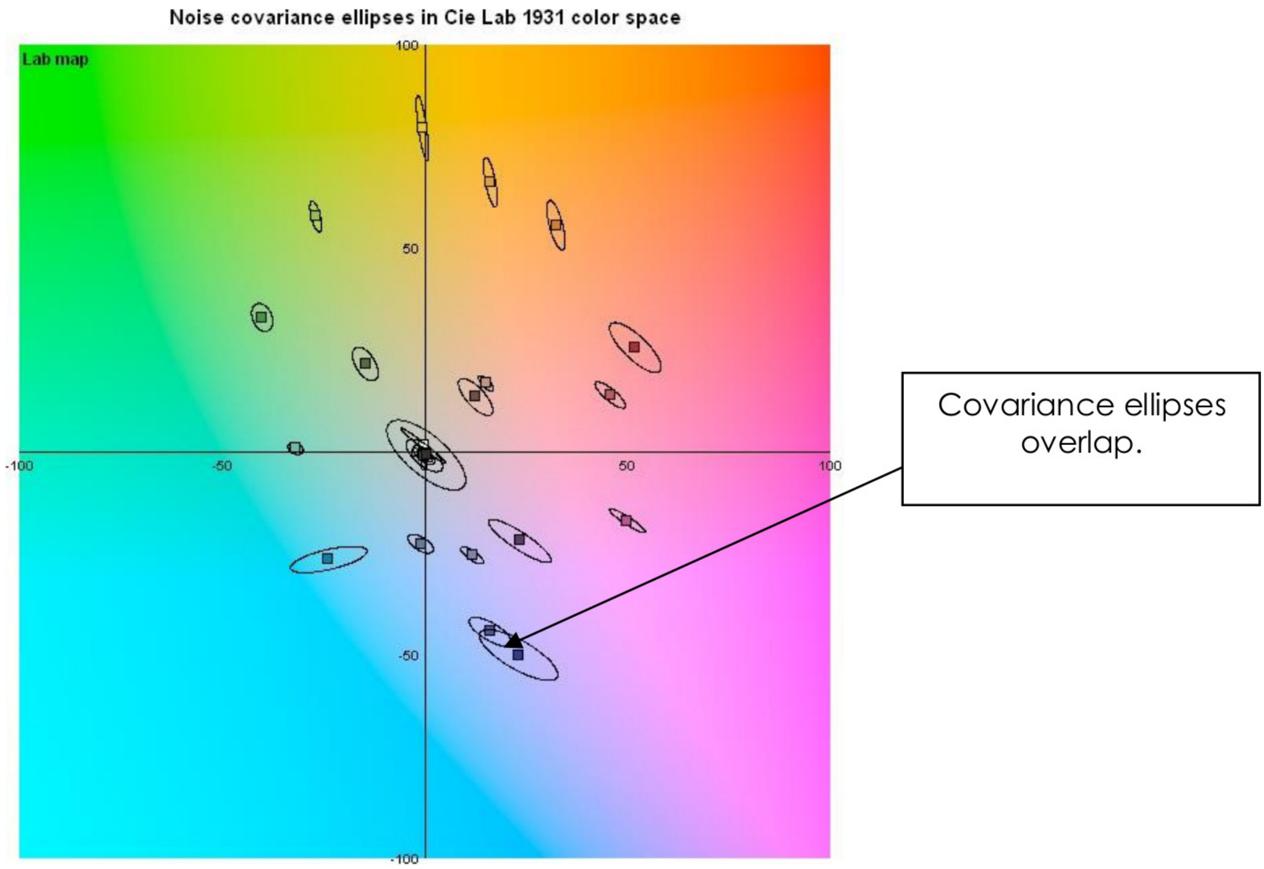
The raw channel decomposition shows the good quality of the sensor, especially for the green and the blue channels. The red channel selectivity is slightly less accurate.

The second example is a sensor for camera phone, with the same ISO speed 100:

	in bits	in %
Color sensitivity	18.85	2.81

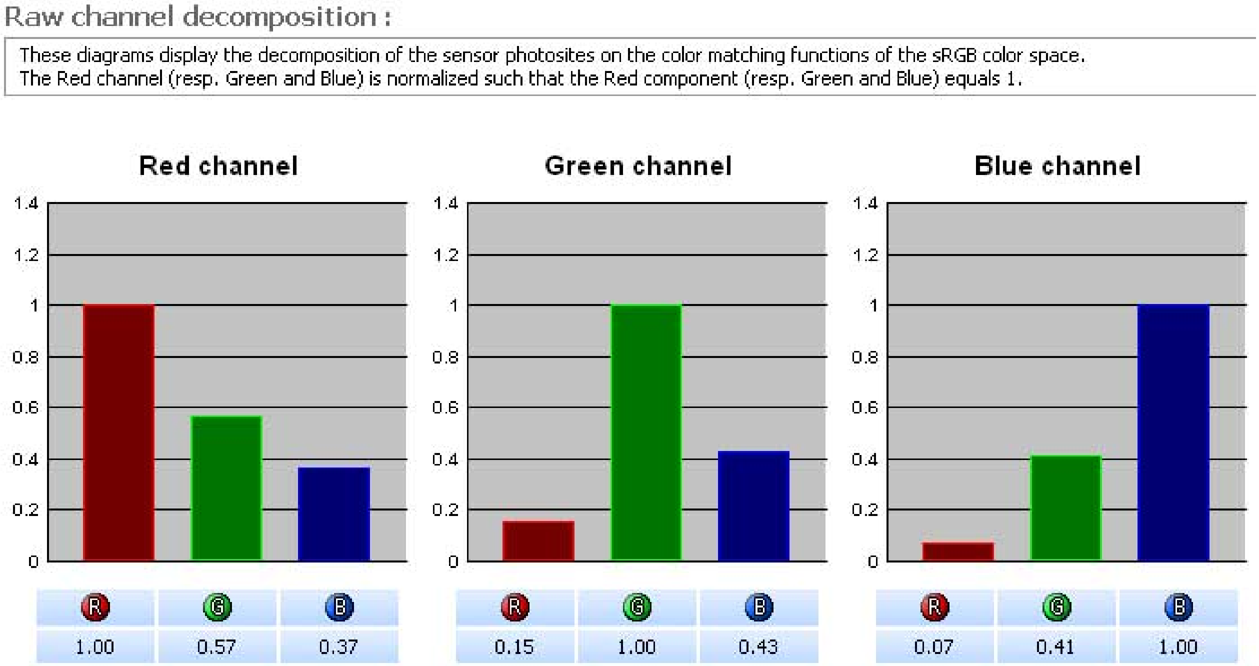
Covered sRGB gamut (in %)	100.00
Sensor used color space (in %)	7.42
Mean ΔE	7.41
Mean Δab	5.16
Sensitivity Metamerism Index (DSC/SMI)	59.25

In 2007, a color sensitivity of 18.80 bits was very good in terms of camera phone sensor standards. The loss of sensitivity compared to a DSLR shows the gap between the two technologies. The 2D noise map in the ab space is as follows:



The colors relative to the two emphasized ellipses have an important overlap. On the X-Rite ColorChecker® classic target, they are still distinguishable because their luminance is different. This information is lost when projected on the ab space. If the luminances were the same, it would be very hard to distinguish these colors. The channel decomposition also gives an insight about the spectral sensitivities of the sensor and their overlap.

The following graphs show the raw channel decomposition:



The sensor red channel is quite sensitive to green, more than 50% as to red.

30.8 Measurement accuracy

Color sensitivity accuracy depends on:

- Noise measurement accuracy: the accuracy for the measured standard deviation is ±0.2 grey levels.
- Exposure and Noise measurement: the total accuracy is ±0.5 bits. Good exposure increases the measurement accuracy.
- Color fidelity accuracy depends on the light source and color vignetting, with a usual measurement error of ±5%.

30.9 Setup parameters influencing the measurement

The following settings may change the Color Sensitivity measurement:

- Exposure: Analyzer requires that the white patch greyscale is 60% (±5%) of the sensor dynamic, so that the noise estimation will be reliable enough. If the detected value is not 60%, Analyzer applies a digital gain, but the gain may change the measurement accuracy.
- Vignetting. It may be necessary to decrease the aperture (f-number) to decrease the vignetting.
- JPEG measurements will be highly influenced by noise and sharpening filters applied to the image.
- The test target should be lit uniformly.
- No dust either on the lens or on the sensor.

30.10 Validity of the measurement

An absolute value of color sensitivity is not relevant. It is always necessary to associate it with the influencing parameters. For example, claiming that the color sensitivity of a camera is 19.2 bits is meaningless. On the other hand, it is perfectly meaningful to indicate that a camera shooting at 100 ISO under a D65 Illuminant has a color sensitivity of 19.2 bits.

30.11 Comparing two cameras

You can compare measurements at identical exposures if the ISO and the illumination are identical. The value of the 19th patch of the X-Rite ColorChecker® classic chart must be the same for each camera (as a percentage of their dynamic). Analyzer applies a digital gain to correct an under-exposed image. This digital gain sets the value of the 19th Patch to 80% of the real dynamic (in raw). But noise may be under-evaluated, so the value of the 19th patch as shot by the two measured sensors has to be close.

The color sensitivities may be compared when the SMI values are close. Indeed, an easy and classical way to decrease the noise, particularly at high ISO sensitivities, is to aim at less-saturated colors. Moreover, the sensor may be simply unable to attain the target values because of the inadequacy between its spectral sensitivities and the lighting conditions.

Here is a comparison of two 2 Mpixel sensors. Both shots have been taken at ISO 100 in the same room at 21 °C. The values of the 19th patch of the X-Rite ColorChecker® classic chart are very close in the two images. We compare 2 raw images so as to study their color sensitivities:

	in bits	in %
Color sensitivity	17.74	1.31

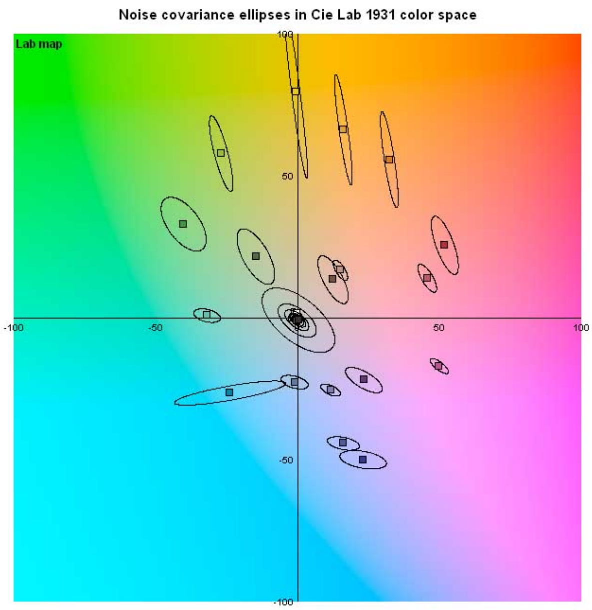
Covered sRGB gamut (in %)	100.00
Sensor used color space (in %)	5.35
Mean ΔE	7.43
Mean Δab	5.34
Sensitivity Metamerism Index (DSC/SMI)	59.11

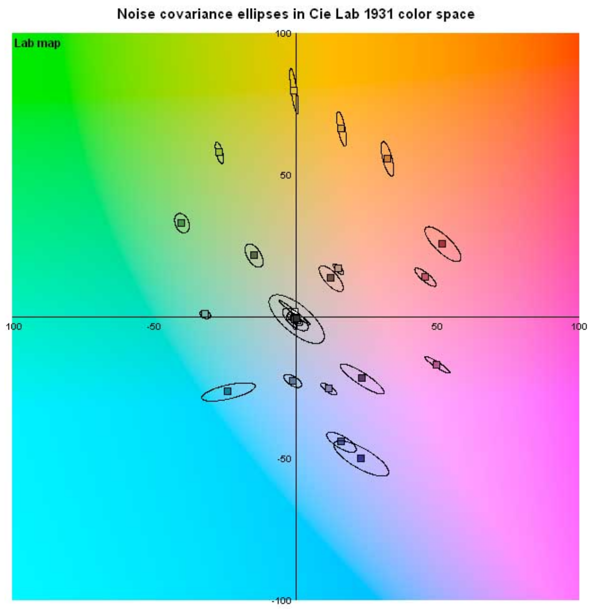
	in bits	in %
Color sensitivity	18.85	2.81

Covered sRGB gamut (in %)	100.00
Sensor used color space (in %)	7.42
Mean ΔE	7.41
Mean Δab	5.16
Sensitivity Metamerism Index (DSC/SMI)	59.25

For these two sensors, color sensitivities are very different, despite the fact that their noise levels are similar: SNR (grey level = 512) = 34.93 for sensor 1; SNR (grey level = 512) = 35.58 for sensor 2. It important to notice that the mean *ΔE* values are pretty close, too.

The noise 2D maps in ab space are as follows:



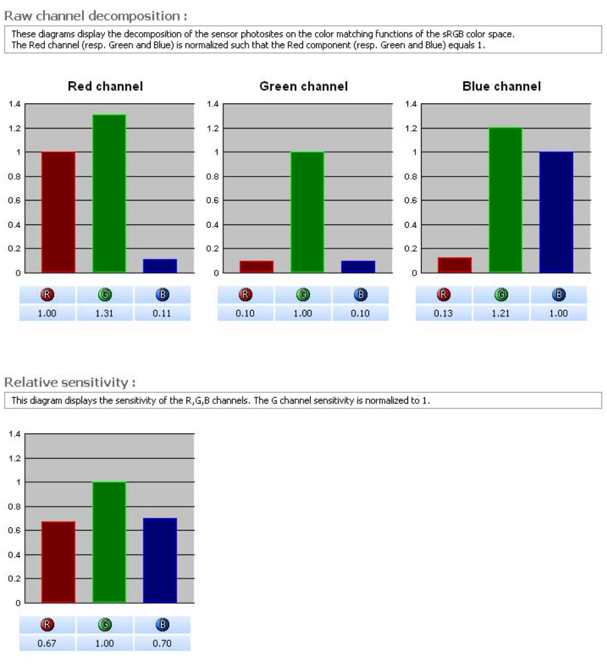


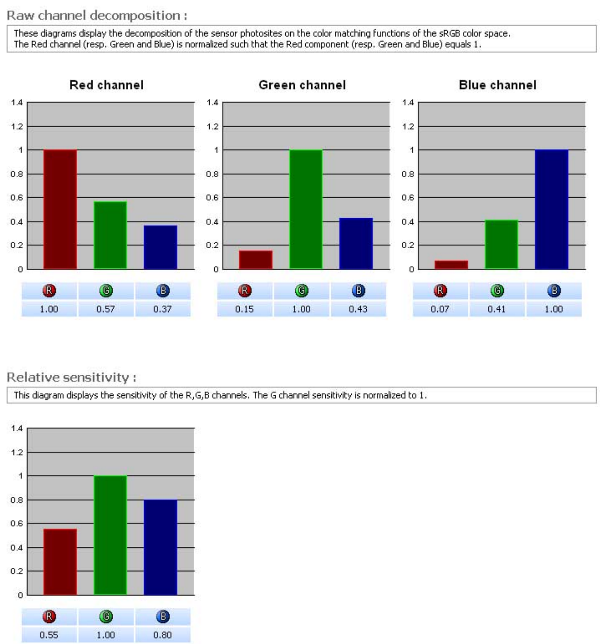
The ellipses of sensor 2 are much smaller than the ellipses of sensor 1. This may be explained by two different reasons:

- The raw noise of sensor 1 is higher.
- The spectral sensitivities of the second sensor are better, in the sense that the white balance and the chromatic adaptation matrix do not amplify the noise.

In this particular case, it turns out that the raw noise for both these sensors is very close, thus disqualifying the first hypothesis. The channel decomposition validates the second hypothesis.

30.11.1 Raw channel decomposition





With raw channel decomposition, we see that the main difference between these two sensors is in fact their respective color sensitivity. Sensor 1 shows a huge overlap between red and green and also between blue and green. The price for this lack of selectivity can be either a loss of color fidelity, or an amplification of noise. Since the Color Sensitivity measurement aims at color fidelity, the noise increases.

30.12 Shooting

a) Install the appropriate X-Rite ColorChecker® classic (see Section 4.12). We strongly recommend using the frame with markers that facilitate automatic detection.

b) Decide on the important parameters, if applicable:

- ISO.
- A good value for the X-Rite ColorChecker® classic white patch (80% of the dynamic in raw format, use of an unsaturated image in RGB format).
- Maximal resolution.
- To avoid vignetting effects, the X-Rite ColorChecker® classic target should not fill more than 2/3 of the image field.

30.13 Sidecar parameters

You can use the the common section to manually measuring noise on the X-Rite ColorChecker® classic chart for raw and RGB formats if automatic detection fails. Coordinates are the positioning coordinates of the chart, not the markers of the frame.

```
[Common]
// Manual X-Rite ColorChecker\textregistered\ classic chart position
X1=... // x coordinate of the top-left corner
Y1=... // y coordinate of the top-left corner
X2=... // x coordinate of the top-right corner
Y2=... // y coordinate of the top-right corner
X3=... // x coordinate of the bottom-left corner
Y3=... // y coordinate of the bottom-left corner
X4=... // x coordinate of the bottom-right corner
Y4=... // y coordinate of the bottom-right corner
```

The Color section lets you specify the illuminant, with the default illuminant as D65. Changing the illuminant modifies the target values of the X-Rite ColorChecker® classic chart.

```
[Color]        // Color section
Illuminant=... // A, B, C, D50, D55, D65 or D75
```

Include section lets you specify the noise curve of the camera, computed from a different Noise measurement (such as that used with the HDR Noise chart). The resulting noise file is the simple spreadsheet export of the measurement, with its absolute path.

```
[Include]
NoiseXLSFile=...
```

31 – TMR: Timing

31.1 Introduction

The choice of the exposure time, also called shutter time, is an important part of the art of photography. A photographer must carefully choose the exposure time depending on the desired rendering of the final photo.

For sports and wildlife photos, a very short exposure time is needed to stop motion and have a sharp subject. For subjects such as waterfalls, a longer exposure time may be preferred to smooth the water droplets and create a fairy-like effect.

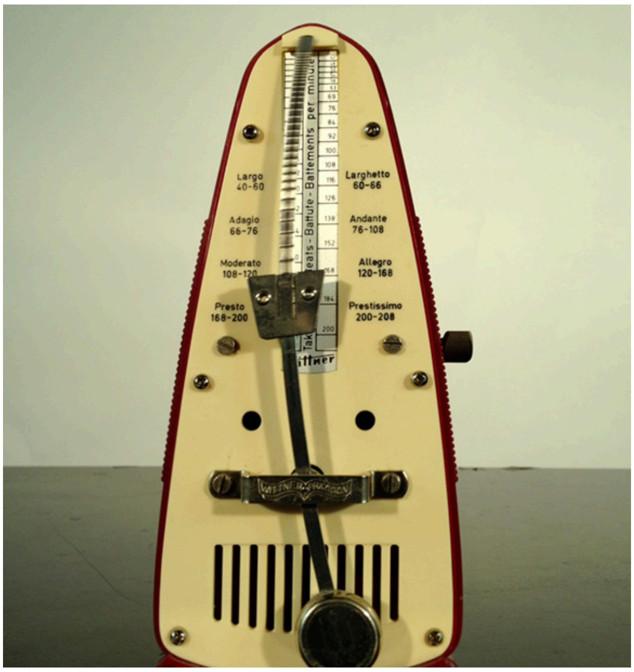
Same subject, different exposure time

A poorly-selected shutter time will result in motion blur, or a noisy image, or bad image exposure. For example, in low-light conditions, some cameras automatically shoot at very long exposure times, as if the camera were on a tripod, leading to blurry images because of the motion of the photographer. So exposure time has to be taken into account when evaluating image quality in low-light conditions.

Another source of time-related effects is the rolling shutter.

Rolling shutter is a method of acquiring an image from a sensor. Most CMOS sensors have a rolling shutter, which means that not every pixel on the sensor is exposed at the same time. Instead, image acquisition is performed one line after another. As a result, the different parts of the images are not recorded at exactly the same time. (CCD sensors usually have an electronic global shutter, and thus don't have this limitation.) A rolling shutter can be mechanical or electronic. In the latter case, it is called an "Electronic Rolling Shutter," or ERS.

Because all pixels are not exposed simultaneously, unpleasant effects can appear on images (or videos) if the scene or the camera is moving. A fast-moving camera, or fast-moving subjects with a speed roughly the same as the rolling shutter, can cause still-image distortions or "jello effect" vibrations in videos. And if some camera configuration parameters (exposure, focus, etc.) are modified during shooting, the resulting image can contain parts with different exposures or sharpness.



Rolling shutter effect on a fast moving object

The above photo of a metronome shows a perfectly straight pendulum shot while quickly bouncing back and forth from right to left. The image is acquired from top to bottom, which means that the top of the image was acquired when the pendulum was upright, but the bottom of the image was acquired when the pendulum was moving to the left, leading to this distorted effect.

In videos, it is usually the motion of the video maker that creates the jello effect: a slight shaking of the hands (usually a small rotation) is amplified by the focal length, and results in a significant motion in the image, and thus to rolling shutter effects. These effects can be reduced by a good stabilization system (either mechanical or image processing-based; see the chapter on stabilization for more information).

As the shooting protocol is different for Time Lag measurement than for the other Timing measurements, this measurement has its own chapter in this manual. However, the resulting values of Time Lag measurements are displayed in the Analyzer "Timing" measurement.

31.2 Definitions

Analyzer measures several kinds of time:

31.2.1 Exposure time

The exposure time, also called shutter speed, is the effective time interval during which light fills up the sensor photosites (or the film).

If the camera is equipped with a mechanical shutter, this is the time that the shutter is open. For digital cameras, which do not always have a mechanical shutter, the exposure time is the integration time for each pixel of the sensor.

For this measurement, it is assumed that all the pixels of the sensor have the same integration time, but this does not imply that this integration is simultaneous.

31.2.2 Rolling shutter

As previously described, rolling shutter is an image acquisition method in which the sensor lines are read out one after another.

The speed of the rolling shutter is a hardware characteristic that depends on the bandwidth of the transmission line of the sensor. Fast rolling shutters are better since they allow faster frame rates and yield less image deformation in case of motion.

The rolling shutter time is defined as the time needed by the sensor to read all the pixels of the image — that is, the time between the read-out of the first line and the last line of pixels.

31.2.3 Frame time / framerate

The frame time is the delay between two frames in a video. Its inverse is the frame rate. A frame rate of 25 fps (frames per second) means that the delay between two frames is 40 ms (1000/25). During this time, the image is acquired (pixel integration), read out by the camera processor, and processed.

31.2.4 Vertical blanking

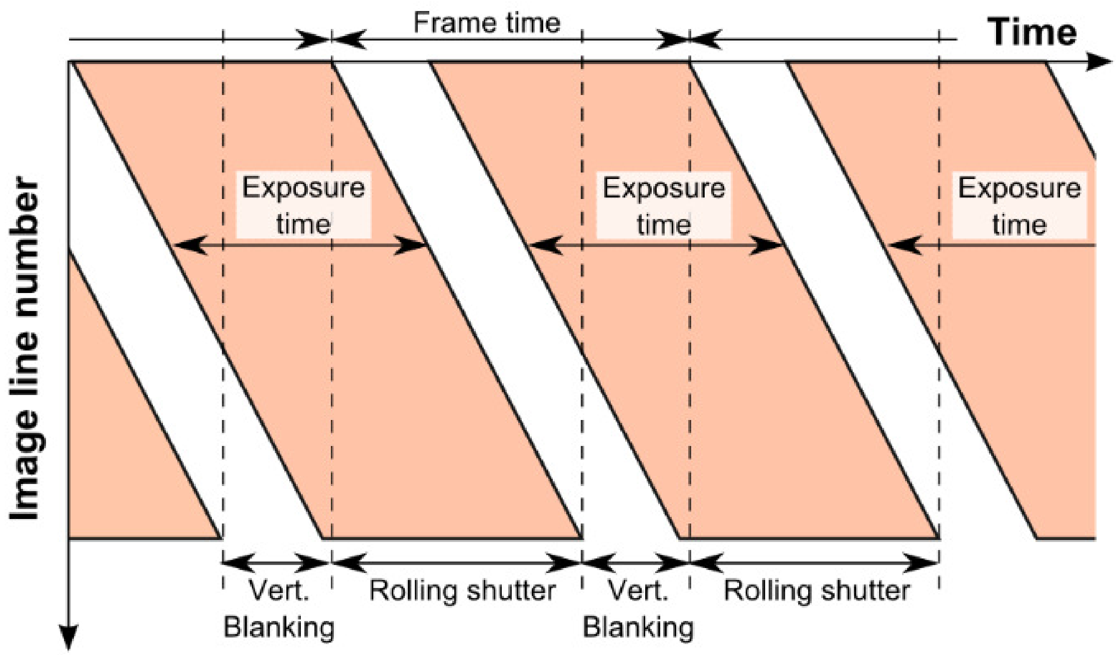
In a video, vertical blanking is the time difference between the reading of the last element in one frame and the reading of the first element in the next frame. This length of time is used for some camera controls and image processing.

It is calculated as the difference between frame time and rolling shutter time:

$$T_V = T_F - T_{RS}$$

with T_V the vertical blanking, T_F the frame time, and T_{RS} the rolling shutter time.

The diagram below shows three intervals, plus exposure time, during the acquisition of a video on a digital camera:



31.2.5 Shooting time lag

The time between fully pressing the exposure button on a digital still camera (or activating a module built into a mobile device) and the beginning of the exposure.

31.2.6 Shutter release time lag

This type of time lag is defined as the duration of the time between fully pressing down the shutter button and the start of exposure — *after* having stabilized the focus operation by half-pressing the shutter button (i.e., for imaging devices that distinguish between pressing the shutter button halfway and fully).

31.3 Influencing factors

Measured timings are primarily influenced by:

- Exposure (illumination of the scene)
- Camera motion

When an automatic exposure algorithm is used, the selected exposure time will be influenced by the ISO setting (gain) and the sensor exposure.

Camera setup parameters have a big influence on the timings (see the section on setup parameters below for more detailed information).

31.4 Measurement of timing metrics

Timing measurements are performed using images of the LED Universal Timer.

Exposure time is computed by counting the number of lit LEDs on each line, computing the resulting exposure time, and returning the average.

Rolling shutter, frame time, and shutter lag are computed using the position of the first lit LED on each line.

The following is an example of the timing computation for two consecutive frames of a 1080p video, as displayed in the diagram below.

For every line of the timer, it takes 50 ms to light all the LEDs. Each LED is lit for only 0.5 ms. Calibration is thus “50”.

On average, 82 LEDs are lit per line. The exposure time for one line is

$$T_E = N_{\text{LED}} \times \frac{\text{Calibration}}{100}$$
$$T_E = 82 \times 0.5 = 41 \text{ ms}$$

On the first frame, on the first line, the 10th LED is the first lit LED, and on last line it is the 35th. There are H = 400 pixels between first and last line, and the frame height is 1080 pixels. Thus the rolling shutter time is

$$T_{RS} = \quad \text{mod}\,(L_2 - L_1; 100) \times \frac{\text{Calibration}}{100} \times \frac{\text{Height}}{H}$$
$$T_{RS} = (35 - 10) \times 0.5 \times \frac{1080}{400} = 33.75 \text{ ms}$$

The same computation is done for each pair of LED lines with the same calibration (here 50 ms for all lines) for each frame, and then averaged.

On the second image, the 93rd is the first lit LED on the first line. The frame time is

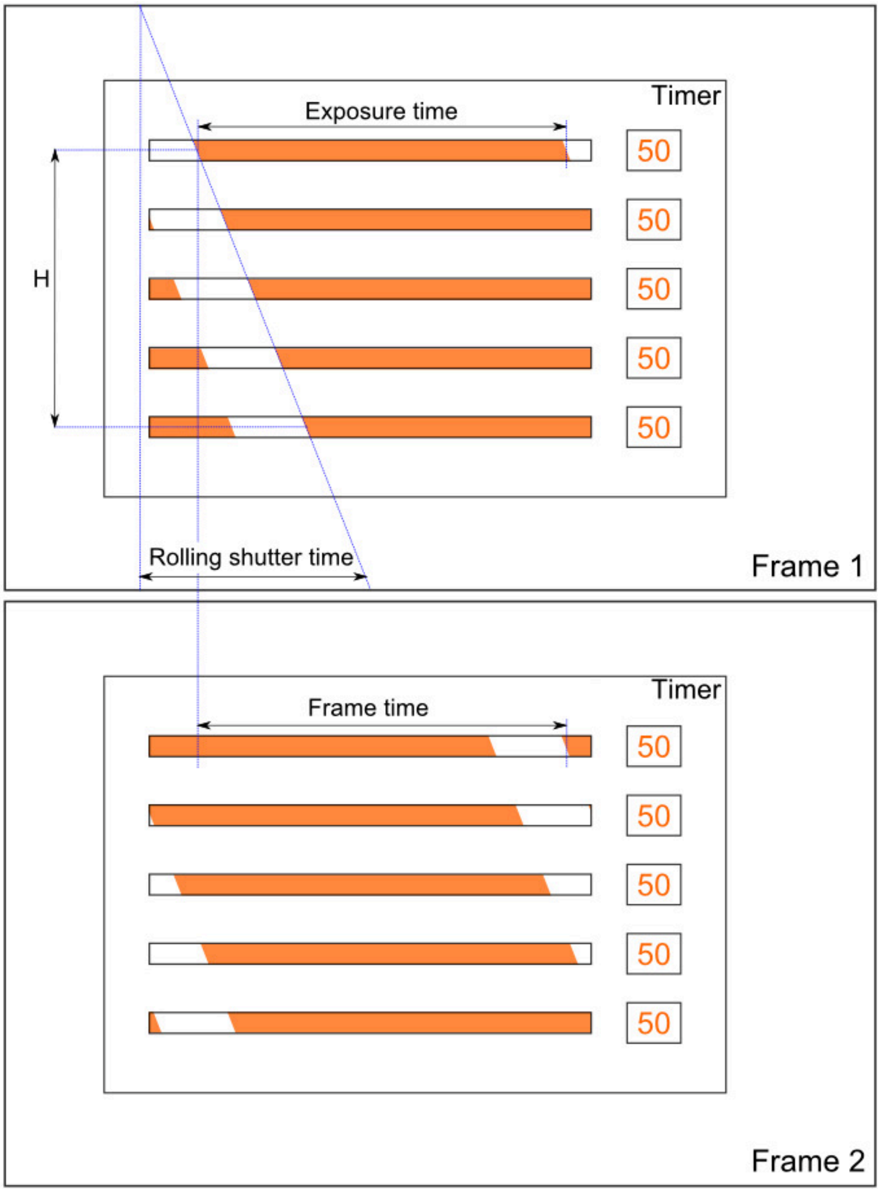
$$T_F = \quad \text{mod}\,(L_2 - L_1; 100) \times \frac{\text{Calibration}}{100}$$
$$T_F = (93 - 10) \times 0.5 = 41.5 \text{ ms}$$

The same computation is done for each LED line for each pair of successive frames, and averaged. The framerate is $\frac{1000}{T_F}$ = 24 fps.

Vertical blanking is the difference between frame time and rolling shutter:

$$T_V = T_F - T_{RS}$$
$$T_V = 41.5 - 33.75 = 7.75\,\text{ms}$$

For each measurement, Analyzer uses all the possible LED lines or pairs of lines, depending on the calibration of the timer, and averages the results.



31.5 Measurement in raw format

Analyzer is able to perform the measurement on both raw and RGB images. The presentation and the meaning of the results are the same.

31.6 Analyzer output

Analyzer returns the following data:

- The shooting conditions tab contains general shooting conditions values, and also the content of the of the sidecar file (timer calibration).
- The summary tab contains the results of the Timing measurements.
  - Single photo measurement contains the following table:

	Time (ms)	Precision (ms)
Exposure time	11.50	1.00
Rolling shutter	49.45	10.50
Time lag	-66.30	1.06

    Results for exposure time, rolling shutter time and time lag are displayed.

    Depending on the shooting protocol, the time lag result may be either shooting time lag or shutter release time lag.

    If no capture information is given in the sidecar file, the time lag is not visible.

    Precision is the accuracy of the result given the calibration of the timer. If the calibration is not adapted to the measured timing, precision will be low (see section on accuracy for more details).
  - For video measurement (video file or list of images):

	Mean (ms)	Std. Dev.	Ratio to frame time	Precision (ms)
Exposure time	16.80	0.07	50 %	0.10
Rolling shutter	27.51	0.39	82 %	0.61
Vertical blanking	5.85	0.40	18 %	0.61
Frame time	33.35	0.00	100 %	0.02

Measured frame rate (fps)	29.98
Number of frames	352
Number of missed frames	0
Number of duplicate frames	0

Results for exposure time, rolling shutter time, vertical blanking, and frame time are displayed.

As the results have been computed for each frame, the average result for all frames is displayed as well as the standard deviation for each result.

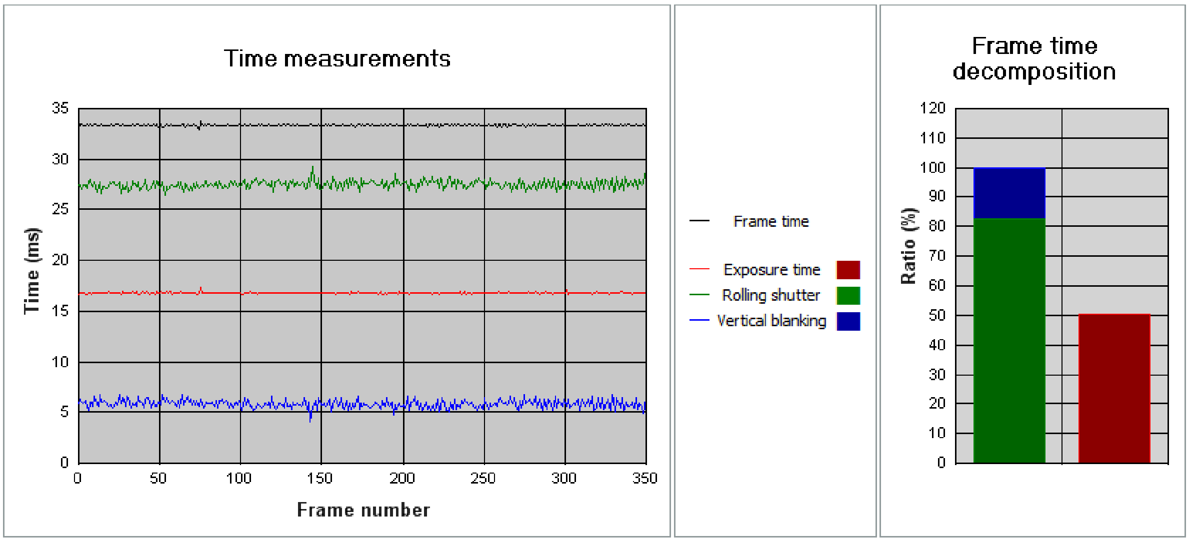
Precision is the accuracy of the result given the calibration of the timer. If the calibration is not adapted to the measured timing, precision will be low (see the section on measurement accuracy for more information).

Frame rate (from averaged frame time) and number of frames are also displayed.

A frame is considered missing if the time between two frames is twice the average frame time.

A frame is considered duplicate if the time is null.

- The graph tab (video only) contains the results for each frame displayed as a graph, along with a graphic decomposition of the frame time that corresponds to the column “ratio to frame time” in the summary tab.



31.7 Examples

The first example measures rolling shutter in photo mode of a single image from an iPhone 5 camera. Ambient light is 2600 lux; the timer is calibrated at 20 ms for each line.

The Exif data of the image file, displayed in the shooting conditions tab, shows an exposure time of 8.33 ms:

Image format	RGB
Image depth	8 bits/channel
Width	3264 pixels
Height	2448 pixels
Date	31/01/2013 - 16:47:05
Color space	sRGB

Brand	Apple
Model	iPhone 5
Aperture	2.4
Focal length	4.13 mm
Shutter speed (ms)	8.33
ISO speed	50
Ev bias	
White balance	Auto white balance

The measurement result is consistent with this information, and gives an exposure time of 8.24 ms:

	Time (ms)	Precision (ms)
Exposure time	8.24	0.20
Rolling shutter	45.01	1.50

Rolling shutter time is 45 ms in photo mode (8 Mpix), which will lead to rolling shutter effects. This time is also long compared to exposure time, which means that under these lighting conditions, the effects will be even more visible, because low exposure time will “stop motion,” resulting in low motion blur. (Motion blur visually degrades image quality but also makes rolling shutter effects less visible.)

Given the selected timer calibration, the accuracy of the measurement is quite good (±3.3%).

The next example shows exposure time and frame rate adaptation to the ambient light. Three videos were shot at 20 lux, 800 lux and 2600 lux with the same iPhone 5 camera. The camera is in full automatic mode.

The results are:

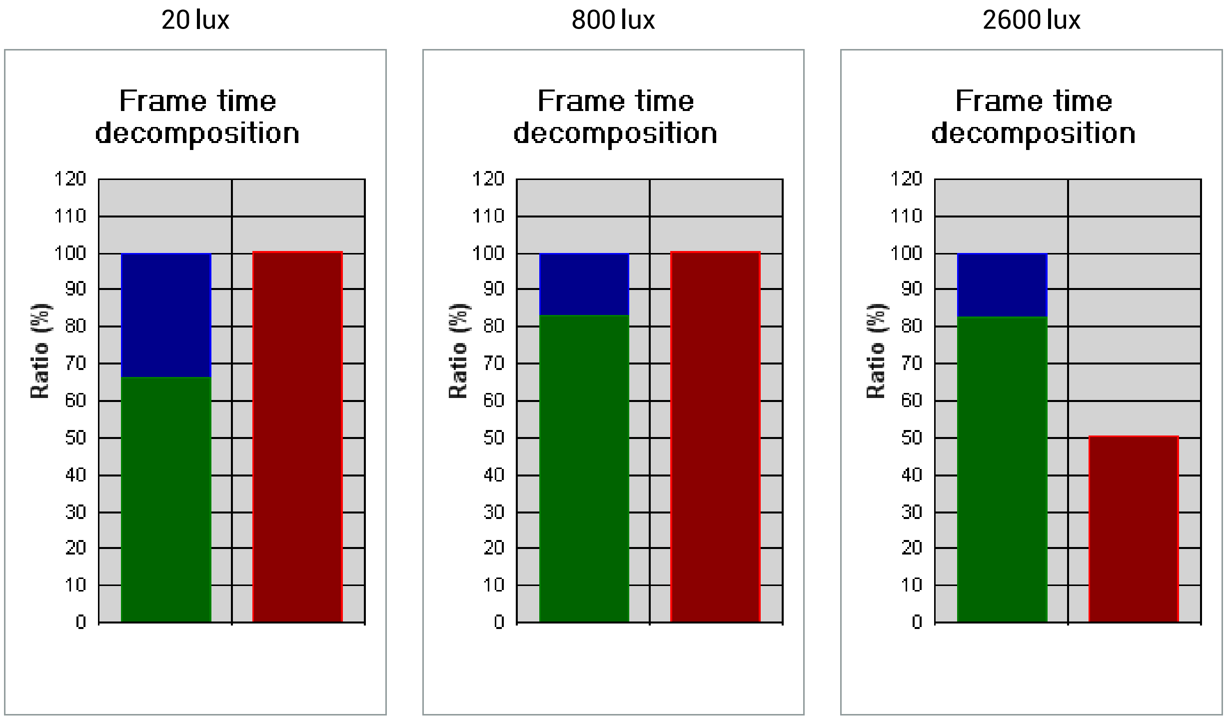
20 lux		**Mean (ms)**
	Exposure time	41.77
	Rolling shutter	27.53
	Vertical blanking	14.13
	Frame time	41.65
	Measured frame rate (fps)	24.01
800 lux		**Mean (ms)**
	Exposure time	33.51
	Rolling shutter	27.68
	Vertical blanking	5.68
	Frame time	33.37
	Measured frame rate (fps)	29.97
2600 lux		**Mean (ms)**
	Exposure time	16.80
	Rolling shutter	27.51
	Vertical blanking	5.85
	Frame time	33.35
	Measured frame rate (fps)	29.98

Note that with the lower resolution in video mode (1080px), rolling shutter time is shorter than in still mode.

Under low light, the camera reduces its frame rate to allow longer exposure times. Here at 20 lux, the frame rate is only 24 fps. Exposure time and frame time are equal; the small difference comes from the level of LED line reading accuracy.

With enough light, the frame rate increases to 30 fps. Note that the frame rate is limited by the rolling shutter. With a rolling shutter time of 27.5 ms, the frame rate is theoretically limited to $\frac{1000}{27.5} = 36$ fps.

In bright light, frame rate is still 30 fps, but the exposure time is reduced compared to the time between each frame (also visible in the frame time decomposition graph below).



The behavior is a bit different for a DSLR. User can choose resolution, exposure time and frame rate. For example, three video resolutions can be selected for the Nikon D7000: 1920×1080 (Full HD), 1280×720 (HD), and 640×424 (SD). The framing is the same in HD and full HD modes, and slightly changes in SD.

Three videos were shot, with the following results:

Full HD (1080p – 24 fps)		Mean (ms)
	Exposure time	39.60
	Rolling shutter	17.74
	Vertical blanking	23.97
	Frame time	41.70
	Measured frame rate (fps)	23.98
HD (720p – 25 fps)		Mean (ms)
	Exposure time	39.60
	Rolling shutter	17.84
	Vertical blanking	22.15
	Frame time	39.99
	Measured frame rate (fps)	25.01
SD (424p – 25 fps)		Mean (ms)
	Exposure time	39.39
	Rolling shutter	20.73
	Vertical blanking	19.26
	Frame time	39.99
	Measured frame rate (fps)	25.00

Rolling shutter time is the same in Full HD and HD modes: in these cases, reducing the resolution does not reduce the rolling shutter time. Cameras can have a different behavior, and rolling shutter time can also be reduced when the image height is reduced.

Surprisingly, rolling shutter time is longer in SD mode. This may be related to the fact that SD has a 4:3 resolution, while Full HD and HD are at 16:9. This mode is also quite a bit less interesting for users than HD and Full HD, and thus may be less optimized.

31.8 Measurement accuracy

The number of lit LEDs and the position of the first lit LED are detected on images of the Timer with an accuracy of ±1 LED. The position of the LED lines in the image is detected with an accuracy of one pixel.

Thus the accuracy of the measurement mainly depends on the selected calibration of the timer.

For example, for an exposure time measurement:

$$T_E = N_{\text{LED}} \times \frac{\text{Calibration}}{100} \pm \frac{\text{Calibration}}{100}$$

Thus if 80 LEDs are lit on an image, the accuracy of the exposure time is $\pm\frac{1}{80}$ = ±1.25%. If only 20 LEDs are lit, the accuracy is ±5%.

Frame time and rolling shutter time computations use two LED lines, which means that their accuracy is ±2 LEDs. For rolling shutter, the position of the pair of lines also influences the accuracy: accuracy is better if a large portion of the image is between the top and bottom LED lines.

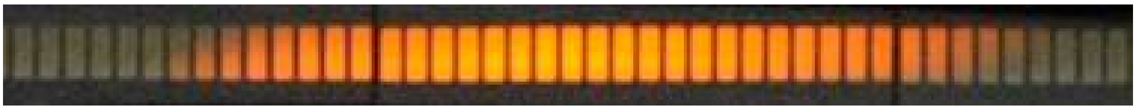
Thus for good accuracy, it is important to correctly select the timer calibration in accordance with the measured times.

To help users select the proper calibration, Analyzer returns the accuracy for each measurement. If the accuracy is too low, it is better to use a different calibration and to reshoot the images.

While measuring very low exposure times on cameras with a mechanical shutter, the accuracy of the measurement may be lower than the precision value given by Analyzer. There are two reasons for this:

First, the measurement implies that the exposure time is the same for all pixels. With a mechanical shutter at its maximal speed, this is not always true, and (for example) the bottom of the image may have a longer exposure time than the center. Thus at high speed, the results may vary depending on the position and the size of the timer in the image.

Secondly, the shutter does not open instantaneously, but rather, it opens and closes progressively. While this opening time is fast compared to total exposure time, it has no influence on the measurement. But if its speed is on the same scale as the exposure time, it will result in an image that displays LEDs with different exposures and blur. Then the threshold detection of lit LEDs will be less accurate, and may also differ between raw and RGB images (due to the OECF).



Influence of the mechanical shutter's opening time on the image of an LED line. Middle LEDs are more exposed than others. Accuracy is reduced

These inaccuracies due to the mechanical shutter will impact measurements when exposure time is on the same scale as shutter characteristics. For example, if the opening time of a mechanical shutter is 0.3 ms, this could be considered as the accuracy of the Timing measurements for that camera.

31.9 Measurement scales

The following table gives a subjective scale for rolling shutter:

Rolling shutter time	Qualitative effect
$x < 10$ ms	Very good. Little or no electronic rolling shutter (ERS) effect.
10 ms $< x < 30$ ms	Good. Some ERS effect visible for fast-moving subjects or camera.
30 ms $< x < 50$ ms	Acceptable. Visible RS effects.
$x > 50$ ms	Bad. RS effects visible even for slow-moving subjects or camera.

Note that the perceptual effects of a slow rolling shutter also depend on the framerate and/or the exposure time. If the rolling shutter time is small compared to the exposure time, its perceptual effects are reduced. Conversely, if it is roughly equal to the exposure time, its effects are increased.

The following table gives a subjective scale for framerate:

Framerate	Qualitative effect
$x > 60$ fps	Excellent. Usable for slow-motion videos.
60 fps > x > 30 fps	Very good. Good for sports and fast-moving subjects or camera.
30 fps > x > 25 fps	Good. Video is smooth in most cases.
$x < 25$ fps	Bad. Video is not smooth.

As for rolling shutter, the perceptual effects of the framerate also depend on the exposure time. If exposure time is low compared to the time of each frame, the video will appear less smooth because there will be less motion blur, and large motions may look discontinuous.

There is no qualitative scale for exposure time, as this may depend on the photographer's intention. However, it is generally admitted that exposure time should not exceed 1/focal (with focal being the 24×36 equivalent one), or motion blur will be too high. Of course, this also depends on the camera and whether a stabilization system is activated.

31.10 Setup parameters influencing the measurement

Depending on the camera body, setup parameters may influence the measured timings:

- Resolution (for rolling shutter)
- Framerate
- Auto-exposure mode (point, full image, etc.)
- Stabilization: if stabilization is activated, the camera can choose to increase the exposure time.
- Focal length: longer focal lengths need shorter exposure times to limit motion blur. A camera can choose to change the exposure time accordingly depending on focal length.
- Focusing mode
- Flash setting

As an example, rolling shutter time is a sensor characteristic, and is generally reduced if the image resolution is reduced; for the same sensor, rolling shutter will usually be different for video (2 megapixels) and photos (8 megapixels).

Changing the resolution of the video (1080p or 720p) can also change the rolling shutter time.

31.11 Validity of the measurement

The Timing measurements are meaningful only if the information about exposure is given. Likewise, giving an exposure time or a frame rate without mentioning the lighting, lux value, and the kind of scene shot, is meaningless.

It is also important to mention if a particular ISO speed or EV bias or particular exposure selection mode was chosen.

31.12 Comparing two cameras

The main factor influencing Timing measurements is the exposure. To obtain a fair comparison, it is important to use the same lights with the same lighting parameters, and to shoot the same scene.

For example, you can compare the behavior of two cameras at 20 lux (low light), or compare their behavior while shooting the same “natural scene” (in a laboratory setup).

Comparing two cameras, one shooting a scene at 20 lux, and the other a scene at 2600 lux, would be meaningless.

A camera’s rolling shutter time is constant for a given resolution. For the same camera, however, it can be different for video and photo modes, or for Full HD, HD, or SD modes.

It would be meaningless to compare two cameras with one in video mode (HD) and the other in photo mode (8 Mpix). A fair comparison requires using the same resolution for both cameras, or selecting the best possible resolution for each one.

31.13 Shooting

This measurement uses images of the Timer.

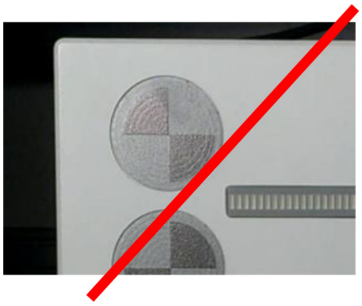
31.13.1 Positioning the camera

- The camera must be firmly fixed to the head of the tripod, either by using the tripod screw (if the camera has a socket), or by using device holder or MeFoto clamp (for shots taken with a mobile phone or a digital tablet, for example).
- The timer must be fully visible in the image. For automatic detection, detection markers should be at least 35/40 pixels high in the image.
- As with other charts, the timer must be orthofrontal to the camera. It also should not be skewed (a skewed target reduces the accuracy of rolling shutter time measurements because the pixels lines are not aligned with the LED lines of the timer).
- Distortion of the LED lines must be avoided. If distortion is high, put the timer in the center of the image, and reduce the size of the timer in the image if necessary.
- LED lines must be perpendicular to the direction of the rolling shutter. This means that if the rolling shutter goes from top to bottom or from bottom to top, the LED lines must be horizontal in the image. (This is the usual case.)

For cameras with a rolling shutter that goes from left to right, or from right to left, the LED lines must be vertical.

31.13.2 Setting up the timer

- The lighting of the target must be constant during shooting.
- Avoid reflections on the target when adjusting the lighting. The lighting axes should be at an angle of 30–45° with the plane of the timer. For example, because of the reflection, the following marker will hardly be detected:



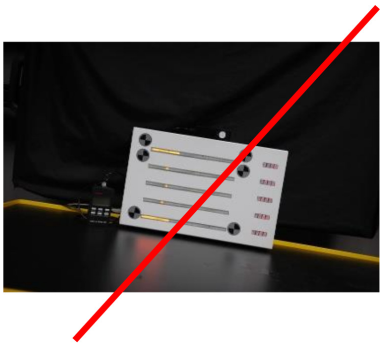
- Calibration of the LED lines should be carefully chosen. This calibration will vary with the exposure time. If the exposure time is unknown, select a calibration (for example, 40 ms) and tune it following the rules below. It is also possible to make an image with the timer set in “crescendo mode” to obtain a first estimate of the exposure time.
  - For each image and on every line, there must be some LEDs that are not lit. If this is not the case, decrease the line period calibration and reshoot.
  - Accuracy will be better if more LEDs are lit (but not all). So increase the line period calibration if there are fewer than 20 lit LEDs. Accuracy is ±5% for exposure time if 20 LEDs are lit.
  - For the rolling shutter measurement, there must be at least two lines with the same calibration. For better accuracy, these must be the top and the bottom lines.
- The luminosity of the LEDs must be adapted to the ambient light.
  - Increase the LED luminosity if the contrast between lit and unlit LEDs is low, particularly in bright light.
  - Decrease the luminosity in low light to avoid saturated pixels.

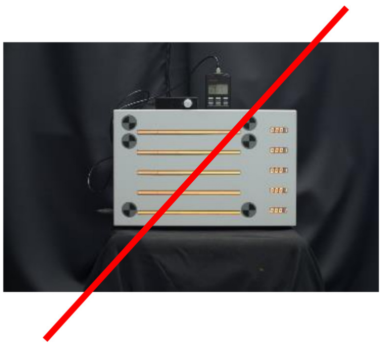
Here is a good image of the timer:

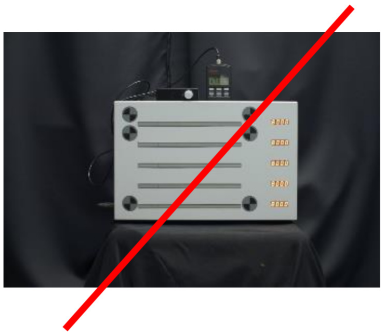
Correct picture of the Timer

There are more lit LEDs than unlit LEDs. The target is not skewed, and lit LEDs are clearly visible. A luxmeter has also been used to measure ambient light.

These are not acceptable images:







The first image is skewed, all the LEDs are lit in the second image, and the LEDs in the last image are barely visible (low LED luminosity).

A skew up to 1° is tolerated. A warning is displayed from 1° to 5°. If the skew is higher than 5°, the measurement will return an error.

Note that it is possible to take images of only the first (top) LED line. In this case, the four top markers should also be visible. Only exposure time and frame time can be measured using this configuration; ERS time and vertical blanking cannot be measured.

Here is an example of a possible image of a scene with the timer inside:

31.14 Sidecar parameters

For both video and still image files, sidecars must have the same name as their associated video file, plus the .ini extension.

The calibration of the timer should be given for each image in the video file. These are the values that are displayed to the right of the LED lines:

```
[TimeBoxCalibration]
LineCalibration1=... // top line
LineCalibration2=...
LineCalibration3=...
LineCalibration4=...
LineCalibration5=... // bottom line
```

For a Time Lag measurement, the capture information as given by the timer pilot, must also be indicated:

```
[TimeBoxCapture]
LineCapture1=... // top line
LineCapture2=...
LineCapture3=...
LineCapture4=...
LineCapture5=... // bottom line
```

The *Common* section is useful for manually indicating the position of the markers if automatic detection fails.

```
[Common]
// Manual texture chart position
X1=... // x coordinate of the top-left marker
Y1=... // y coordinate of the top-left marker
X2=... // x coordinate of the top-right marker
Y2=... // y coordinate of the top-right marker
X3=... // x coordinate of the bottom-left marker
Y3=... // y coordinate of the bottom-left marker
X4=... // x coordinate of the bottom-right marker
Y4=... // y coordinate of the bottom-right marker
```

32 – TMR: Time lags

32.1 Introduction

Most users expect to produce the image they see when pressing the camera trigger, thus a too-long delay between the trigger instant and the actual capture can ruin a photograph.

However, in order to capture an image, the camera has to perform many time-consuming operations, the most time-consuming of which (in most cases) is the focus adjustment.

To reduce this time lag, most DSLR and DSC cameras perform some of these time-consuming operations before the photographer triggers the shot. For example, users can set the autofocus by depressing the trigger button half-way.

These two use cases primarily define the shooting time lag and the shutter release time lag that users directly experience.

During the heyday of analog photography, time lags were primarily limited by mechanical aspects. In particular, the shutter release time lag was short enough for most users, and was not a critical problem. But when the first digital point-and-shoot cameras appeared, the time lags were significantly longer because new time-consuming operations were introduced, such as the changing of sensor configurations between live-view and capture.

Shutter release time lag has become a distinguishing factor among imaging devices, with point-and-shoot cameras on the one hand having a reputation for being slow, and DSLRs on the other hand being considered as very fast.

Analyzer measures these two important characteristics — shooting time lag and shutter release time lag.

32.2 Definitions

Most time lag-related terms used in this section are defined by the upcoming ISO 15781 standard. The following definitions (shooting time lag, shutter release time lag, pre-capture point, and capture point) all refer to this standard.

32.2.1 Shooting time lag

The time between pressing the exposure button on a digital still camera or on a module built into a mobile device, and the beginning of the exposure.

32.2.2 Shutter release time lag

In the case of imaging devices that distinguish between half-pressing and full-pressing, the duration of the time between fully pressing down the shutter button after having stabilized the focus operation by half-pressing the shutter, and the actual beginning of the exposure.

32.2.3 Time lag

Either the shooting time lag or the shutter release time lag, depending on the measurement being performed, since those two values follow most of the same measurement protocols.

32.2.4 Pre-capture point

The position of a user control (such as a button) on an imaging device, at which it activates pre-capture processes such as autofocus and exposure calculation (typically half-way pressing on most digital still cameras).

32.2.5 Capture point

The position of a user control (such as a button) on an imaging device, at which it activates the image capture operation.

32.2.6 Start Point

Either the pre-capture point or capture point, depending on the measurement being performed.

32.2.7 Integration start

The beginning of sensor integration. On sensors that use progressive scanning, the integration start can vary significantly over the sensor (see the section on rolling shutter measurement), and it is important to take this factor into account when computing time lags.

32.3 Influencing factors

Measuring time lags is influenced by:

- The lens used on an interchangeable-lens camera (particularly affects shooting time lag).
- The AF setting (this should be set to focus priority mode, with continuous autofocus turned off).
- The background chart or scene.
- The exposure time and/or the illumination.
- The stabilization settings (we recommend turning off any optical, mechanical, and electronic stabilizations).
- The output resolution (we recommend using the maximum or default resolution, unless this is the subject of the test).
- The digital zoom factor (we recommend no digital zoom, unless this is the subject of the test).
- Any special post-processing settings that are time-consuming, especially those resulting in negative shutter lags (we recommend turning off or keeping all special settings in their default states).

The illumination level of the chart has a strong influence on both shooting and shutter release time lags. A higher illumination level during the shooting Time Lag measurement allows the autofocus sensor to run at a higher frame rate and thus facilitates faster focusing. (This is especially true with contrast AF technologies.) For the shutter release time lag, a higher frame rate due to a shorter exposure time can lead to close to null values with technologies such as live view or zero shutter lag.

In general, any camera settings that have a direct influence on the sensor frame rate may also have an influence on the Time Lag measurements. Examples of such settings include ISO sensitivity, exposure compensation, exposure time, sport modes, electronic image stabilizations that reduce motion blur by reducing exposure time, lower-resolution settings, digital zooms/cropping, etc.

The chart used may influence the focusing speed: the autofocus may need more time to focus on a chart with few details than on a chart with significant contrast.

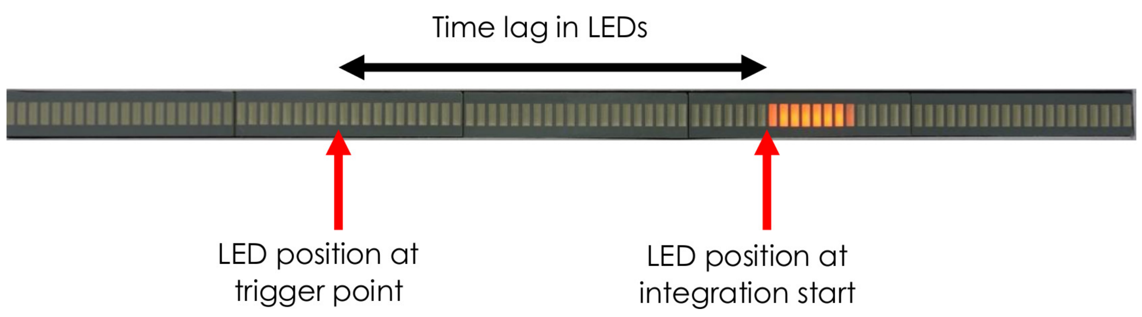
Image stabilizations, especially mechanical ones, require a certain time delay to be fully operational, and depending on the camera priorities, the image stabilization settings may influence time lag measurements.

Finally, any time-consuming image settings can influence the measurements. For example, the HDR mode available on some devices requires two captures instead of one, and some “smart capture” modes shoot a row of images and then automatically select the best one.

32.4 Measuring time lags

Time lag is measured by calculating the time interval between the integration start and the trigger point.

The trigger point is measured by synchronizing the device trigger with the LED Universal Timer, which records the LED positions on each line at the trigger point. Measuring the capture beginning is possible by capturing an image of the LED Universal Timer. Basically, the first lit LED on a LED bar represents the capture beginning, modulo the bar period.



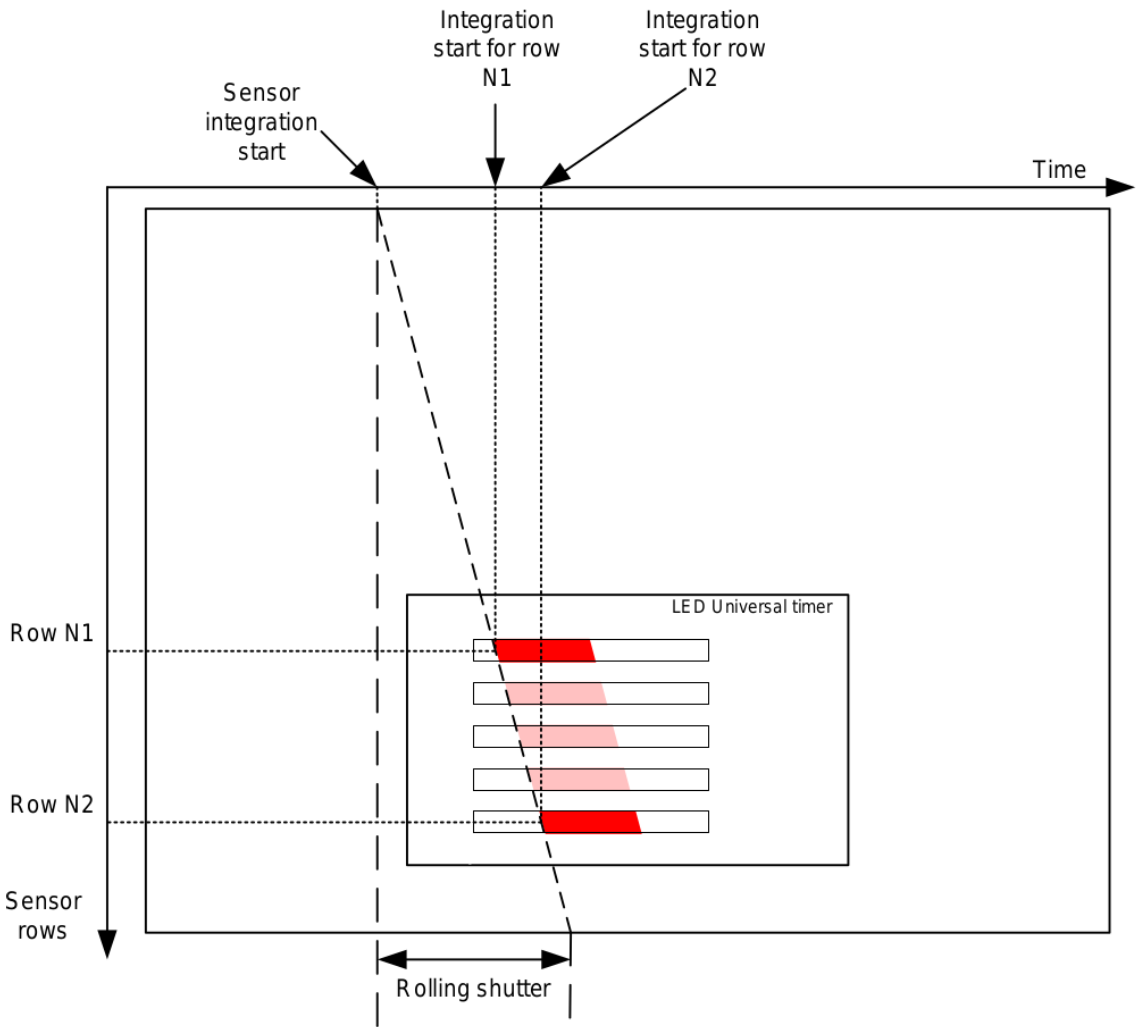
Each LED is lit only during one hundredth of the total line period or calibration. The time lag is therefore:

$$T_L = \Delta_{\text{LEDs}} \times \frac{\text{Calibration}}{100}$$

With one LED bar, the minimal measurable time is one LED. To increase measurement accuracy, one could use a shorter line calibration. But if the line calibration is too short, there can be one or more periods during the time lag, and these would not be visible. So with only one bar, the accuracy of the measurement is severely limited.

By using several LED bars at different periods or calibers, it is possible to accurately calculate the capture beginning with maximal accuracy (about 1/100 of the fastest line): the slowest line permits calculating a rough estimate of the time lag, and a faster line permits calculating a better estimate from this value.

Depending on the technology used, the effect of the rolling shutter may be non-negligible, especially with devices that use progressive scan (i.e., electronic rolling shutter). It is therefore essential to be able to measure the read-out speed.



32.5 Measurement in raw format

Analyzer is able to perform the measurement on both raw and RGB images. The presentation and the meaning of the results are the same.

32.6 Analyzer output

32.6.1 Analyzer output for individual measurement

Analyzer returns the following data in the Timing measurement, if capture data are given:

- The shooting conditions tab contains general shooting condition values, and also the content of the sidecar file (LED Universal Timer calibration and LED positions at trigger moment).
- In addition to the possible Timing measurements (exposure time and rolling shutter), the summary tab contains the results of the Time Lag measurement, i.e., the measured time lag in ms, and the accuracy of the integration start measurement.

	Time (ms)	Precision (ms)
Exposure time	8.00	± 1.00
Rolling shutter	44.96	± 11.16
Time lag	172.70	± 2.80

As for the Timing measurement, the measured exposure time and rolling shutter are displayed with their accuracy values. (See the Measurement accuracy Section 31.8 for more details).

32.6.2 Analyzer output for aggregated Timing measurement

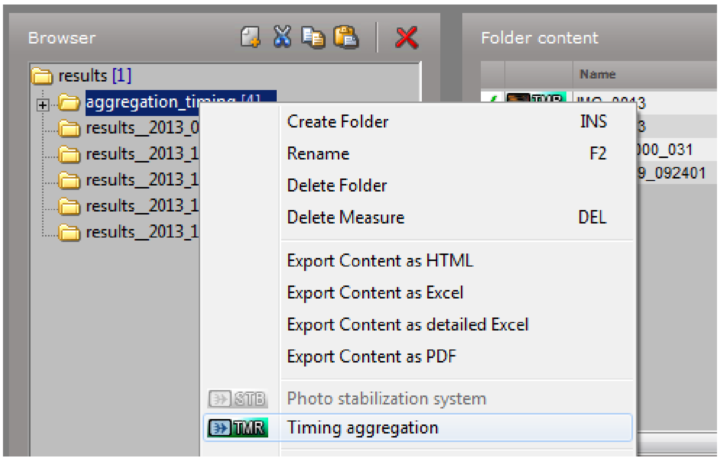
For a given set of individual measurements, Analyzer can return an aggregated measurement with statistics for individual measurement outputs:

	Average (ms)	Std. Dev. (ms)
Exposure time	20.82	0.24
Rolling shutter	67.12	1.60
Time lag	98.29	11.16

There are two ways to generate this aggregated measurement:

- Timer Pilot: The aggregated measurement is automatically generated when measurements are launched from Timer Pilot (see the Timer Pilot user manual). This is the standard way of generating this aggregated measurement since it is completely integrated with the measurement process.
- Analyzer: The TMR measurement results for a series of shots can be aggregated to provide a synthetic mean and standard deviation of the calculated shutter speed, ERS, and time lag.

  This feature is accessible through the context menu in the *Browser* tree view:



  – Group the results to be aggregated into a (new) subfolder.
  – Right-click on the folder and select *Timing aggregation*.

Note: All non-TMR results found in the aggregated folder will be ignored.

32.7 Examples

32.7.1 Nikon D3

Shutter release time lag:

	Time (ms)	Precision (ms)
Exposure time	3.00	± 1.00
Rolling shutter	4.37	± 4.47
Time lag	42.64	± 2.42

According to the manufacturer's specifications, this camera can run at 9 fps. One would therefore expect the shutter release time to be shorter than $\frac{1\,\mathrm{s}}{(2 \times 9)} = 56\,\mathrm{ms}$. The Time Lag measurement confirms this expectation.

32.8 Measurement accuracy

Measurement accuracy is the sum of the accuracy of the detection of the trigger instant and the accuracy of the measurement of the integration start.

The error for the trigger instant estimation for a mechanical trigger is limited by the delay introduced by the mechanics, and is less than 10 ms. With a capacitive touch screen, the maximal error on the trigger instant is about 1/200 of the period of the fastest line.

The accuracy of the integration start is given as a Analyzer output, and described in the Timings measurement section. It is limited by the period of the fastest line, the size of the LED Universal Timer in the field (for the rolling shutter estimation) and its position in the field (the closer to the sensor integration start, the better).

Analyzer may raise a warning concerning measurement accuracies for images shot with the time lag protocol: given the small size of the LED Universal Timer in the frame, the accuracy of the rolling shutter measurement is particularly low compared to what is possible with Analyzer. It is strongly advised to use the specific protocol for rolling shutter measurement.

32.9 Measurement scale

The following table gives a subjective scale for the shooting time lag:

Shooting time lag	Qualitative effect
$x < 200$ ms	Very good.
200 ms $< x < 500$ ms	Good.
500 ms $< x < 1000$ ms	Acceptable to bad, depending on the scene.
$x > 1000$ ms	Bad.

The following table gives a subjective scale for the shutter release time lag:

Shutter release time lag	Qualitative effect
-200 ms $< x < 0$ ms	Very good. Typical of devices that continuously shoot and store images in a buffer. Also called “zero shutter lag.”
0 ms $< x < 100$ ms	Very good. Below human reactivity. Can also be considered as “zero shutter lag.”
100 ms $< x < 500$ ms	Noticeable.
$x > 500$ ms	Bad.

32.10 Setup parameters influencing measurement

The following camera settings may influence Time Lag measurements:

- The image quality and format: many imaging devices perform corrections when converting images to JPEG. Among these corrections, the distortion correction can severely impact the sensor geometry as recorded in the JPEG image file, especially if the lens suffers from strong distortion. It is therefore preferable to make measurements on uncorrected raw images if possible.

32.11 Measurement validity

Because of the way most continuous shooting and live views work, there is a large variability in shooting time lag and shutter lag values. Variations in measurements that are far above the accuracies of devices are therefore to be expected, so you will need to perform a large number of measurements to produce a small confidence interval for the average shooting time lag and shutter release time lag.

Distortion can reduce the accuracy of the measurement, because this means that the LEDs are no longer aligned on the image. With very strong distortion, Analyzer may return an error. Note that correcting distortion will not give a correct timing measurement.

32.12 Comparing shooting time lag and shutter release time lag

According to CIPA DCG-002 (*Specification Guideline for Digital Cameras*), the difference between shooting time lag and shutter release time lag can be considered as an estimate of the focusing speed.

This means that under the same shooting conditions, the shooting time lag should always be greater than the shutter release time lag.

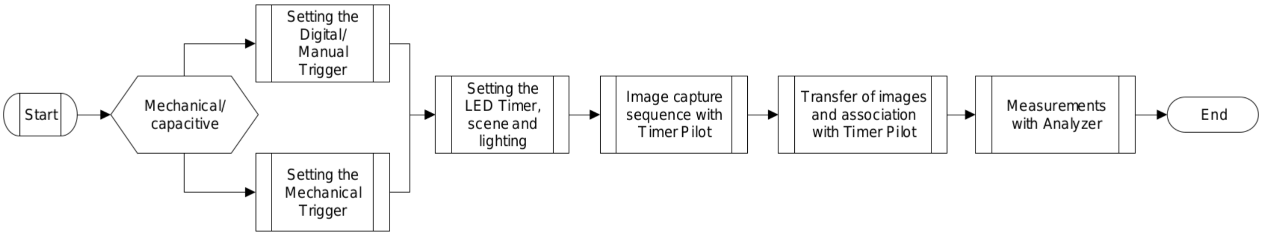
However, this interpretation of the difference between shooting time lag and shutter release time lag is not always meaningful. In particular with imaging devices that have negative shutter release time lag (by continuously shooting images stored in a buffer), the difference is greater than the actual focusing speed.

32.13 Comparing two cameras

The two main factors that influence Time Lag measurements are the illumination level and the chart. To obtain a fair comparison between two devices, you must use the same chart with the same illuminant.

The illumination level is particularly important, as it has a direct influence on the exposure time and therefore on the sensor frame rate with continuous streaming.

32.14 Shooting



32.14.1 Hardware descriptions

32.14.1.1 LED Universal Timer

LED Universal Timer is a device designed by DXOMARK IMAGE LABS to measure different kinds of camera timings.
With its five rolling LEDs lines and synchronization capability, this device can also help you measure time lags. It is can be remotely controlled from a computer with a B-USB type cable.
For more information on how to use the LED Universal Timer, refer to the device specifications.

32.14.1.2 Touchscreen Probe

The Touchscreen Probe allows you to electronically simulate a human finger on a capacitive touch screen. It is attached to the touch screen with the help of a hook-and-loop fastener, and must be plugged into a Digital Trigger.

32.14.1.3 Digital Trigger

The Digital Trigger has been designed to remotely control a Touchscreen Probe and to simultaneously send synchronization signals to a Universal LED Timer. It accurately simulates a push whose duration you can define, and sends a synchronization signal to a LED Universal Timer either on push or on release.

The Digital Trigger has to be plugged into a Touchscreen Probe, a LED Universal Timer with a mini-Din cable (S-video cable), and a remote computer with a micro-USB cable.

For more information, see the section on Managing the Digital Trigger in the Timer Pilot user manual.

32.14.1.4 Mechanical Trigger

The Mechanical Trigger allows you to synchronize the pressing of the mechanical button and the sending of the signal to the LED Universal Timer, thus making it possible to measure the time lags of imaging devices equipped with mechanical buttons (i.e., most DSLRs). The Mechanical Trigger can hold the pre-capture point. It can be fastened with a standard 1/4-inch bolt and therefore can be used on any tripod. It uses a cable to synchronize with a LED Universal Timer.

32.14.2 Measurement equipment

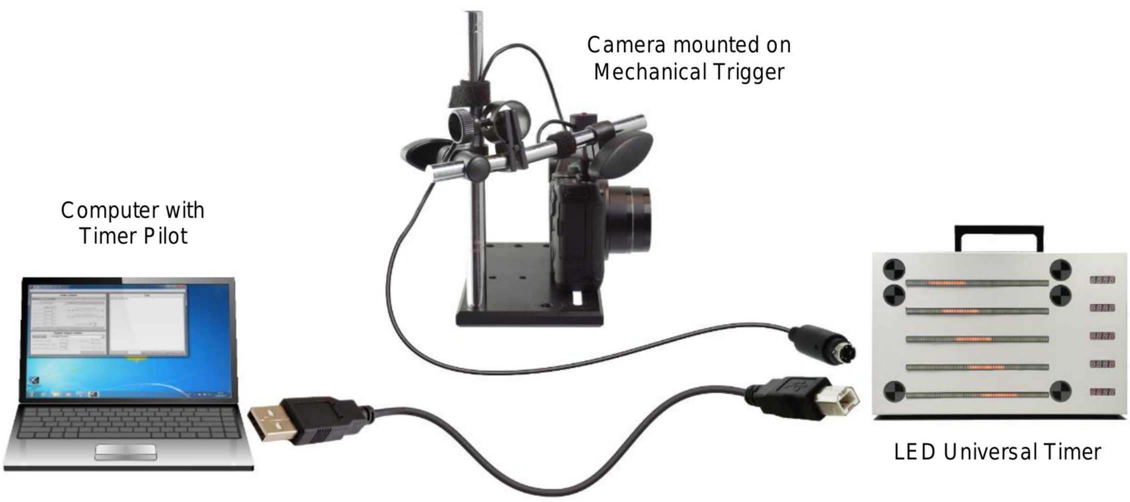
Measuring time lag requires the following equipment:

- The LED Universal Timer.
- A tripod with a 3-axis head for a stable shooting.
- A chart that allows the imaging device to focus easily. The ISO 12233 Resolution chart or dot chart are good examples of such charts. Take care that the chart does not contain any visible markers. Natural scenes can also be used.
- The Mechanical Trigger, If capture is activated with a mechanical button (as in the case of most DSLRs)
- If the capture is activated through a capacitive touch screen (as it is the case with most mobile devices), you will need a Touchscreen Probe and the Digital Trigger (and associated cables).
- A USB cable to connect the imaging device to a computer is also required.
- A remote computer with Timer Pilot installed.

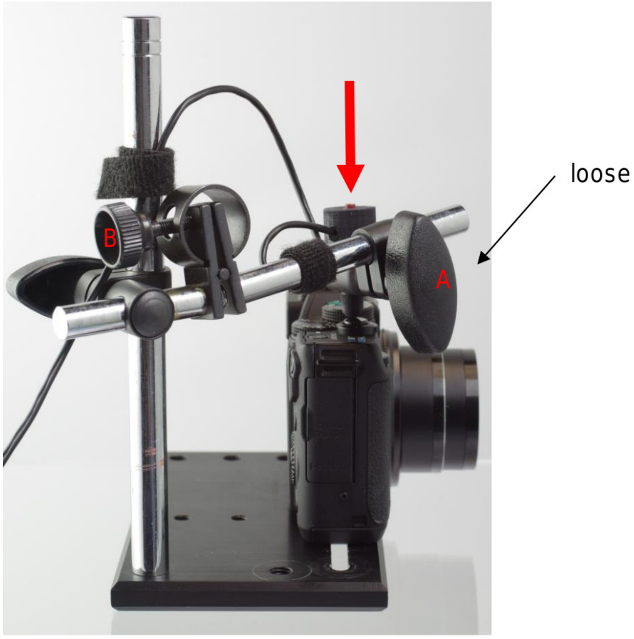
32.14.3 Measurement settings

32.14.3.1 Measuring devices with mechanical buttons (e.g., DSLRs)

32.14.3.2 Shooting time lag

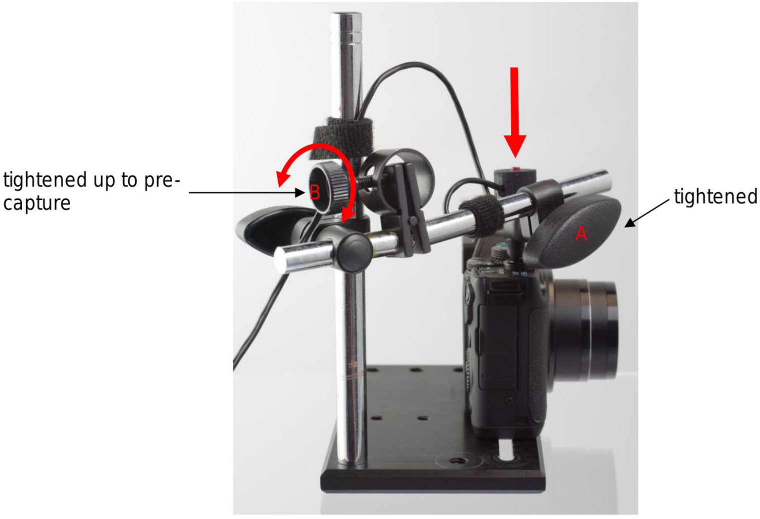


Connections among the remote computer, the LED Universal Timer and the Mechanical Trigger



Simply place the depressor above the trigger button and keep the A clamp loose.
A firm and fast push on the red switch will trigger the camera and the LED Universal Timer with a minimal delay between the two.

32.14.3.3 Shutter lag



The A clamping handle must be tightened. Use the B adjusting bolt to push the exposure button down to the pre-exposure point (usually the camera will focus at this point)

Some devices require the exposure button to be completely released between two captures. This can be done by loosening the B bolt and tightening it again.

32.14.4 Measuring devices with capacitive touch screens (e.g., mobile devices)

Not all mobile devices can be measured for either shooting time lag or shutter lag following ISO 15781 protocols. Before testing, be sure to check what the user interface allows.

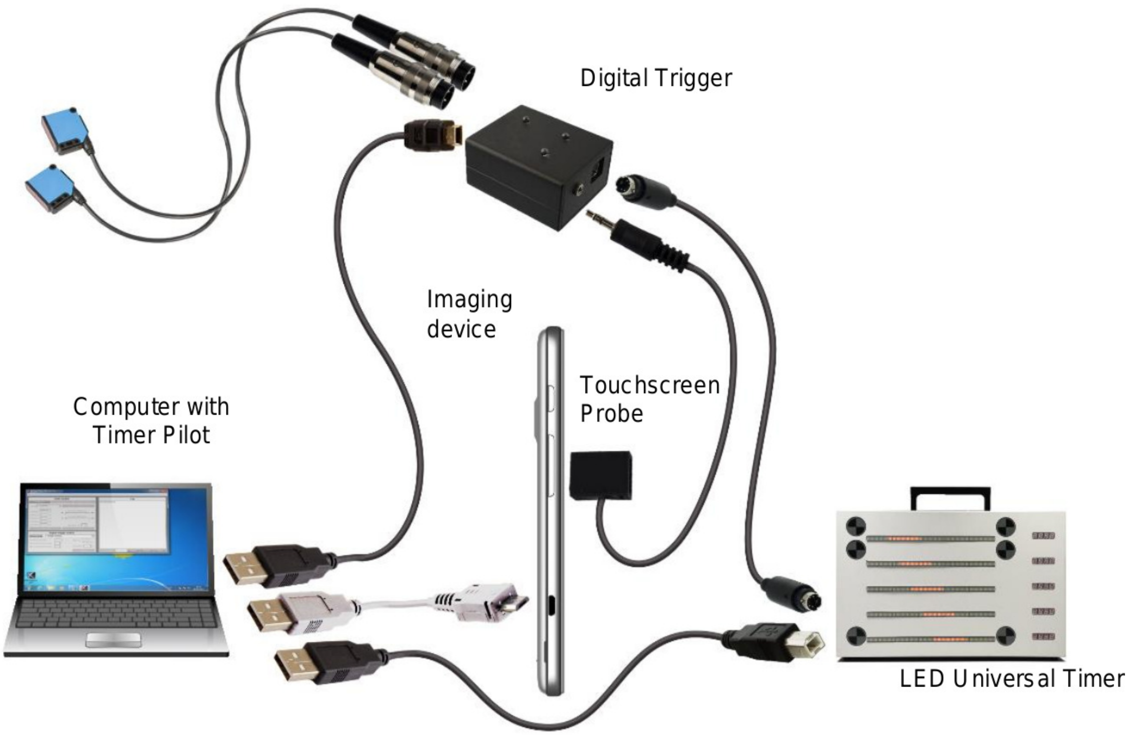
32.14.4.1 Connections between hardware

You must plug the LED Universal Timer and the imaging device into a remote computer.

The Digital Trigger, must be plugged into the LED Universal Timer, the Touchscreen Probe, and the remote computer.

Timer Pilot must be installed on the remote computer.

The imaging device must be connected to the computer via its proprietary USB cable not provided by DXOMARK IMAGE LABS.

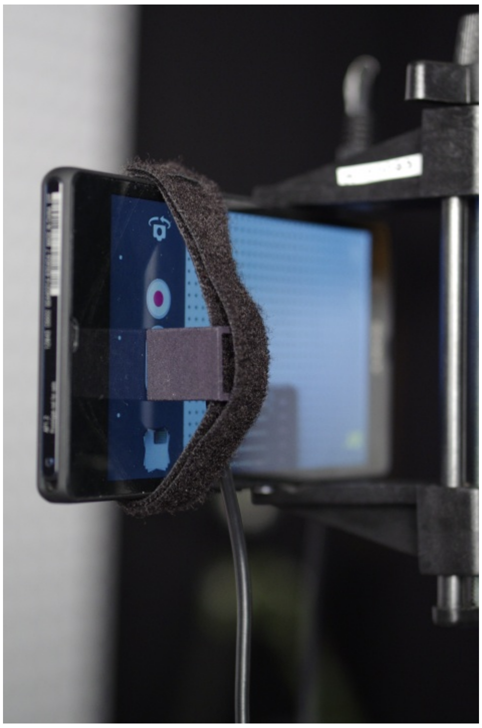


Connections among the imaging device with its proprietary USB cable (shown in white), the remote computer, the LED Universal Timer, the Touchscreen Probe, and the Digital Trigger

32.14.4.2 Positioning the Touchscreen Probe

Be sure that the capacitive screen is off (the usual stand-by state for such devices) before you begin positioning the Touchscreen Probe.

- Using the hook-and-loop fastener, firmly attach the Touchscreen Probe to the device screen while it is off (i.e., while the device is in standby mode). The probe must be fastened securely enough so that it won't move off the device screen.
- Place the probe at the location of the camera application trigger. Some user interfaces use the preview itself as a trigger button, so touching anywhere on the preview will make the camera focus on that location before capturing the image. In this case it is preferable to put the probe in the middle of the preview.



Touchscreen Probe on the still-capture trigger area of the user interface

- Turn on the device (i.e., exit stand-by mode) and start the camera application.
- Use Timer Pilot to make a sequence of captures.
- There should be at least 3 to 5 seconds between two trigger orders, as the device may reject commands that are too close in time to one another (typically 2 commands per second).

32.14.4.3 Troubleshooting the Touchscreen Probe

A. The Touchscreen Probe interferes with unlocking the device: on some imaging devices, the physical position of the trigger area in the camera application is shared with the unlocking area. In such cases:

   - Change the unlocking method in order to move its physical area, or
   - Slide the Touchscreen Probe off of the unlocking area, and after the camera application has started, slide the Probe back onto the triggering area. Take care that the Touchscreen Probe does not slide off of the screen.

B. The imaging device refuses to take pictures even without the Touchscreen Probe attached, or freezes after a number of captures:

   - Use the “charging only” USB mode. Internal memory is handled differently by each device and USB connection protocol when plugged into a computer. Some devices forbid the camera application to access the internal memory when plugged in using a USB protocol other than “charging only,” or reserves only a limited portion of this memory, which may not be enough.

C. The trigger area stays in “push” state:

  - Check that all the connections are correct and restart the positioning protocol again from the screen off state.
  - The Touchscreen Probe has moved off the screen because the fastener is too loose. Fasten it tighter and restart the positioning protocol again from the screen off state.
  - The Touchscreen Probe has moved off the screen (while unlocking the device, for example). Restart the positioning protocol again from the screen off state.

D. Trigger orders are not accepted by the camera application:

  - If you are using a Digital Trigger, increase the “push time” in Timer Pilot. triggering devices can simulate a push of a very short duration — shorter than what is usually possible with a human finger. Depending on the device, pushes shorter than a given duration might not be accepted by the camera application.
  - See also the solutions in The trigger area stays in “push” state (above).

32.14.5 LED Universal Timer position and configuration

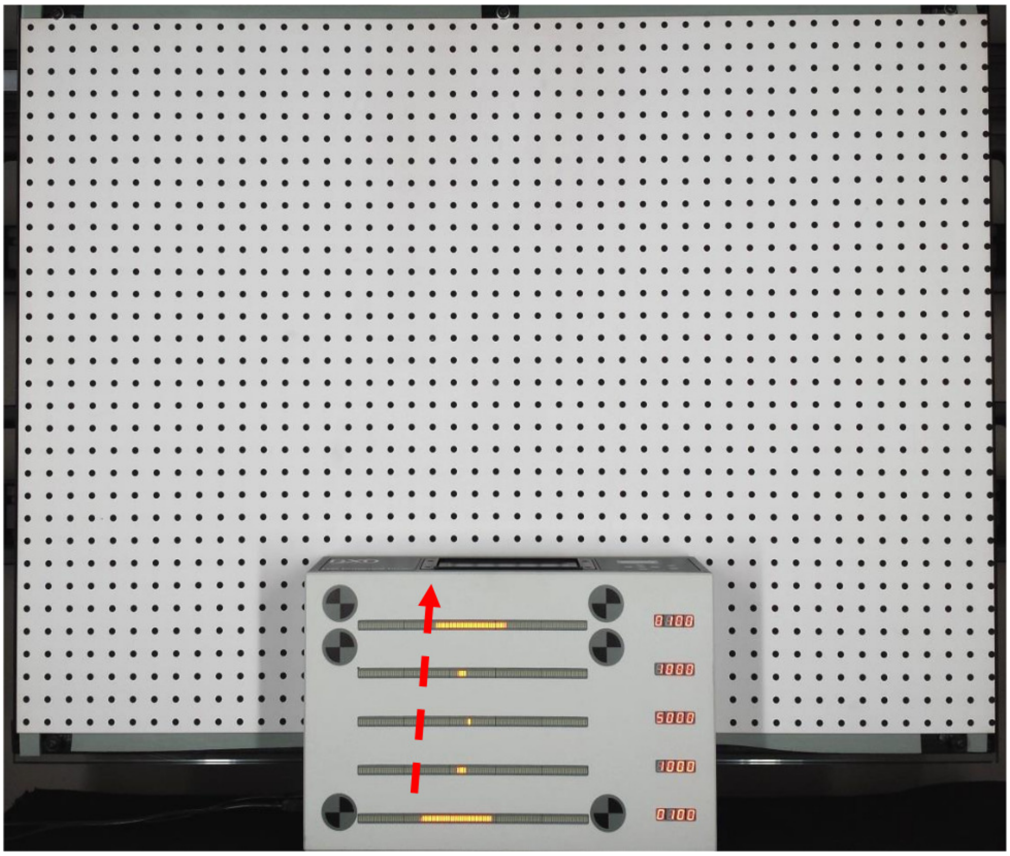
Place the imaging device so that it faces the chart. According to standard ISO 15781, you should place the chart about 33× the 35 mm equivalent focal length of the imaging device. You must also place the LED Universal Timer close to the chart in terms of depth of field.

For optimal accuracy, place the LED Universal Timer so that it is in the first captured part of the image. This is particularly important when measuring imaging devices with a rolling shutter, and depending on the position of the LED Universal Timer, the accuracy of the measurement can be severely impacted. To ensure that the LED Universal Timer is in the right place in the frame, you can either turn the device (the easiest way), or you can move the LED Universal Timer itself.

In general:

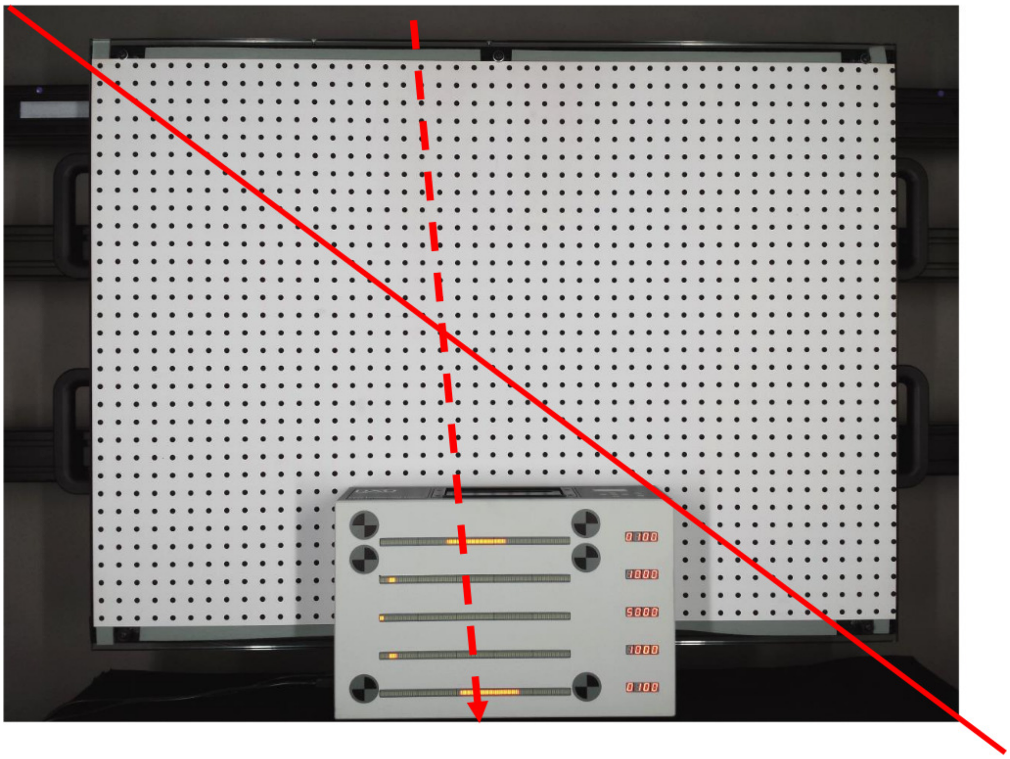
- DSLRs use focal-plane shutters, and the integration starts at the bottom of the image field. In this case, you can place the LED Universal Timer at the bottom of the frame.
- DSCs use global shutters. The position of the LED Universal Timer is therefore not crucial.
- Smartphones use an electronic rolling shutter, and integration starts at the top of the image field when a smartphone is held in landscape mode (i.e., the device's bottom is on the right). Simply turn over smartphone and put the LED Universal Timer at the bottom of the frame.

The image below shows the position of the LED Universal Timer in the frame so as to achieve optimal accuracy:



Sensor integration starts (indicated by the rolling shutter) on the bottom rows of the image. The accuracy is optimal

The configuration below shows how the position of the LED Universal Timer in the frame (or the orientation of the imaging device) reduces measurement accuracy. The accuracy of the capture start measurement is severely reduced by the inaccuracy of the rolling shutter measurement.



Integration starts on the top rows, whereas the LED Universal Timer is placed on the bottom of the frame. The inaccuracy of the rolling shutter measurement thus has a strong influence on the Time Lag measurement

The LED Universal Timer should be level and orthofrontal to the camera during the Timing measurement, and fully visible in the image. To be automatically detected in an image, detection markers should be at least 35/40 pixels in height. However, they must not impact the AF measurement by taking up too much space in the frame (i.e., not more than one third of the image height).

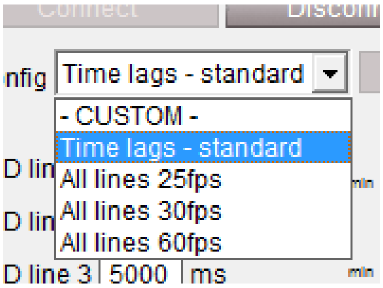
Example of the LED Timer's position having a strong impact on the AF measurement

LED lines must be perpendicular to the rolling shutter direction. This means that if the rolling shutter goes from top to bottom or bottom to top (as is generally the case), the LED lines must be horizontal in the image.

The recommended periods for each line of the LED Universal Timer are as follows:

- 100 ms
- 1000 ms
- 5000 ms
- 1000 ms
- 100 ms

This configuration allows the measuring of time lags from –1s to 3.5s with a maximum accuracy of 1 ms. This is a standard configuration in the Timer Pilot (see the section on Managing the Timer in the Timer Pilot user manual).



If possible, set the exposure time of the device to shorter than 100 ms. If this is not possible, then set the illumination so that the resulting exposure time chosen by the auto-exposure algorithm is shorter than 100 ms.

However, if you must perform measurements with exposure times longer than 100 ms, change the calibration of the LED Universal Timer so that the fastest lines have a period longer than the exposure time.

If you use custom calibrations, they must satisfy the following conditions (*Ln* is the period of line *n*):

- $L1$ > exposure time
- $L3 > 1.33 \times$ Max shooting Time Lag
- $L1 = L5$
- $L2 = L4$
- $L1 < L2 < 20 \times L1$
- $L2 < L3 < 20 \times L2$

The maximum accuracy of the Time Lag measurement is given as 1/100 of the fastest line, i.e., line 1.

The measurement works for a shooting time lag in the range $[-0.2 \times L3 \quad 0.75 \times L3]$.

32.14.6 Using the Timer Pilot

See the Timer Pilot user manual.

32.14.7 Number of images for a measurement sequence

According to standard ISO 15781, you should perform at least 10 measurements, and if the first measurement is significantly different from the average of these measurements, you should make 10 additional measurements.

Most mechanical shutters found in DSLRs repeat consistently enough so that the average of 10 measurements is a good estimator of the time lag.

However, once the sensor is continuously running (i.e., the device is running in live view), the device's performance is synchronized with the sensor's frame rate, and therefore the time lags are at best repeatable at more or less half of the frame period. For *N* measurements, the width of the confidence interval for the average time lag is in milliseconds (ignoring the inaccuracy of each measurement):

$$CI = 4 \times \frac{\sigma}{\sqrt{N}} = 4 \times \frac{\frac{1000}{\text{fps} \times \sqrt{12}}}{\sqrt{N}}$$

The table below gives some typical minimum numbers of individual measurements for a given frame rate and desired confidence interval:

	1 ms	5 ms	10 ms	50 ms
5 fps	460	93	46	10
10 fps	230	46	23	5
15 fps	150	31	15	3
20 fps	115	23	12	3
30 fps	77	16	8	2

However, this is only a lower limit, and depending on how the device works and on the average time lag being measured (especially if the autofocus is involved), you may need to make far more individual measurements to reach this level of accuracy.

32.15 Sidecar parameters

Most of the sidecar parameters are automatically written by Timer Pilot, so it is usually not necessary to modify these files. Specifically, Timer Pilot automatically fills the `[TimeBoxCalibration]` and `[TimeBoxCapture]` sections of the sidecar file (see section "Associating log records with images" in the Timer Pilot user manual).

If needed, these sections must be filled as follows:

```
[TimeBoxCalibration]
LineCalibration1=... // calibration of the top line in ms
LineCalibration2=...
LineCalibration3=...
LineCalibration4=...
LineCalibration5=... // calibration of the bottom line

[TimeBoxCapture]
LineCapture1=... // position of the LED on the top line at trigger point
LineCapture2=...
LineCapture3=...
LineCapture4=...
LineCapture5=... // position of the LED on the bottom line
```

The `[Common]` section is useful if marker automatic detection fails. In this case, you can provide the positions manually as follows:

```
[Common]
X1=... // x coordinate of the top-left marker
Y1=... // y coordinate of the top-left marker
X2=... // x coordinate of the top-right marker
Y2=... // y coordinate of the top-right marker
X3=... // x coordinate of the bottom-left marker
Y3=... // y coordinate of the bottom-left marker
X4=... // x coordinate of the bottom-right marker
Y4=... // y coordinate of the bottom-right marker
```

33 – AF: Autofocus

33.1 Introduction

An autofocus (or AF) camera system uses a sensor, a control system, and a motor to focus on an automatically- or manually-selected region of interest. An electronic rangefinder has a display instead of a motor; the optical system has to be adjusted manually until focused. Autofocus methods are classed as active, passive, or hybrid variants.

The two main autofocus technologies are phase detection and contrast detection, both of which are passive systems.

Users expect to have an autofocus that is both fast and accurate to ensure that every single picture from their device is sharp and recorded precisely when they press the trigger. To capture an image, however, the camera has to perform many time-consuming operations, the most time-consuming of which (in most cases) is the focus adjustment. Analyzer measures a large number of user-triggered focusing iterations to calculate the sharpness repeatability and the time lag for the pictures in a series; the result of this analysis is the Autofocus measurement.

33.2 Definitions

33.2.1 Shooting time lag

The time between pressing the exposure button on a digital still camera or on a module built into a mobile device, and the beginning of the exposure.

33.2.2 Delay

The amount of time between the scene change and the capture command. It must be higher than 100 ms and lower than 25 000 ms.

33.2.3 Acutance

Acutance is a single-value metric calculated from a MTF result. A higher value means a sharper image. See Section 10 for more information.

33.2.4 Viewing conditions

Acutance is always related to the size of the image (be it print or on-screen) and the viewing distance, such as a 40×60 cm print seen at 60 cm. See Section 10 for more information.

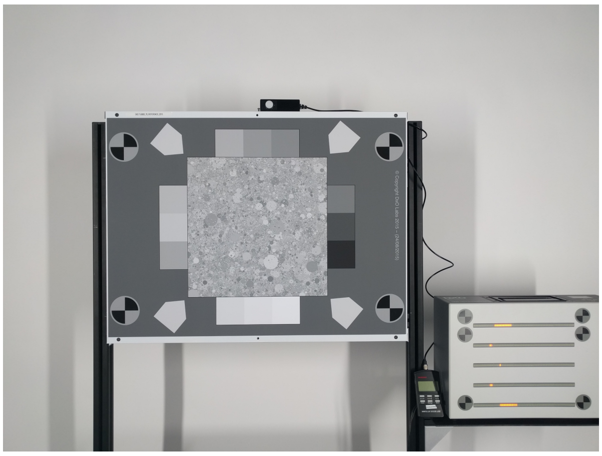
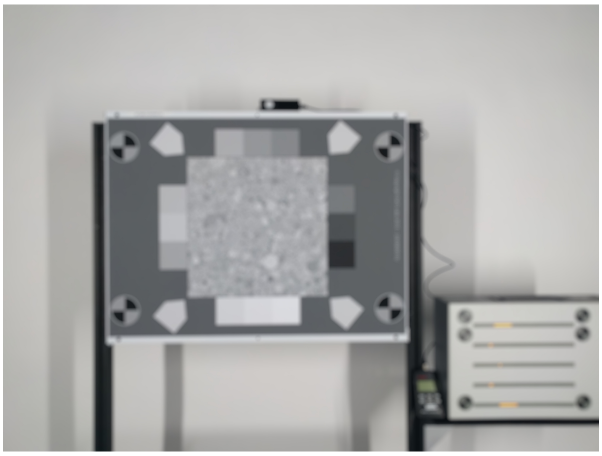
33.3 Influencing factors

Measuring autofocus must take into consideration:

- The influencing factors of the Time Lag measurement. See Section 32 for more information.
- The influencing factors of the Texture Preservation measurement. See Section 10 more information.
- The influencing factors for the whole measurement:
  - The user-provided delay to let the device focus.
  - The lighting conditions.

33.4 Measurement of autofocus metrics

The autofocus target is set up as follows:

The left picture of the target shows good autofocus behavior, while the right shows bad autofocus behavior (due to bad lens positioning).

The target contains two main elements:

- The Texture Preservation ("Dead Leaves") target.
- The LED Universal Timer.

The Texture Preservation target is used to compute the acutance from the SFR Edges as described in Section 10, and the LED Universal Timer is used to compute the shooting time lag as described in Section 32.

This measurement requires multiple shots (30 is an acceptable number of shots) and all the pictures must be shot under the same conditions (illumination, delay etc.). You must not move the setup between shots.

33.5 Measurement in raw format

As this measure is using the texture measure, it is also available for RGB images only, and measurement on raw images is not available.

33.6 Analyzer output

Analyzer returns the following data:

- The “Shooting conditions” tab contains general shooting condition values, the selected viewing conditions, the content of the sidecar file (LED Universal Timer calibration, LED positions at trigger moment, and user-selected delay), as well as the image paths:

Overview

Video name	C:\Users\probisson\Desktop\20151109_165004.jpg
Side car	sidecar.ini

Image format	RGB
Image depth	8 bits/channel
Width	5312 pixels
Height	2988 pixels
Date	18/07/2016 - 15:07:50
Color space	sRGB
Description	01 - Consumer Photo Print
Distance	250 mm
Print height	100 mm
Use MTF display	Yes

Video format	Frames
Extension	jpg
Decoder	
Frame count	3
Frame rate	
Pixel ratio	13029736:4451616

Side car content

Line 1 calibration	100
Line 2 calibration	1000
Line 3 calibration	8000
Line 4 calibration	1000
Line 5 calibration	100
TimeDelay	500

Source files

IMAGE PATHS

- The “Summary tab” contains statistical metrics as average acutance, average shooting time lag, acutance irregularity, and the standard deviation of the shooting time lag.

- In case the measurement fails for a picture in the series (for instance, bad marker detection in a blurry image), Analyzer assigns 5% for the acutance, and a random shooting time lag is included in a normal distribution calculated from succeeded pictures. Therefore these metrics reflect a failed focus via the acutance, without penalizing the shooting time lag.
- The irregularity metric is defined as the average acutance difference between the highest acutance in a series and the acutance for each shoot, measured on the Luminance channel.

Average edge acutance	0.746
Average shooting time (ms)	1072
Acutance irregularity	0.333
Std dev shooting time (ms)	86

- The "autofocus tab" contains a graph that shows the acutance against the time. A straight line shows the delay you chose, and the shooting time lag is the time that elapses from this line to a point, which represents a picture.
  - If the measurement fails for a picture in the series, the same rule applies: 5% for the acutance and a random shooting time lag included in a normal distribution calculated from succeeded pictures, thus clearly indicating the failed pictures on the graph.

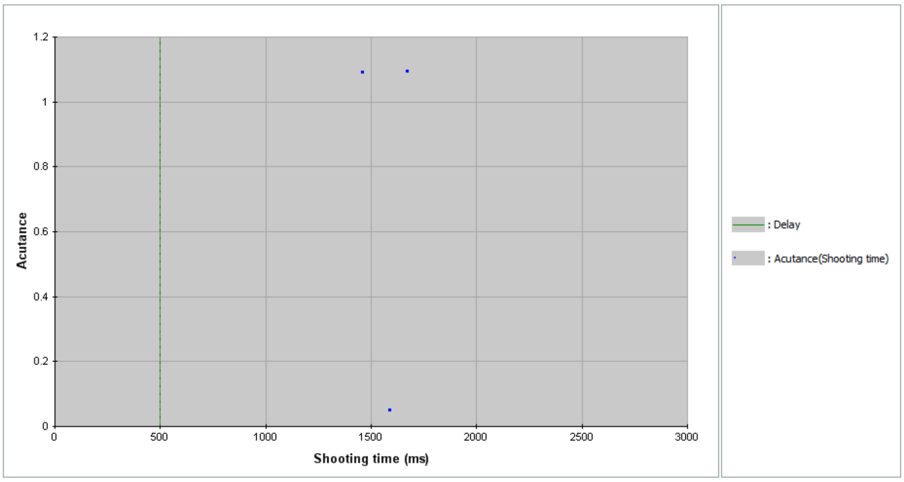


Chart showing the results of a device

- The "autofocus tab" also contains a table with acutance and shooting time lag results for each picture.

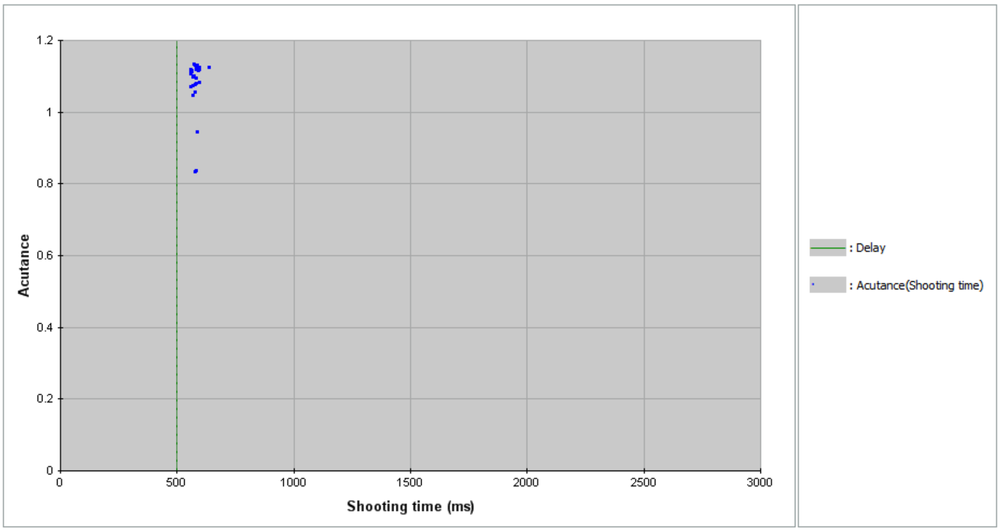
– The symbol '-' indicates that Analyzer was unable to compute the metrics for a picture in the series. In most cases, this is due to autofocus failure resulting in blurred pictures, but we advise you to check that the picture really is blurry, in case there is a different problem.

Filename	Edge Acutance	Shooting Time Lag (ms)
9_165004.jpg	1.094	1170
9_165010.jpg	-	-
9_165018.jpg	1.092	960

33.7 Examples

Here are several examples of Autofocus measurement results. The selected viewing condition is Professional Photo Print (closer) and 30 pictures are used.

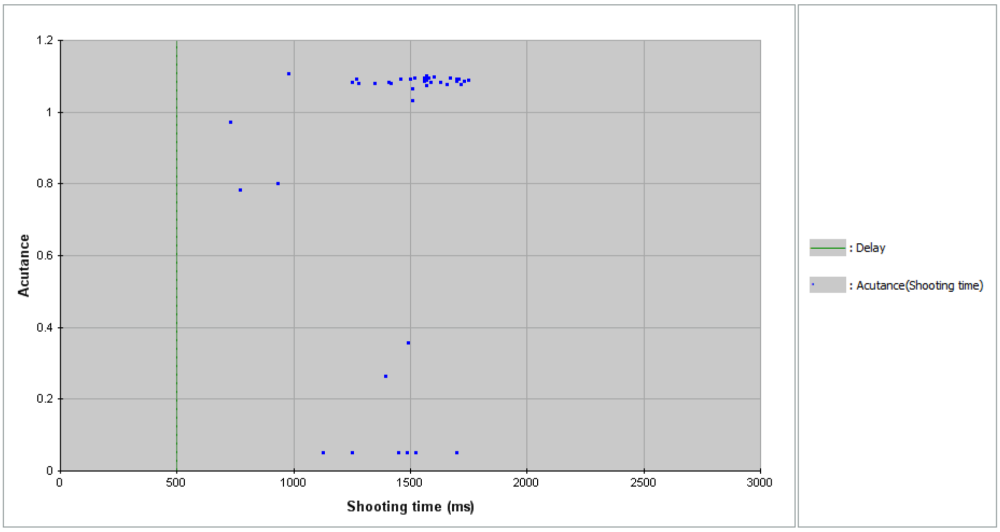
The following figure corresponds to a measurement of a smartphone camera tested in bright light conditions (1000 lux) with a delay of 500 ms. The autofocus is fast because the average shooting time lag is under 100 ms with a low spread of dots, and it is also accurate because the average acutance is up to 100% with low irregularity.



Results of a smartphone at 500 ms, 1000 lux

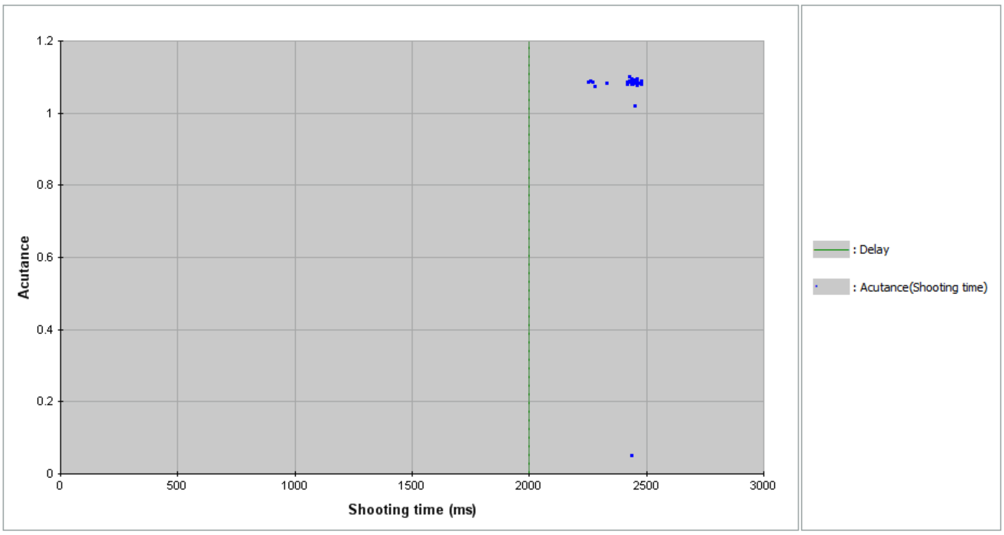
The following figure shows the same smartphone camera tested in low light (20 lux) with a 500 ms delay.

This example shows the importance of the lighting conditions. Indeed, the shooting time lag increases significantly in low light and there are some autofocus failures (very low acutance).



Results of a smartphone at 500 ms, 20 lux

The next example is the same device tested in low light (20 lux) with a 2000 ms delay (see 33.13.1). This example shows the importance of the chosen delay. Although the lighting conditions are the same as the previous example, the shooting time lag is lower because the delay is longer. In other words, the camera has more time to focus. There are also fewer failures with a 2000 ms delay.



Results of a smartphone at 2000 ms, 20 lux

33.8 Measurement accuracy

The repeatability of the Autofocus measurement is ±0.04 for acutance and ±10 ms for shooting time lag. However, this depends on the following points:

- If the autofocus is inaccurate or not repeatable, as for some camera phones, results may have low repeatability even for consecutive images taken under the same shooting conditions.
  - Autofocus repeatability depends on the device itself, the lighting conditions, and the delay.
- If the autofocus is inaccurate or not repeatable, Autofocus measurement accuracy depends on the number of shots.

33.9 Measurement scale

The following tables give a subjective scale for acutance irregularity, average shooting time lag, and standard deviation (stdDev) of the shooting time lag:

Acutance irregularity	Qualitative effect
$x < 7\%$	The autofocus is very regular.
$7\% < x < 20\%$	The autofocus has some irregularities.
$20\% < x < 50\%$	The autofocus is unrepeatable and can produce some critical failures.
$x > 50\%$	The autofocus is unrepeatable and produces many critical failures.

Average shooting time	Qualitative effect
$x < 100$ ms	Very fast for human perception.
100 ms $< x <$ 500 ms	Fast for human perception.
500 ms $< x <$ 1000 ms	Slow for human perception.
$x > 1000$ ms	Very slow for human perception.

StdDev shooting time	Qualitative effect
$x < 100$ ms	Very repeatable.
100 ms $< x < 250$ ms	Repeatable.
250 ms $< x < 500$ ms	Unrepeatable and can produce some critical failures.
$x > 500$ ms	Unrepeatable and produces many critical failures.

33.10 Setup parameters influencing the measurement

- The HDR algorithm can influence the shooting time lag and the acutance.
- Auto white balance algorithms can introduce irregularities into the Autofocus measurement.
- Flash can influence the shooting time lag and the acutance.
- Any other special post-processing settings may have an effect.

33.11 Measurement validity

Depending on the accuracy and repeatability of the tested device, you may need to shoot a large number of pictures for the Autofocus measurement to produce a small confidence interval for the average shooting time lag and the average acutance.

Distortion can reduce the accuracy of the measurement, because it means that the LEDs are no longer aligned on the image. With very strong distortion, Analyzer may return an error. Note that correcting distortion will not give a correct timing measurement.

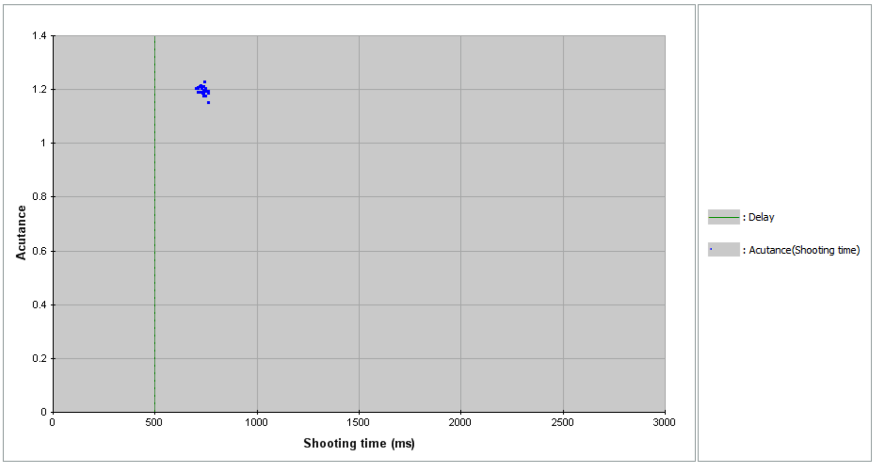
As for the Texture Preservation, the Autofocus measurement is meaningful only if the conditions described in Section 10.12 are met.

33.12 Comparing two devices

It is possible to directly compare the autofocus of two cameras, if the viewing conditions, lighting conditions, and delay periods are the same. The comparison is meaningful if the two devices have a similar focal length and field of view.

The following is a comparison of results obtained with the smartphone A and the smartphone B, using viewing conditions named "Professional Photo Print (closer)," in low light (20 lux) with a 500 ms delay.

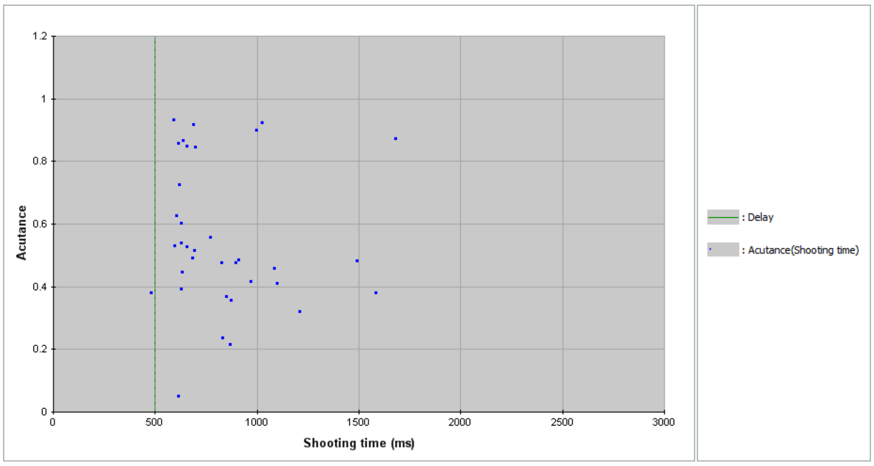
The chart below shows the results for the smartphone A. It is very accurate and very fast for the difficult lighting conditions. Moreover, the dots are grouped together, which means that the repeatability of the device is very good. All this information is confirmed by the metrics provided in the "Summary tab".



Average edge acutance	1.196
Average shooting time (ms)	237
Acutance irregularity	0.050
Std dev shooting time (ms)	16

Results of the smartphone A: fast, accurate and repeatable

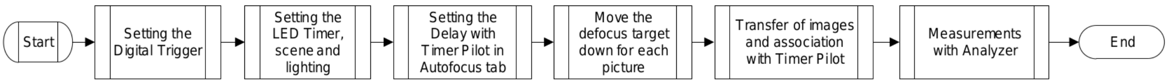
As for smartphone B, the dots are more scattered. It means that the autofocus is not repeatable, and the acutance and the shooting time lag vary widely from one picture to another. In general, its acutance and shooting time lag are lower than for smartphone A. All this information is confirmed by the metrics provided in the "Summary tab". This example shows a dot that appears before the end of the delay, meaning that the shooting time lag is negative. This may be due to the algorithm using a picture from a buffer that continuously takes pictures. Ideally, this kind of algorithm should provide zero shutter lag.



Average edge acutance	0.556
Average shooting time (ms)	337
Acutance irregularity	0.377
Std dev shooting time (ms)	287

Results of the smartphone B: inaccurate and unrepeatable

33.13 Shooting



33.13.1 Hardware descriptions

33.13.1.1 Tested device

The tested device must have a capacitive touchscreen to work properly with the Touchscreen Probe.

33.13.1.2 LED Universal Timer

LED Universal Timer is a device designed by to measure different kinds of camera timings. See Section 31 for more information.

33.13.1.3 Touchscreen Probe

The Touchscreen Probe lets you electronically simulate a human finger on a capacitive touch screen. It is attached to the touch screen using a hook-and-loop fastener, and must be plugged into a Digital Trigger. See Section 31 for more information.

33.13.1.4 Digital Trigger

The Digital Trigger remotely controls a Touchscreen Probe and to simultaneously send synchronization signals to a Universal LED Timer. See Section 31 for more information.

33.13.1.5 Infrared sensors

The infrared sensors are plugged into the Digital Trigger to send it a signal when the defocus target disappears, which is when the device starts to focus.

To command the trigger, place the defocus target in front of the device, with the two red dots from the infrared sensors, displayed on the upper and lower borders of the screen. This is important for simulating the disappearance of the defocus target from the device's field of view.

Infrared sensor

33.13.2 Measurement equipment

Autofocus setup

Measuring Autofocus requires the following equipment:

- The LED Universal Timer.
  - The target must be on the bottom right in the image.
- A tripod with the specific plate that includes infrared sensors and clamps, and hardware adjusted for the Autofocus measurement.
- A texture chart.
  - Target must be centered in the image.
  - The visible background behind the target must be uniform (A matte white background is recommended).
  - Borders of the target must be parallel to the borders of the image.
  - Texture area must fill one third of the image's height.
  - Lighting must be uniform.
- A Touchscreen Probe and the Digital Trigger (and associated cables).

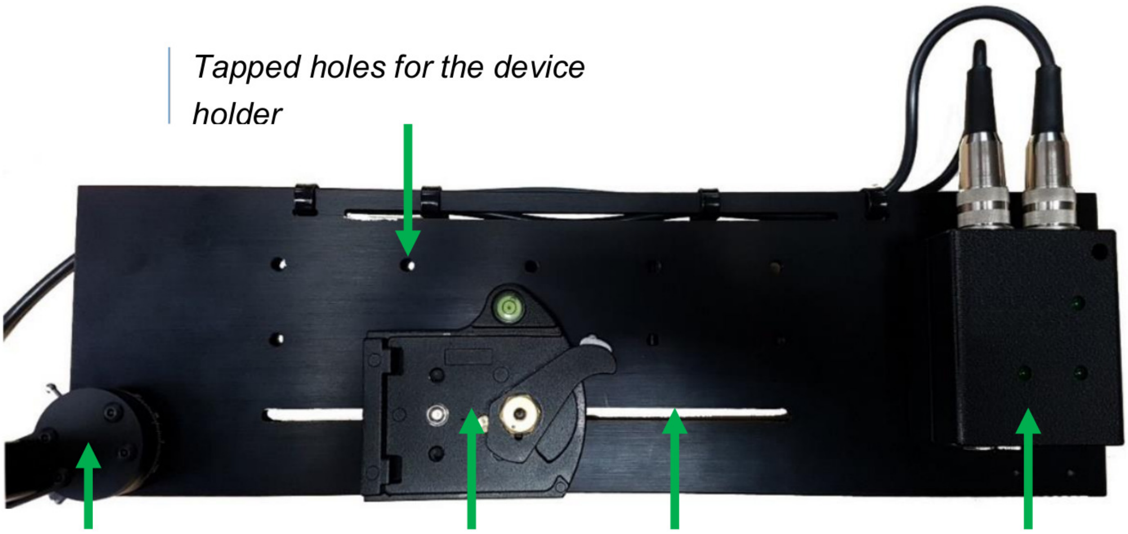
- A USB cable to connect the imaging device to a computer is also required.
- A remote computer with Timer Pilot installed.

33.13.3 Measuring devices with capacitive touch screens (e.g., mobile devices)

Not all mobile devices can be measured for either shooting time lag or shutter lag following ISO 15781 protocols. Before testing, be sure to check what the user interface allows.

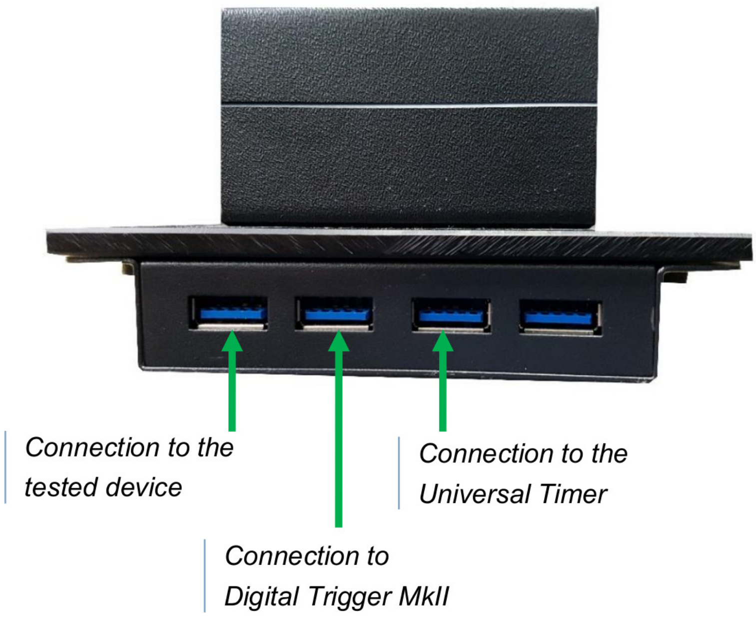
33.13.3.1 Assembling the setup

The Digital Trigger “MkII”, the USB 3.0 Hub, and the rotary plate are screwed on the main plate. The main plate has a slot which is used to screw on the Manfrotto 394 Adapter, on which you can attach a highly-flexible and adjustable MeFoto holder. This plate also contains several tapped holes for the Device Holder.

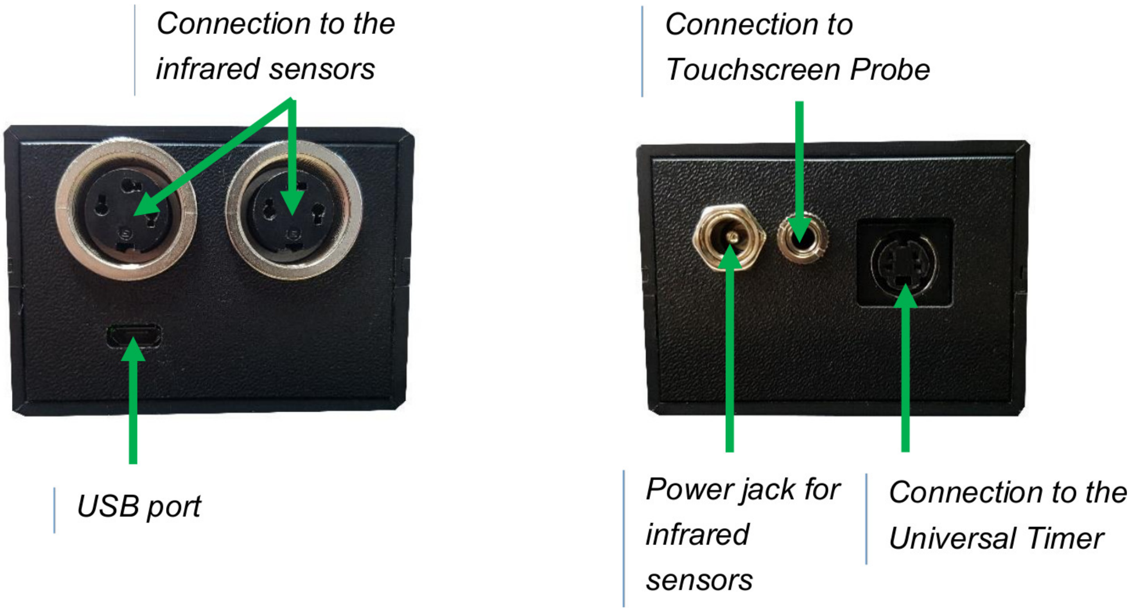


33.13.3.2 Connections between hardware

You must plug the LED Universal Timer, the Digital Trigger “MkII” and the imaging device into a remote computer or a hub as follows:

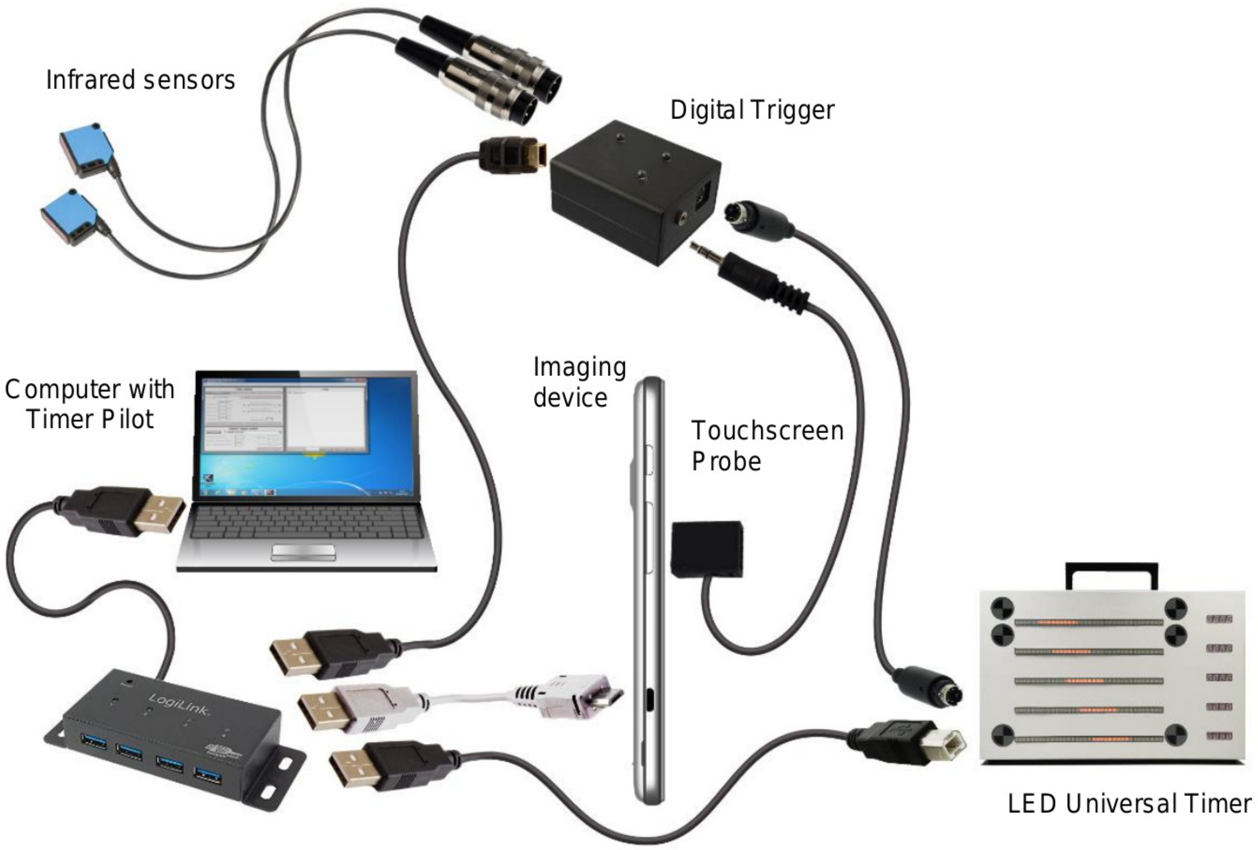


The LED Universal Timer and the Touchscreen probe must be plugged into the Digital Trigger “MkII”. The infrared sensors and the power must be plugged into the Digital Trigger as follows:



Timer Pilot must be installed on the remote computer.

The imaging device must be connected to the computer via its proprietary USB cable (not provided by DXOMARK IMAGE LABS).



Connections among the imaging device with its proprietary USB cable (shown in white), the remote computer, the infrared sensors, the LED Universal Timer, the Touchscreen Probe, and the Digital Trigger. You can use a hub so as to have only one USB cable connected to the computer

33.13.3.3 Positioning the Touchscreen Probe

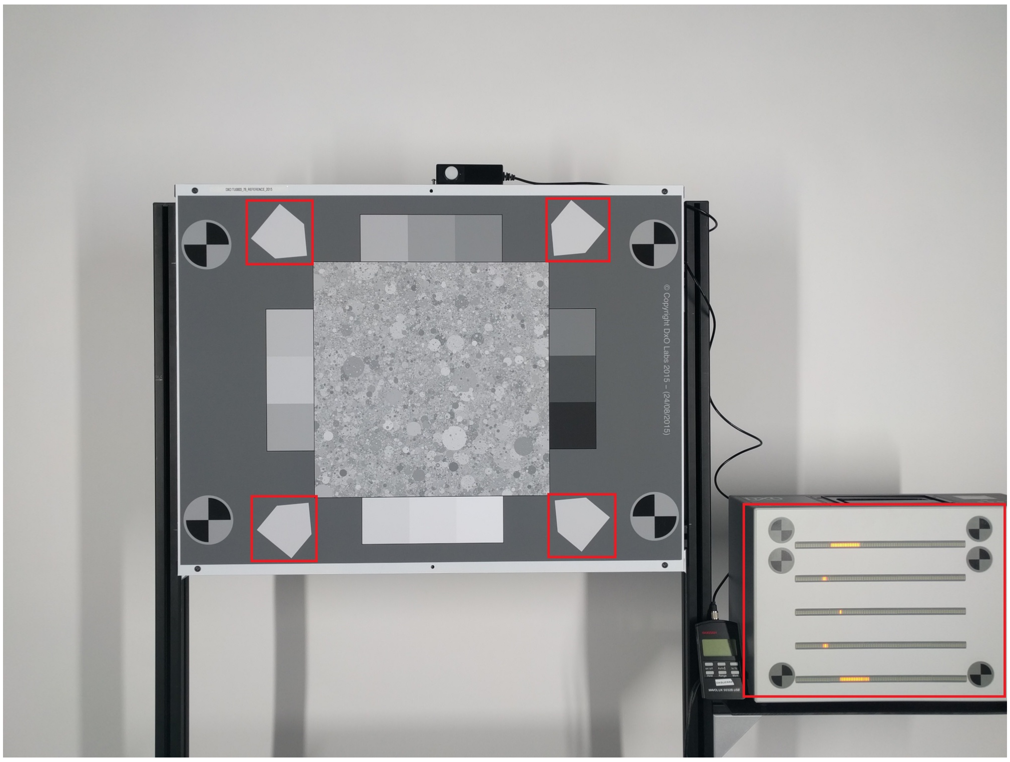
Be sure that the capacitive screen is off (the usual stand-by state for such devices) before you begin positioning the Touchscreen Probe. See Section 31 for more information.

33.13.4 Chart and LED Universal Timer position and configuration

Place the imaging device so that it faces the charts. The texture chart must be centered, and the LED Universal Timer must be to the right and at the bottom, as shown below. You must also place the LED

Universal Timer and the texture chart on the same plane.

The image below shows the position of the texture chart and the LED Universal Timer in the frame so as to achieve optimal accuracy. The acutance is computed from the edges and the shooting time lag is computed from the LED Universal Timer.



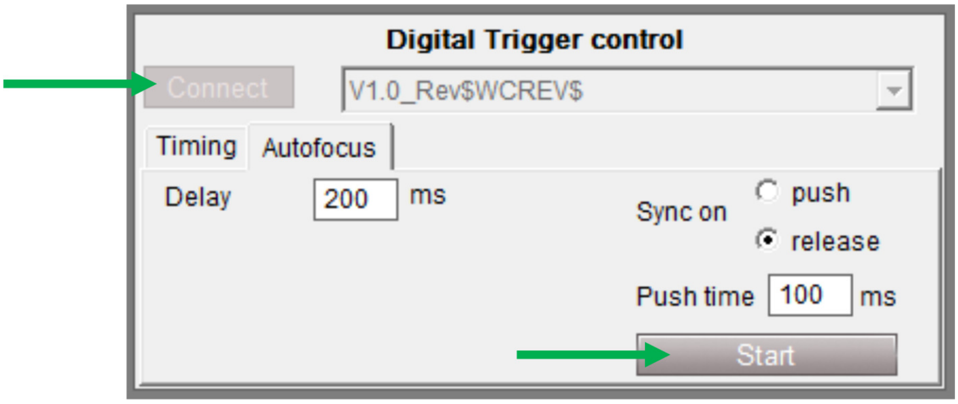
Areas (outlined in red) used to compute the metrics

The recommended periods for each line of the LED Universal Timer are as follows:

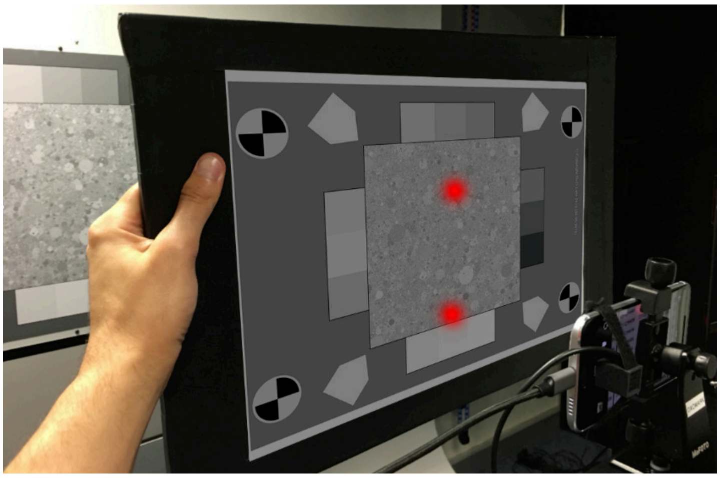
- 100 ms
- 1000 ms
- 8000 ms
- 1000 ms
- 100 ms

Avoid reflection on the Universal Timer and be certain the two chart are in the same plan.

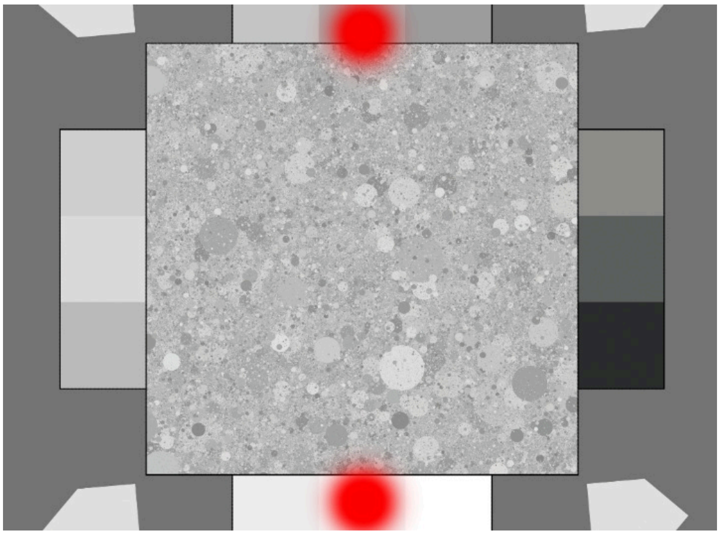
- Choose the device settings.
- Connect to the digital trigger through Timer Pilot, and choose the desired settings in the autofocus tab. Click “Start”. (See the Timer Pilot manual for more information).



- Place the defocus chart in front of the device.

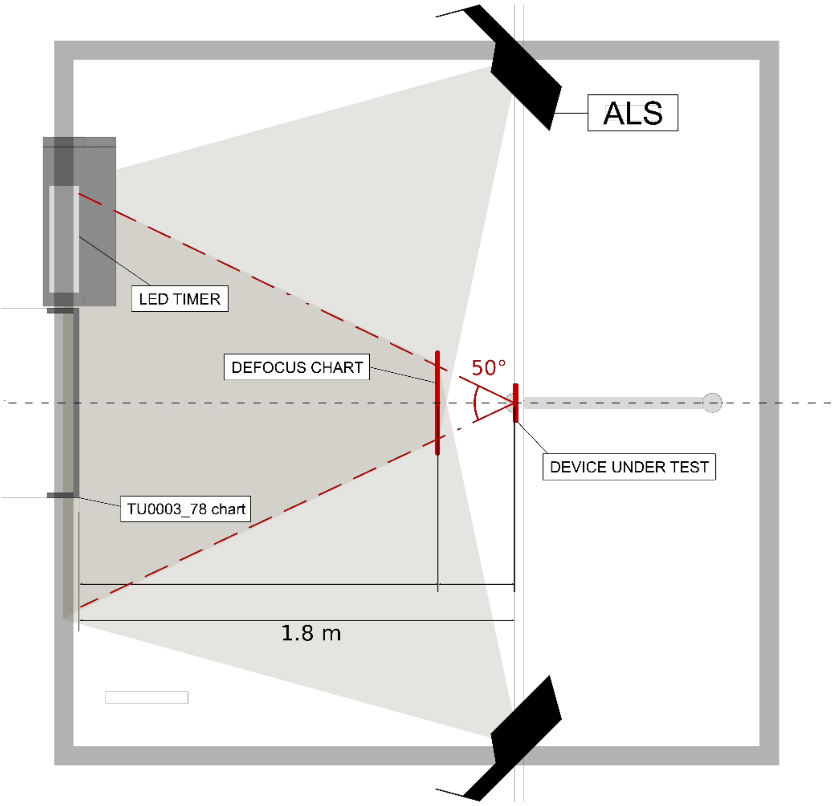


- The two red dots need to be on the upper and lower borders of the device screen to simulate the device's field of view. The red dots must be less distant from the borders than 10% of the screen height.



- Check that the defocus chart is lit correctly, in order for it to affect the autofocus system of the imaging device as intended.

  The recommended position distance between the Automated Lighting System (ALS) and the texture chart is 1.8 meters. In this condition, the defocus chart will be lit correctly for devices with a field of view between approximately 50° and 80°.



- Move down the chart. The shot will trigger after the delay period you entered in Timer Pilot is up. Repeat this step several times to get more data.
- Do not move the device nor the setup between shots.

33.13.5 Using the Timer Pilot

See the Timer Pilot user manual.

33.14 Sidecar parameters

Timer Pilot automatically writes all the sidecar parameters, so you usually will not need to modify these files. Specifically, Timer Pilot automatically fills the `[TimeBoxCalibration]` and `[TimeBoxCapture]` sections of the sidecar file (see section 3.5, "Associating log records with images," in the Timer Pilot user manual).

If needed, fill out these sections as follows:

```
[TimeBoxCalibration]
LineCalibration1=... // calibration of the top line in ms
LineCalibration2=...
LineCalibration3=...
LineCalibration4=...
LineCalibration5=... // calibration of the bottom line

[TimeBoxCapture]
LineCapture1=... // position of the LED on the top line at trigger point
LineCapture2=...
LineCapture3=...
LineCapture4=...
LineCapture5=... // position of the LED on the bottom line

[Delay]
TimeDelay=... // delay used for the series in ms
```

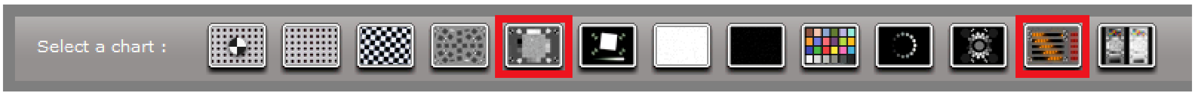
The `[Common]` section is useful if marker automatic detection fails. In this case, you can provide the positions manually as follows:

```
[Common]
X1=... // x coordinate of the top-left marker
Y1=... // y coordinate of the top-left marker
X2=... // x coordinate of the top-right marker
Y2=... // y coordinate of the top-right marker
X3=... // x coordinate of the bottom-left marker
Y3=... // y coordinate of the bottom-left marker
```

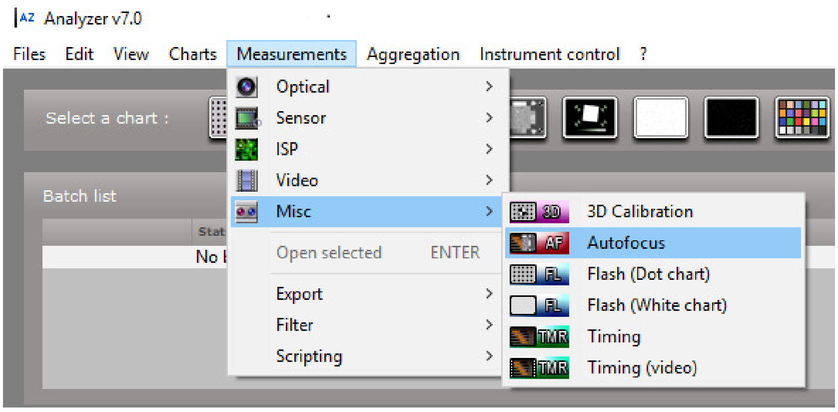
```
X4=... // x coordinate of the bottom-right marker
Y4=... // y coordinate of the bottom-right marker
```

33.15 Launching Analyzer Autofocus measurement

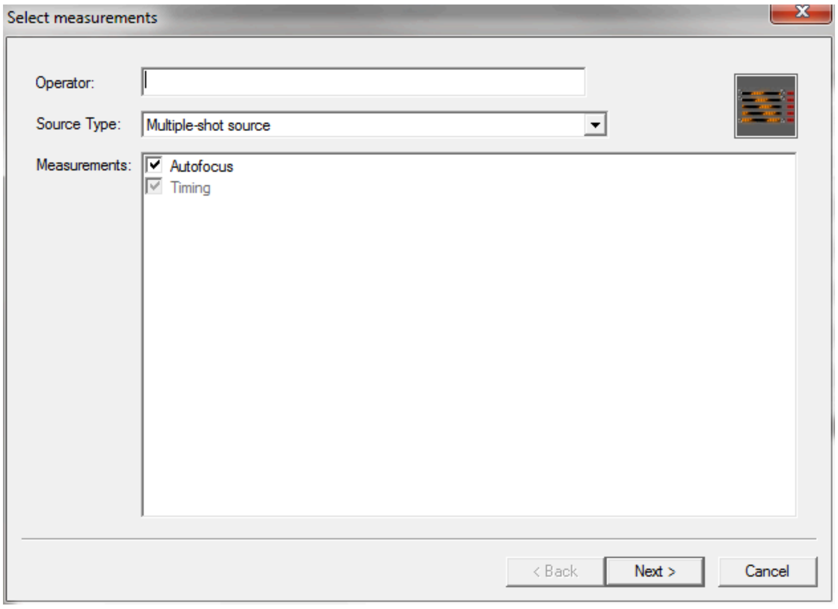
- Select the texture chart or the LED Universal Timer in the Analyzer chart menu. Autofocus measurement is also available in the “Measurements menu”.



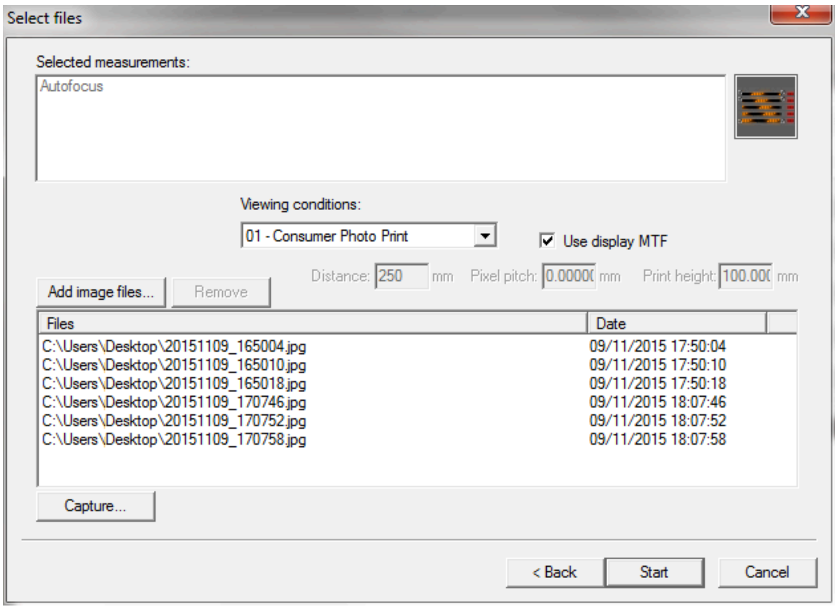
- You can also choose the “Measurements tab” to launch the Autofocus measurement.



- To select the “Autofocus” measurement, choose “Multiple-shot source” in the Source Type dropdown menu.



- To launch an Autofocus measurement:
  - Select the required viewing conditions
  - Click "Add image files..." and select your pictures (minimum 2).
  - Click "Start".

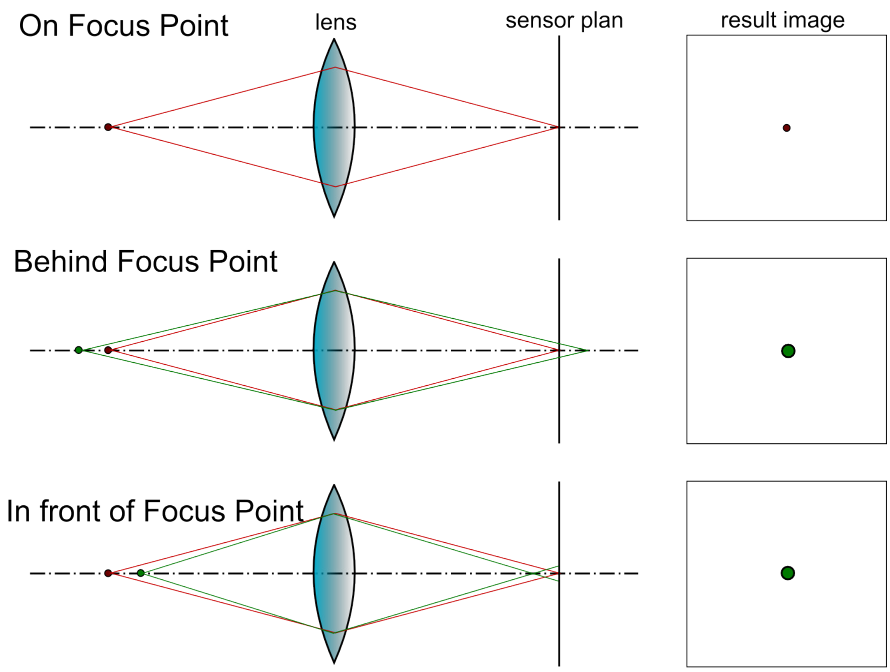


34 – ROF: Range Of Focus

34.1 Introduction

The optical system of a digital camera is able to produce a sharp image only in a restricted range of distances near the point of focus.

In fact, a precise focus is possible at only one distance, precisely at the point of focus. At this distance, the image of a point is a point, up to diffraction effect. At any other distance, the subject is defocused and the image of a point is a blur spot with a mean radius depending on the distance to the point of focus. But in a range of distances around this point, this blur spot is sufficiently small to be indistinguishable from a point, and images appear sharp.



At any other distance than the focus distance, the image of a point is a circle

The largest circle indistinguishable from a point is called the *circle of confusion*, and it depends on the focal length and the aperture.

Therefore, there is a minimum shooting distance where the subject appears sharp, and a maximum distance. That maximum distance may be infinite.

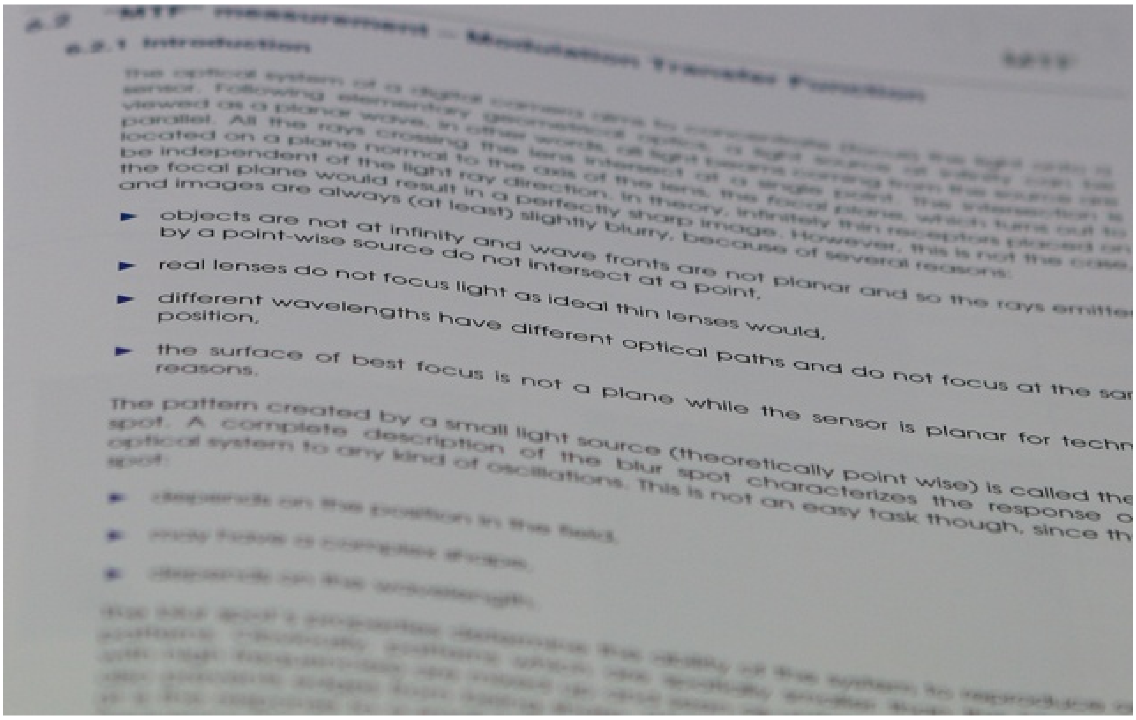


Image of a book taken with a 70 mm lens at aperture 3.2. Objects at different shooting distances (book lines) appear in the same image. Only center lines are sharp

Optical systems with adjustable focus can be theoretically sharp from a short distance near the lens to infinity. But this range of focus is narrower in the case of fixed focus optical systems like the ones in camera phones.

To compensate this reduced range of focus, manufacturers have developed solutions extending the depth of field beyond the capabilities of the optical system. Such systems are called EDOF (for extended depth of field).

The aim of this protocol of measurement is to determine the real range of focus of these cameras.

34.2 Definitions

34.2.1 Sharpness

The Perceptual Blur measurement (Section 6) is used to describe the sharpness. An image is said to be “acceptably sharp” if its BxU value is lower than 2. Only the value in the center of the image for the luminance channel is used.

It is also possible to use a result of the MTF measurement to compute sharpness: the value of MTF50%.

34.2.2 Details

Details preservation is given by the MTF measurement (see MTF, Section 7). Interesting values are

- The limiting resolution (MTF 10%)
- The blur (MTF 50%)
- The MTF values at Nyquist/2 and Nyquist/16

34.2.3 Dots Charts

To obtain a good measurement of perceptual blur at each distance, it is important to choose the chart that suits best the selected distance.

The following table shows the distances of use of each Dots chart for a camera phone with a diagonal field of view of 70°. You will need to adapt these values for a different field of view.

dots chart	Shooting distance
D0001	1.10 m < d < 1.70 m
D0002	55 cm < d < 110 cm
D0003	35 cm < d < 55 cm
D0004	15 cm < d < 35 cm
D0005	D < 15 cm

Note that this table aims to provide an example of which chart to use for a selected distance. It is more important to respect the shooting conditions of the Perceptual Blur measurement than to follow this table.

Furthermore, it is possible to use charts to make Blur measurements at more than 1.7 m. Although the shooting conditions will not be observed, the resulting values obtained in the center of the image will still be usable.

34.2.4 SFR Charts

The following table gives the distance of use of each SFR Chart for a camera phone with a diagonal field of view of 63°. Again, these distances will need to be adapted to the camera being tested.

SFR chart	Shooting distance
S0001	1.22 m < *d* < 1.94 m
S0002	71 cm < *d* < 122 cm
S0003	41 cm < *d* < 70 cm

34.3 Influencing factors

Factors influencing the range of focus are:

- The focal length of the lens,
- The aperture

34.4 Measurement of the range of focus

Measuring perceptual blur or MTF is done at different distances to obtain information about sharpness or detail at each shooting distance.

The Analyzer BxU measurement protocol can be used to measure the ROF at differing shooting distances. It is possible to adapt it for the MTF measurement. Sharpness is then given by MTF 50%, and limiting resolution and MTF@Nyquist/2 give information about detail preservation.

Shooting distances are given for camera phones with a diagonal depth of field of around 65° and an f-number around 4. You may need to adapt these distances if you want to make this measurement for a different kind of camera or an optical system such as a DSLR lens. Measuring the range of focus must be done as follows:

34.4.1 Take four shots: one at each of 20 cm, 40 cm, 60 cm and at 3 m.

Respect the shooting conditions for a Perceptual Blur measurement (or MTF):

- Verify the orthofrontality with the mirror manipulation (see Section 5.2)
- Lighting must be uniform at 15%

For each shooting distance, you must measure the length between the camera and the chart with a laser telemeter.

Three meters is the maximum distance obtainable using the charts with camera phones, because these cameras have a wide field of view. At 3 m, the chart will be visible in the center of the image, but some elements outside the chart will also be visible. As only the values in the center of the image are important, you can ignore any warnings about bad composition of the shot.

Examine each shot in Analyzer, and correlate MTF or BxU values in the center of the image with the shooting distance.

34.4.2 Measuring sharpness at infinity

If the shot taken at 3 m is sharp, you can consider that the camera is sharp at infinity and skip this section.

If its BxU is higher than 2, the camera is not sharp at infinity and you will be able to determine the maximum distance of sharpness with the following method:

- Take a shot at 2 m, and measure its BxU value.
- If the image is sharp at 2 m, the maximum distance of sharpness will be between 2 m and 3 m. See below for an explanation of how to determine the maximum distance of sharpness.
- If the image is not sharp at 2 m, take another shot at 1 m. It should be sharp. If it is not, verify your camera's focusing, as there may be a problem.

Now the results for two distances are known:

- A distance d_0, at which the shot is sharp.
- A distance $d_1 > d_0$, at which the shot is not sharp.

The maximum distance of sharpness is therefore between d_0 and d_1. To find this distance, use this procedure:

1. Compute the mid-value between d_0 and d_1: $d_2 = \frac{d_0 + d_1}{2}$
2. Take a shot at distance d_2.
3. If the shot at d_2 is sharp, the limit of sharpness is between d_2 and d_1, repeat the first step using distances d_2 and d_1.

   If shot at d_2 is blurry, the limit is between d_0 and d_2, repeat the first point step with distances d_0 and d_2

Continue with this method until you reach the precision you want, or until you reach the precision of the Blur measurement, which is 5%, so if the difference of blur value at a distance d_X and a distance d_Y is lower than 5%, there is no need to continue.

34.4.3 Measuring sharpness at close distances

Use the following procedure to find the minimum distance of sharpness:

- If shot is sharp at 20 cm, take a shot at 10 cm, and then 5 cm if shot is sharp at 10 cm
- With the two distance d'_0 (shot is blurry), and $d'_1 > d'_0$ (shot is sharp), determine the distance $d'_2 = \frac{d'_0 + d'_1}{2}$ of the next shot
- Continue until you reach the desired precision or the precision of the measurement

34.4.4 Summary curves

You can draw one or more curves showing the measurement values and their corresponding distances.

34.5 Measurement in raw format

Measurement in raw format gives results only for the optical system's range of focus. Software extension of depth of field does not appear, and for camera-phones, the range of focus may be much shallower in raw than in RGB.

This means that the measurement in raw format can be used to estimate the gain in range of focus obtained with the "extended depth of field" plug-in.

34.6 Examples

Here are three examples of this measurement. One is for a camera phone with a standard fixed focus; one is for with an auto-focus, and one is with fixed focus but with an "extended depth of field" plug-in.

34.6.1 Fixed focus camera phone (Nokia N70)

We measured BxU at four distances using Dots charts. The values of BxU are the values in the center of the image for the luminance channel.

Distance	20 cm	40 cm	60 cm	3 m
Chart	D0004_60	D0003_60	D0002_120	D0001_200
BxU	17.52	3.4	1.82	1.4

This camera is sharp at 3 m and 60 cm, but not at 20 cm and 40 cm.

We took another shot at 50 cm of a D0002_120 Dots chart; the BxU value was 2.52 (blurry). As it was blurry, we took another measurement at 55 cm on a D0002_120 Dots chart, obtaining a BxU value of 2.05. A value of BxU of 2.05 is higher than 2.0, but it remains within the precision range of the measurement (i.e., 5%), so we can consider that we have found the first distance for sharpness (55 cm).

We can then consider that this camera phone is sharp from 55 cm (±2.5 cm) to infinity.

34.6.2 Auto-focus camera phone (Nokia N90)

Measurement of BxU is done for four distances with the Dots Charts as follows:

Distance	20 cm	40 cm	60 cm	3 m
Chart	D0004_60	D0003_60	D0002_120	D0002_120
BxU	1.18	1.12	1.49	1.63

This camera is sharp at all selected distances.

We took another shot at 10 cm of a D0005_42 Dots chart, with a BxU value of 1.33 (sharp). We did another measurement at 6 cm, obtaining a BxU value of 6.82 (blurry). We ascertained that this camera phone is sharp from 8 cm (±2 cm) to infinity.

34.6.3 Fixed focus camera phone with EDOF

We measured BxU at four distances using Dots charts as follows:

Distance	20 cm	41 cm	60 cm	3 m
Chart	D0004_60	D0003_60	D0002_120	D0001_200
BxU	1.16	0.61	0.48	0.33

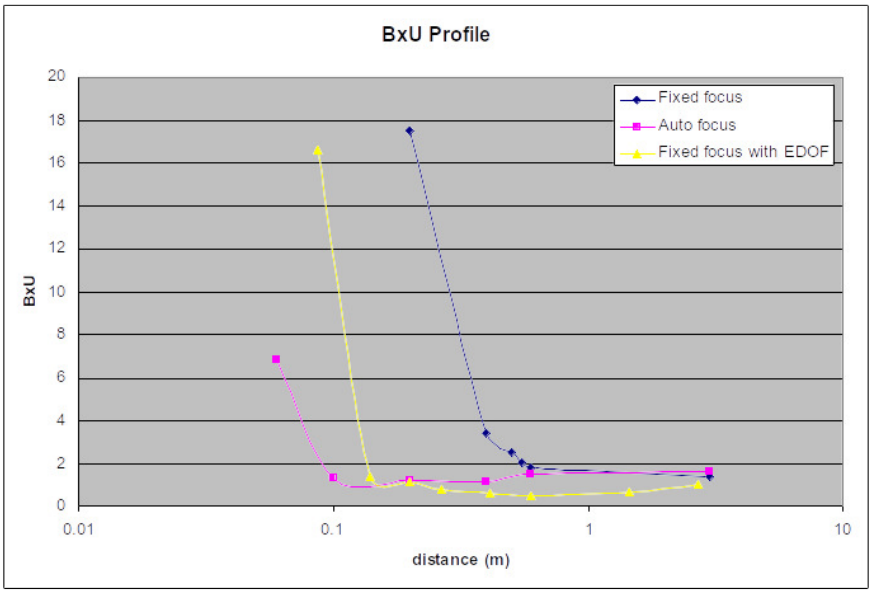
This camera is sharp at all selected distances.

We took another shot at 9 cm of a D0005_42 Dots chart, obtaining a BxU value of 16.59 (blurry). We took another shot at 14 cm of a D0005_42 Dots chart, obtaining a BxU value of 1.39.

We ascertained that this camera phone is sharp from 11.5 cm (2.5 cm) to infinity.

34.6.4 Summary curves of the BxU profiles

The values of BxU against distance for these three camera phones can be graphed and further analyzed:



Curves of BxU against distance for three camera phones

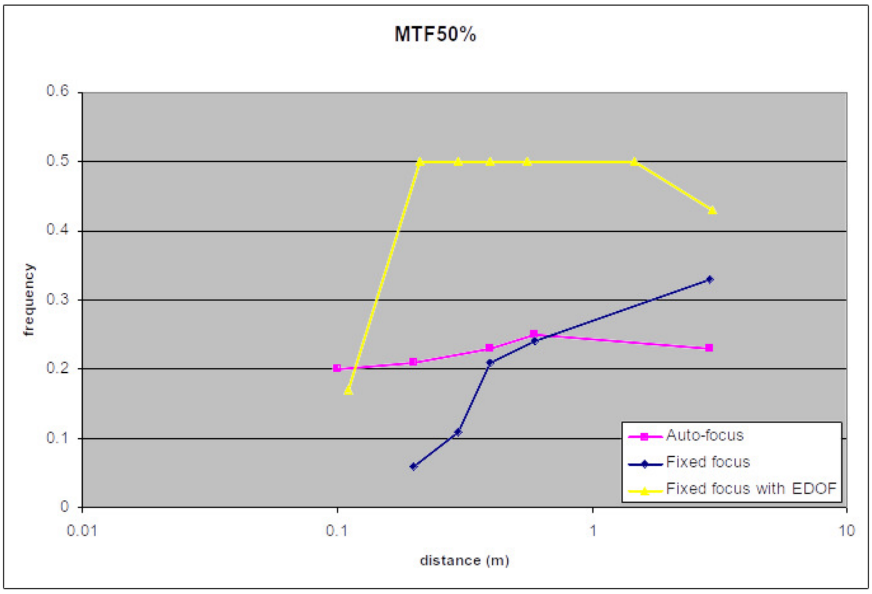
34.6.5 Measuring the MTF

Measuring the MTF at different distances is also possible. We measured the frequency at MTF 50% in the image center for the green channel, at several distances for the three camera phones, as follows:

camera / distance	20 cm	40 cm	60 cm	3 m
Fixed focus (cycle/pixel)	0.06	0.21	0.24	0.33
Auto focus (cycle/pixel)	0.21	0.23	0.25	0.23
EDOF (cycle/pixel)	0.5	0.5	0.5	0.45

Note that a good frequency value would be a frequency higher that of Nyquist/2 (0.25) for an attenuation of 50%. The first two cameras do not respect this criterion, but the autofocus camera has a result close to Nyquist/2, which is roughly correct. However, we can look for the distance at which these frequencies become even worse.

As the frequency at 50% is very low at 20 cm for the fixed-focus camera phone, we took another shot at 30 cm. For the autofocus and EDOF camera phones, we took another shot at 10 cm. The resulting curves are as follow:



- For the auto focus camera phone, frequency at MTF50% is pretty similar at all distances from 10 cm to infinity.
- For the fixed focus camera phone, frequency at MTF50% is acceptable from 35 cm (±5 cm) to infinity
- For the EDOF camera phone, frequency at MTF50% is acceptable from 15 cm (±5 cm) to infinity. Images are also sharper for this camera than for the two others.

Note that for the fixed-focus camera, images are sharp from 55 cm to infinity, but MTF 50% is acceptable from 35 cm to infinity. The difference comes the selected limits, an absolute limit for BxU (BxU = 2), and a relative limit for MTF 50% (i.e., MTF 50% difference from its "acceptable" value). Furthermore, BxU and MTF 50% represent two different measures which are not strongly correlated.

34.7 Measurement accuracy

The accuracy of the Blur measurement is 5% (see Perceptual Blur Measurement, in Section 6.7). The accuracy of the laser telemeter alone is 0.5 cm. The accuracy of the MTF measurement depends on the studied frequency (see MTF, Section 7).

The accuracy of the Range Of Focus measurement will depend on the accuracy of the chosen sharpness measurement (BxU or MTF), and on the accuracy of the measurement of the distance from the chart. This accuracy may be slightly lower than the telemeter precision, for example, if the back of the telemeter is inaccurately placed in front of the camera.

Note also that with auto-focus cameras, the distance of focus chosen by the camera will be slightly different even with two shots at the same distance from the chart. So for auto-focus cameras, you may want to make several measurements at the same distance and select the median value.

34.8 Measurement scale

The table below characterizes the quality of the range of focus of a camera, depending on its minimum and maximum sharpness distance.

Sharpness	Qualitative level
From 10 cm to infinity	Excellent
From 30 cm to infinity	Good
From 60 cm to infinity or image not sharp at infinity	Bad

34.9 Setup parameters influencing the measurement

See Sections 6.9 (BxU measurement) and 7.9 (MTF measurement) for details about parameters influencing each of these measurements.

The two following parameters influence the Range Of Focus measurement:

- Focus distance
- For auto-focus lenses, , the range of focus will change depending on if the focus is set on “manual” or “auto.”
- For EDOF cameras, if EDOF is activated or not.

34.10 Validity of the measurement

See Sections 6.10 (BxU) and 7.10 (MTF) for the validity of the measurement of each of these measures.

If it is possible to activate auto-focus or EDOF for the selected camera, or to change the focus distance, an absolute value of range of focus is not relevant, and focus parameters must be associated with the measurement results and the influencing parameters of the selected measurement (MTF or BxU).

34.11 Comparing two cameras

There are restrictions on comparing the results of BxU or MTF measurements. For example, two cameras with different resolutions cannot be directly compared.

See Sections 6.11 (BxU) and 13.12 (MTF) to see how to compare results from these measurements.

The three cameras shown as example in Section 34.6 have the same resolution (1600×1200 pixels) and close to the same sensor size. Their BxU results can thus be compared.

- The fixed focus camera has the worst result, with a range of focus from 55 cm to infinity,
- The auto-focus camera has the best result, with a range of focus from 8 cm to infinity,
- The EDOF camera, even with its fixed focus lens, has a result comparable to the auto-focus with a range of focus from 11.5 cm to infinity,
- Within their ranges of focus, the EDOF camera is sharper than the two other cameras (BxU < 1) because of the application of a sharpen filter (see MTF results, section 34.6)

34.12 Shooting

See Sections 6.12 (BxU) and 13.13 (MTF) for the shooting conditions for these measurements.

For each shot, you must measure the distance between the chart and the camera with a laser telemeter.

35 – LL: Low Light

35.1 Introduction

A camera transforms photons into a digital signal. When the signal is encoded on 8 bits, processing usually tries to scale the signal so that an important part of the image has good exposition. However, cameras, and especially camera phones, are commonly used in low-light conditions, typically indoor scenes with an illumination of about 20 Lux or less. There are ways that cameras compensate for this lack of light:

- Adding light to the scene by using a flash, for instance. This is not always possible in every situation, and flash may not be desired because the color rendering and especially the white balance will not be the same; usually objects in the foreground will be too bright with respect to the rest of the photo. For camera modules, a flash increases the cost and also consumes space and power. Moreover, camera phone flashes, typically based on LED technologies, are not powerful enough to create lighting conditions comparable to daylight.
- Increasing the aperture of the lens to let more light pass through the lens. However, on camera phones, the aperture is usually fixed in the camera design. Commonly-used apertures are f/3.2, f/2.8. Increasing the aperture makes the depth of field smaller, and focusing may appear more difficult to do.
- Increasing the exposure time. The amount of light is directly proportional to the exposure time, but the exposure time is constrained by several factors. It must be long enough to shoot indoor scenes and this time has to be a precise multiple of the power supply period. Otherwise, flickering (also called banding) can appear. This constraint is usually not a problem, especially in low-light conditions. But the exposure time cannot be too long in general, of course, because camera phones are usually held by hand and the scene is not static — which can result in unacceptable motion blur, as far as image quality is concerned. Exposure times above 1/15 s are often considered too long to avoid motion blur.
- Amplifying the signal by an analog or digital gain. In both cases, a large gain always results in increased noise and a lower SNR (though not exactly the same gain for analog as for digital). Because of uneven spectral sensitivities, the noise is usually colored, which is visually very annoying. To limit increased noise, ISPs are sometimes tuned to desaturate colors when high-gain values are used.

Analyzer measurements quantify the low-light behavior of a camera module. The Low-Light measurement proposes a set of tests for diagnosing the compromises the camera manufacturer made in order to obtain images in low-light conditions. This measurement comprises the “Noise”, “Color sensitivity”, “Color fidelity” and “Vignetting” measurements.

35.2 Definitions

Analyzer can characterize the correct behavior of a system under different lighting conditions using a set of measurements. Each measurement describes an important aspect of image quality, as described below:

Target exposure: For simulated lighting, the camera must provide a good mean grey level for a typical scene lacking high contrast. We measure this with the Vignetting measurement on the Dots chart.

Noise Measurement (see Section 17.2)**:** Under low-light conditions, a camera applies more and more electronic gain. Although this noise evolution can be a linear function, it is not usually so. Indeed, post-processing, especially that using a noise filter, and JPEG compression can impact the results. The Noise measurement lets us study only the behavior of the whole system, delivering an interpolated SNR value for 50% of the dynamic, which we will use to measure low light.

Color sensitivity (see Section 30.2)**:** This describes the influence of noise on color and color fidelity. Color fidelity can be defined as the ability of a camera to accurately reproduce colors in relation to an objective reference.

Two colors differing by one standard deviation of noise can be considered as indistinguishable, so it is important to compute the number of distinguishable colors up to noise. This is the Color Sensitivity measurement.

Usually manufacturers make a choice to achieve a more saturated image, which often leads to a too-noisy image.

The Low-Light measurement uses Color Sensitivity RGB measurements.

35.3 Influencing factors

The principal three influencing factors are:

- Exposure time
- Gain (analogue or/and digital)
- Light condition

Secondary factors are:

- Exposure correction (influence noise)
- White balance, which influences noise and color, and is particularly dependent on the Illluminant (see below)
- Aperture
- Color Space
- Illuminant: Influences color processing, hence measurement results differ for different illuminants. Sensor are less sensitive to red, so usually illuminant A is more difficult to represent. Low-Light protocol advises using an A illuminant.
- Sharpen filter: influence on noise.
- Compression ratio: The higher the compression ratio, the higher the SNR, but the Image loses high frequencies.
- Brightness/Saturation/Constrast: Color processing influences results for color sensitivity, color fidelity, and noise. Under dark conditions, manufacturers usually aim for a less-saturated image to avoid noise. But a less-saturated image means a worse result for color fidelity.

35.4 Measuring low light

The Low-Light protocol ensures good-quality measurements for defining a camera's behavior under different lighting conditions. For each category, the system characterizes a condition called "lowest acceptable lighting".

35.4.1 Lighting conditions

Using different lighting conditions when characterizing a module enables you to define the minimum lighting source, which is the lowest illumination that can produce a good-quality result for each measurement of the Low-Light protocol.

To define this lowest illumination, you need to test the module using 5 illuminants with differing brightness levels, chosen to simulate five different lighting conditions, from the darkest (e.g., candlelight) to daylight.

For an object with a perfect reflectance of 100%, the illumination levels are:

- 1500 Lux (477 cd/m^2)

- 300 Lux (96 cd/m^2)
- 150 Lux (47.7 cd/m^2)
- 30 Lux (9.5 cd/m^2)
- 3 Lux (0.95 cd/m^2)

35.4.2 Shooting protocol

Follow these steps:

1. Set up the Dots chart.
2. Uniform Target lighting = 1500 Lux.
   a. The target lighting should be as uniform as possible
   b. Do not use any filters.
   c. Follow the protocol for measuring vignetting (see Section 15.13) using a Dots chart.
   d. Set up a X-Rite ColorChecker® classic.
   e. Follow the protocol for measuring color sensitivity (see Section 30.12).
3. Uniform Target lighting = 300 Lux.
   a. The target lighting should be as uniform as possible.
   b. Do not use any filters.
   c. Shoot the shoot for Vignetting measure.
   d. Shoot with density filter 0.3 (simulating 150 Lux).
   e. Shoot with density filter 1 (simulating 30 Lux).
   f. Shoot with density filter 2 (simulating 3 Lux).
   g. Shoot the same series using the X-Rite ColorChecker® classic.
4. Noise Target
   a. Install Noise Target
   b. Shoot with density filter 0.5 (1500 Lux)
   c. Shoot with density filter 1 (300 Lux)
   d. Shoot with density filter 1.5 (150 Lux)
   e. Shoot with density filter 2 (30 Lux)
   f. Shoot with density filter 3 (3 Lux)

35.4.3 Measurement scales

Vignetting measure (grey level at vignetting center):

Measure Result	Qualitative effect	Low-light Rank
Grey Level > 128 L > 3 Lux Exposure Time < 60 ms	Good exposure	Good
Grey Level > 128 L = 3 Lux Exposure Time < 300 ms	Good exposure	Good
Vignetting measure error, Exposure Time > 60 ms (L > 3 Lux) or > 300 ms (L = 3 Lux)	Bad exposure	Questionable

Noise (SNR) measurement scale:

SNR	Qualitative effect	Low-light Rank
x > 45 dB	Noise is scarcely noticeable	Very Good
34 dB < x < 45 dB	Noise is present but acceptable	Good
x < 34 dB	Image is very grainy	Questionable

Color sensitivity (CS) scale:

CS	Qualitative effect	Low-light Rank
CS > 22 Bits	Color distinguishable, Noise very Low	Very Good
18 Bits < CS < 22 Bits	Noise is present but color still distinguishable	Good
x < 18 dB	Noise is too high, Color not preserved from noise.	Questionable

Delta *a*, *b* scale:

$\Delta a, b$ mean	Qualitative effect	Low-light rank
$x < 8$	Chart colors are similar to theoretical colors	Very Good
$8 < x < 15$	Chart color are different from the theoretical colors, but it could be the camera manufacturer's choice	Good
$x > 15$	Colors are bad, or there may be a problem with exposure or white balance	Questionable

35.4.4 Methodology

To determine the lowest acceptable lighting, the Low-Light protocol applies a label to each measurement: "Very Good," "Good", or "Questionable."

The Low-Light measurement characterizes the lowest acceptable lighting as "Good" or "Very Good"; an acceptable rating is that for which 4 measurements ($\Delta a, b$, CS, SNR, and Vignetting) will have at least four "good" results. As soon as a measurement result is "Questionable," the lighting condition is rejected.

35.5 Measurement in raw format

The Low-Light measurement is not available in raw Format.

35.6 Examples

The following examples show the Analyzer results for the Lowlight capability of a camera phone called Module A.

35.6.1 Target exposure

Module A

Illumination	Grey Level Vignetting Center	Exposure Time	LowLight Label
1500	124	6.92	Good
300	127	51.81	Good
150	129	59.21	Good
30	129	59.21	Good
3	<120	220	Questionable

The Module A gives an acceptable result from 1500 Lux to 30 Lux. At 3 Lux, target exposure is not attained, even though exposure time is not too high. This certainly means that the manufacturer bounds the exposure time, so as to avoid motion blur. The lowest acceptable lighting is 30 Lux.

35.6.2 Noise

Module A

Illumination	SNR (Grey Level =128)	LowLight Label
1500	37.03	Good
300	32.63	Questionable
150	31.52	Questionable
30	30.61	Questionable
3	x	Questionable

Results are acceptable at 1500 Lux, not below, so the lowest acceptable lighting is 300 Lux for Noise Measurement.

35.6.3 Color Sensitivity:

Module A

Illumination	Color sensitivity	Color fidelity	CS label	CF label
1500	22.27	8.16	Very Good	Good
300	21.35	7.32	Very Good	Very Good
150	21.42	7.03	Good	Very Good
30	19.97	10.1	Good	Good
3	17.01	11.1	Questionable	Good

The lowest acceptable lighting is 30 Lux for the Color Sensitivity measurement.

In sum, the lowest lighting for the Module A is 300 Lux.

35.7 Measurement accuracy

For details of Noise measurement accuracy see Section 17.7.

For details of Color Sensitivity measurement accuracy see Section 30.8

35.8 Comparing two cameras

Using the Low-Light protocol to compare two cameras provides a lot of information about behavior, and about the manufacturers' calibration philosophy for the modules being compared.

Here are results from two different modules manufactured with the same sensor but with different optics: Module A and Module B.

35.8.1 Target exposure – Exposure Time

Module A

Illumination	Grey Level Vignetting Center	Exposure Time	LowLight Label
1500	124	6.92	Good
300	127	51.81	Good
150	129	59.21	Good
30	129	59.21	Good
3	<120	220	Questionable

Module B

Illumination	Grey Level Vignetting Center	Exposure Time	LowLight Label
1500	176	2.979	Good
300	183	20.96	Good
150	177	32.948	Good
30	182	65.914	Good
3	202	300	Good

For $L > 3$ Lux, Module A, stop Exposure Time at 1/15 s. Module B does not but is still close. The exposure target is better for the Module B.

For $L = 3$ Lux, Module B has good behavior.

35.8.2 Noise measure

Module A

Illumination	SNR (Grey Level =128)	LowLight Label
1500	37.03	Good
300	32.63	Questionable
150	31.52	Questionable
30	30.61	Questionable
	x	Questionable

Module B

Illumination	SNR (Grey Level =128)	LowLight Label
1500	45.04	Very Good
300	41.22	Good
150	39.52	Good
30	37.76	Good
3	36.74	Good

The lowest Lighting is 300 Lux, for Module A and 3 Lux for Module B. Module B is obviously better with the Noise measurement.

35.8.3 Color sensitivity

Module A

Illumination	Color sensitivity	Color fidelity	CS label	CF label
1500	22.27	8.16	Very Good	Good
300	21.35	7.32	Very Good	Very Good
150	21.42	7.03	Good	Very Good
30	19.97	10.1	Good	Good
3	17.01	11.1	Questionable	Good

Module B

Illumination	Color sensitivity	Color fidelity	CS label	CF label
1500	21.09	12.94	Good	Good
300	20.78	13.68	Good	Good
150	20.74	12.85	Good	Good
30	20.06	11.93	Good	Good
3	19.91	13.33	Good	Good

The lowest Lighting is 30 Lux, for Module A and 3 Lux for Module B.

Color fidelity is better for Module A. Comparing the results for the Noise and Color Sensitivity measurements shows the importance of color processing and noise processing.

The price to pay for a sensor's lack of selectivity can be either a loss of color fidelity or an amplification of noise. The manufacturer might set color fidelity lower than ideal for the sensor used, or instead use color processing that is less aggressive about noise.

For Module A, color fidelity is fairly close to an ideal result for a camera module, but the noise amplification is too high.

36 – CPIQ measurements

36.1 Introduction

Camera Phone Image Quality (CPIQ) is a set of standards for camera quality measurements initially developed by the International Imaging Industry Association (I3A), and taken over by IEEE (Institute of Electrical and Electronics Engineers) in 2012 (http://grouper.ieee.org/groups/1858/).

Analyzer measurements have been extended to be compliant with the recently released standards for:

- Color uniformity
- Geometric distortion
- Lateral chromatic aberration
- Texture Preservation
- Spatial frequency response

The metrics of these measurements are displayed in Analyzer measurement result tabs. They are displayed as objective scores, and as JND (Just Noticeable Difference) losses. The reference value for JND is 0 (no image quality loss), and the JND values are less than zero for all other cases. The subjective quality decreases as the JND score becomes more and more negative. (For a complete description of each CPIQ measurement, please refer to the related documents in the standard.)

In the Analyzer Color Vignetting measurement, the CPIQ measurement "Color Uniformity" is now displayed. (See "Camera phone Image Quality – Phase 2; Color Uniformity" for more information.)

In the Analyzer Distortion / Chromatic Aberration measurement, the CPIQ measurements "Lens Geometric Distortion" and "Lateral Chromatic Aberration" are now displayed. (See "Camera phone Image Quality – Phase 2; Lens Geometric Distortion (LGD)" and "Camera phone Image Quality – Phase 2; Lateral Chromatic Aberration" for more information.)

In the Analyzer Texture Preservation measurement, the CPIQ measurement "Texture Blur Metric" is now displayed. (See "Camera phone Image Quality – Phase 3; Texture Blur Metric" for more information.)

The CPIQ measurement "Spatial frequency response" has its own Analyzer measurement, the Radial MTF measurement. See Section 8 for more details.

36.2 Color uniformity output

Analyzer returns the color uniformity results in the “CPIQ CU” tab.

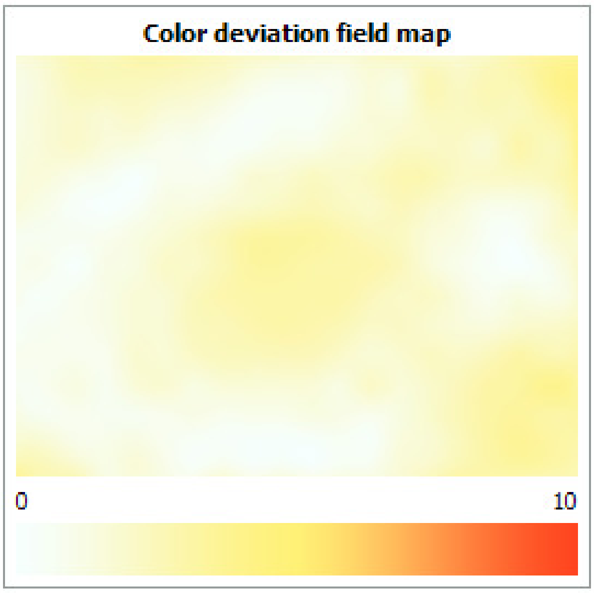
This tab contains two values:

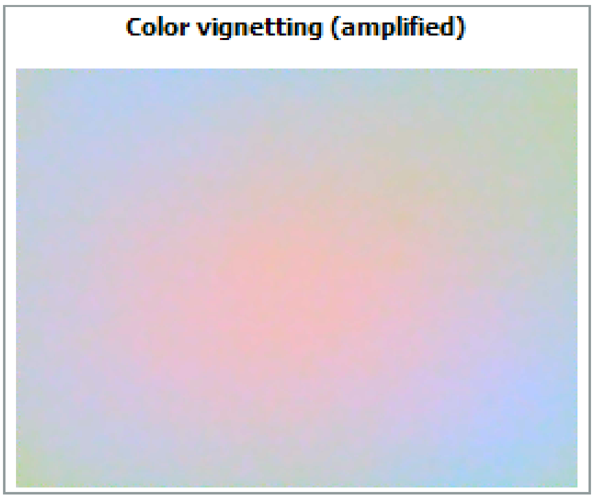
	CIELab Δab	Subjective Quality (JND)
Maximum deviation	4.17	-1.0

- The objective color variation score, computed as the maximum deviation of CIELab *Δab* in the field.
- The corresponding JND value. The formula to compute the JND is extracted from figure 5, graph 1, of the standard:

$$JND_{UC} = \min(0; 1.25 - 0.55 \times \text{deviation})$$

It also contains two maps:





- The first map displays the deviation of CIELab *Δab* in the field. The maximum value on this map is the objective score.
- The second map displays the color component of the input image: the image is converted in CIELab, the *L* is replaced by a constant in the image field, and the (a, b) component is amplified by a factor of four for better visibility.

36.3 Lens Geometric Distortion output

Analyzer returns the distortion results in the "CPIQ LGD" tab.

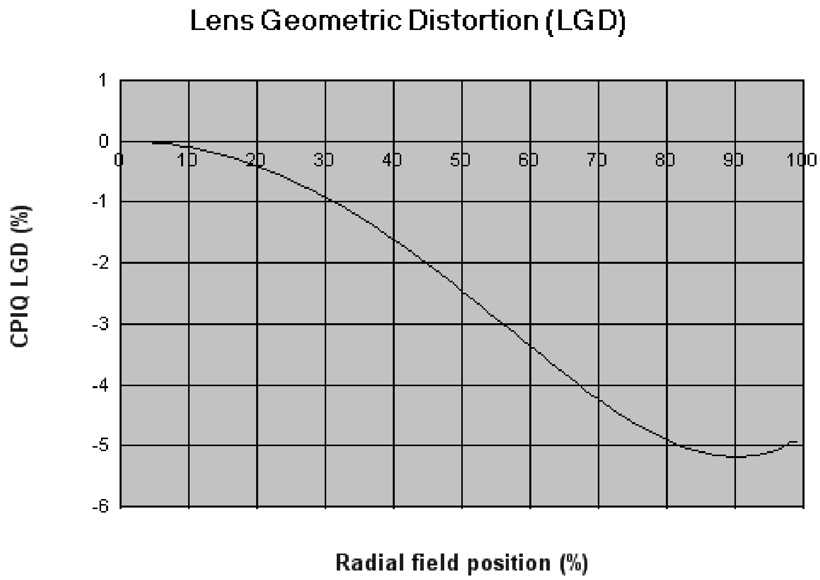
This tab contains two values:

	in %	Subjective Quality (JND)
Maximum LGD	-5.59 %	-1.2

- The maximum LGD in the field, as described in the standard.
- The corresponding JND value. The formula to compute JND is extracted from figure 16 of the standard:

$$JND_{DC} = \min(0; 0.0008 \times DC^3 + 0.0396 \times DC^2 - 0.024 \times DC)$$

It also contains a graph:



- This graph displays the profile of distortion in the field.

36.4 Chromatic aberration output

Analyzer returns the chromatic aberration results in the "CPIQ LCA" tab.

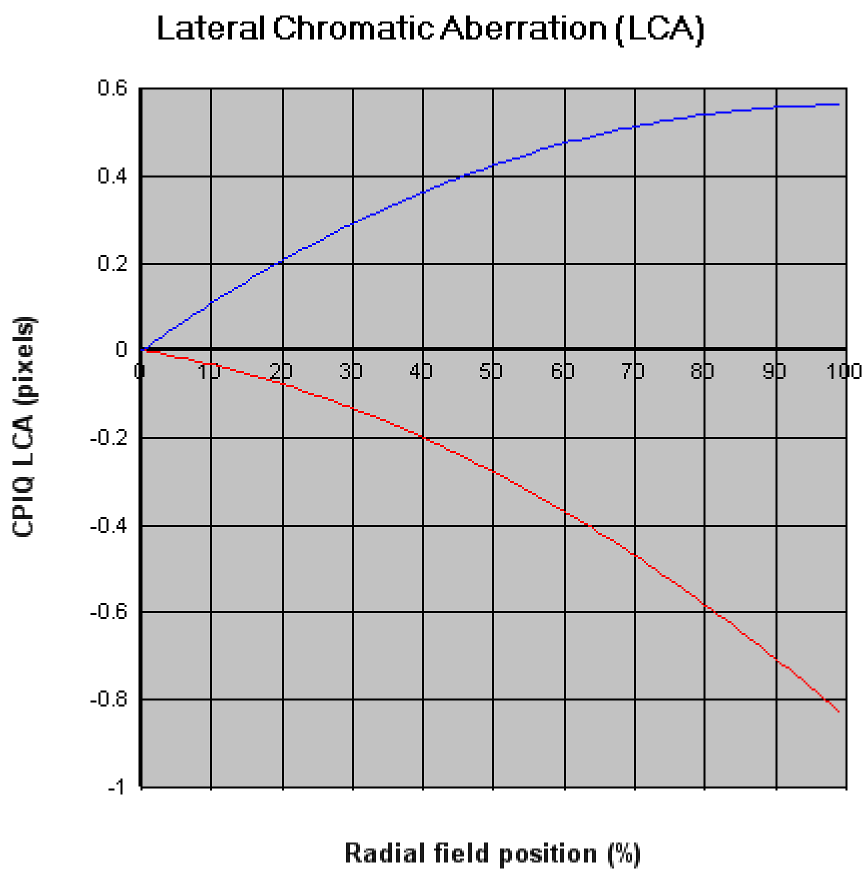
This tab contains three values:

	in %	pixels	Subjective Quality (JND)
Maximum LCA	-0.17 %	-0.8	-0.0

- The maximum LCA in the field as a percentage of the image's height, as described in the standard.
- The maximum LCA in the field in pixels, as described in the standard.
- The corresponding JND value. The formula to compute JND from LCA in pixels is extracted from figure 9 of the standard:

$$JND_{AC} = \min(0; 0.0001 \times LCA^3 - 0.0105 \times LCA^2 - 0.0267 \times LCA)$$

It also contains a graph:



- This graph displays the average profiles of LCA in the field for the red and blue channels.

36.5 Texture blur output

Analyzer returns the texture blur results in the “CPIQ Texture” tab.

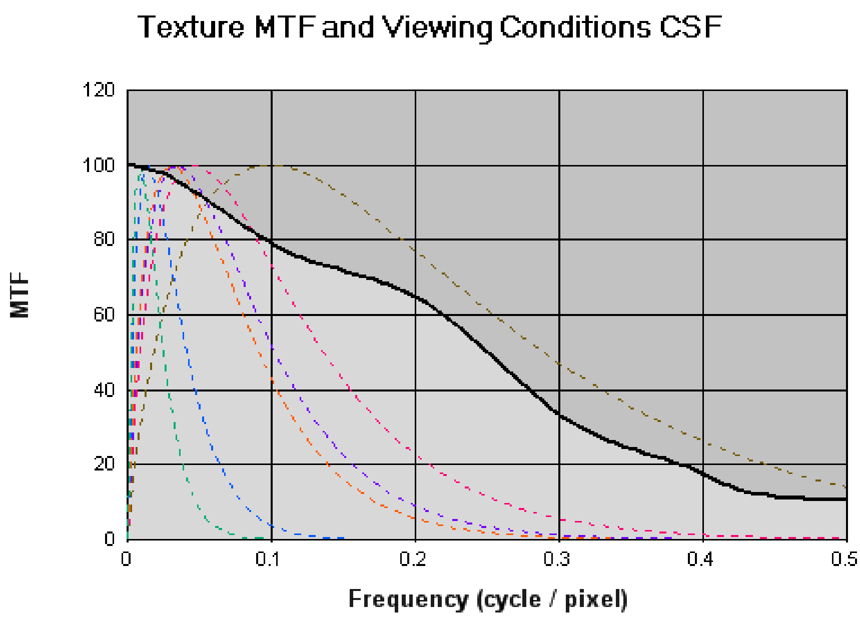
This tab contains two values for each viewing condition defined in the CPIQ standard:

Viewing condition	Acutance	Subjective Quality (JND)
Computer Display	0.593	-17.7
Professional Photo Print	0.718	-12.6
Consumer Photo Print	0.611	-16.9
HDTV Viewing	0.815	-8.6
Cell Phone	0.855	-6.9
Digital Photo Frame	0.946	-3.2

- The acutance, as described in the standard.
- The corresponding JND value. The formula to compute JND is extracted from figure 9 of the standard:

$$JND_{TEX} = \min(0; 21.5 \times \text{acutance} - 20.425)$$

It also contains a graph:



- This graph displays texture MTF (in boldface) obtained from the Dead Leaves patch on the chart, and the CSF curves (the different colored dotted lines) for each of the viewing conditions. For readability reasons, the MTF curves of the screens and printers are not displayed, although they are used for computing acutances.

37 – AZ Mate – DXOMARK chart

37.1 Introduction

The DXOMARK Chart (DMC001) is a still life chart, that can be used to evaluate several image quality attributes such as: Exposure, Texture, Noise, Color, Artifacts, etc.

Three measurements are available from the DMC001 chart: detail preservation, resolution, and target exposure.

37.2 Introduction on detail preservation

A typical way to evaluate the quality of a set of cameras consists of comparing shots of the same visual content in a controlled environment. The common visual content is usually referred to as a chart. The motivation for using the same chart when comparing different cameras is twofold.

First, it facilitates the direct comparison of different cameras. When it comes to subjective evaluation, humans can more easily provide pairwise preferences than an absolute quality score.

Second, when the common noise-free chart is known, this reference can be explicitly included in the quality measurement process. In this context, the modulation transfer function (MTF) is a widely used tool for evaluating the perceived sharpness and resolution, which are essential dimensions of texture quality.

First, MTF-based methods suffer from important drawbacks. MTF-based methods are originally designed for conventional optic systems that can be modeled as linear. Consequently, non-linear processing in the camera processing pipeline, such as multi-images fusion or deep learning-based image enhancement, may lead to inaccurate quality evaluation.

Second, these methods assume that the norm of the device transfer function is a reliable measure of texture quality. However, it has been shown that acutance itself does not always reflect very well the human quality judgment[8].

Hence, researchers at DXOMARK propose learning-based methods that aim at reproducing the score of human experts evaluating the images.

37.3 Influencing factors

Detail preservation and Resolution

Several parameters influence the measurement of detail preservation and resolution:

- The focal length of the lens
- The aperture
- The focus (an inaccurate autofocus will influence the accuracy of the measurement)
- The ISO setting
- For some lenses, the focusing distance may also impact the measure especially at short distances (in macro mode, for example)
- The shooting distance for some fixed focal length lenses
- Noise reduction settings

[8] Tworski et al. "DR2S: Deep Regression with Region Selection for Camera Quality Evaluation.", in International Conference on Pattern Recognition, 2020.

Exposure

Several parameters influence the measurement of exposure:

- The aperture
- The ISO setting
- The exposure time

37.4 Metric of detail preservation

The DMC001 chart contains many diverse objects with varying colors and textures. This chart is designed to represent texture patterns that can be found in natural scenes. The implemented metric treats the texture evaluation problem as a regression problem. This regression is performed through a deep convolutional network with the aim to return a score strongly correlating with a subjective quality judgment. This metric is computed in three selected textured areas: Portrait, Cloth and Banknote.

This estimation is a learning-based method. Let us note our training dataset composed of N color images

$(X_1, \dots, X_N)$ of dimensions $H \times W$ with the corresponding texture quality scores $(Y_1, \dots, Y_N) \in \mathbb{R}^{\mathbb{N}}$.

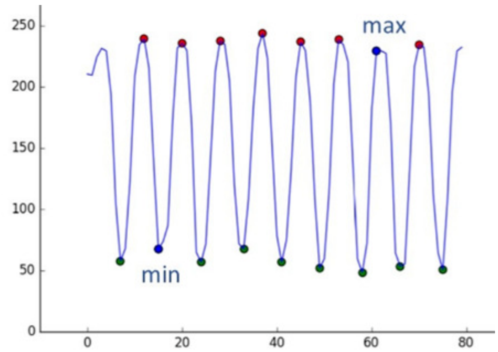
Each score $Y_k, k \in [1; N]$ corresponds to a quality score for one crop at a specific lighting condition, this ground-truth texture quality scores are provided by human annotators. The goal is to train a convolutional network $\varphi(\cdot, \theta)$, with parameters θ. The deep convolutional network can be split into a feature extractor and a regressor. Let $\psi \in \mathbb{R}^{H', W', C}$ be the feature tensor outputted by the backbone network for a given input image. The dimensions H' and W' depend on the input image dimensions, while the number of channels C is fixed. Let $A \in \mathbb{R}^C$ and $b \in \mathbb{R}$ be the trained parameters of the final regression layer obtained in the first stage. The network prediction for a given crop is given by: $\hat{y} = \sigma\left(A \cdot \left(\frac{1}{H' \times W'} \sum_{H', W'} \psi\right) + b\right)$, where σ denotes the sigmoid function. The measurement automatically extracts the regions of interest and gives a comprehensive metric for each crop, that allows to rank images according to their level of details.

37.5 Resolution measurement

The resolution describes the ability to distinguish a fine detail. The image resolution of a camera image depends on many factors: the size of the PSF of the optical system, the number of pixels of the sensor, etc. In addition, the use of color filter arrays (Bayer, RGBE) that require dematricing further degrades the image resolution. The resolution can be measured on the following DMC001 region.

The measurement automatically extracts the region of interest and detects the horizontal, diagonal and vertical rulers.

The measurement consists of extracting the profile along the rulers and studying the relative contrast:



The relative contrast is computed from the smallest value of the maxima and the largest value of the minima.

37.6 Target exposure measurement

The target exposure measurement consists of the L* average value of the following area in the DXOMARK chart.

The measurement automatically extracts the region of interest and computes the average L*.

37.7 Measurement in raw format

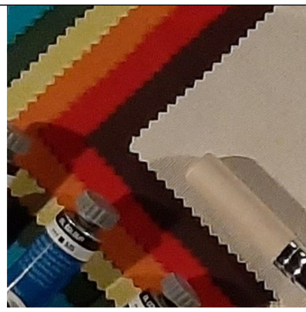
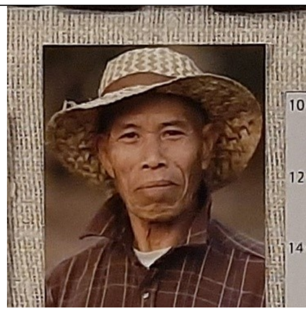
Measurements on DXOMARK Chart are not available in raw format.

37.8 Measurement scale

Detail preservation

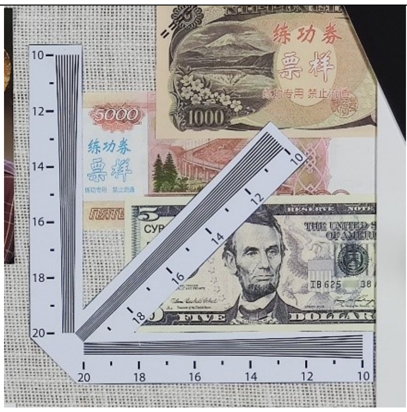
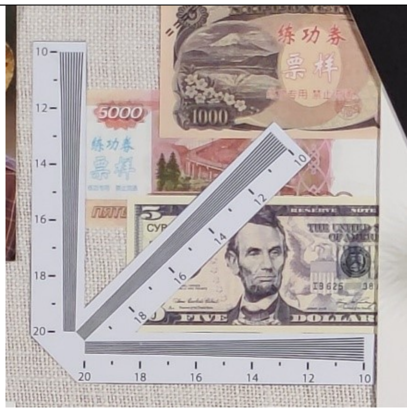
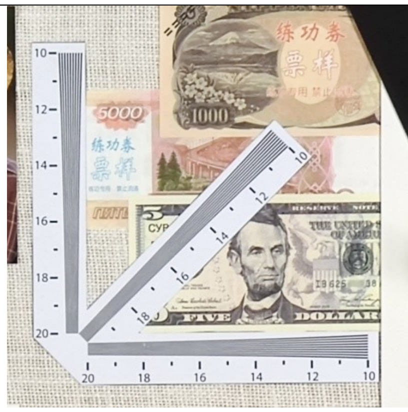
The detail preservation measurement returns a score between 1 low quality and 12.5 very high quality. Examples can be found below; higher score means better level of details.

			
10.38	8.95	6.78	3.22

			
9.23	7.9	6.47	4.15
			
11.66	10	7.52	4.22

Resolution

For each direction, the resolution measured is between 9 LP/mm (very low quality) and 20 LP/mm (high quality).

		
Horizontal 19.5 Diagonal 20 Vertical 19.5	Horizontal 15.5 Diagonal 14 Vertical 18	Horizontal 12 Diagonal 12.5 Vertical 12.5

Exposure

As the measurement is carried out in the CIELab 1976 color space, L* target exposure is between 0 and 100. Ideally, for the L* target exposure to be considered good it should be between: $43 \leq L^* \leq 59$.

			
$L^* = 35$ Visibly under-exposed	$L^* = 41$ Slightly under-exposed	$L^* = 52$ Good target exposure	$L^* = 61$ Slightly over-exposed

37.9 Measurement accuracy for detail preservation

The network was trained on 1260 images for each crop, each annotated with a texture score between 1 and 12.5. These images were acquired under the following conditions: 1 Lux H, 5 Lux A, 20 Lux A, 100 Lux A, 300 Lux TL84 and 1000 Lux D65. The camera used had sensor with resolutions between 5 and 47 mega pixels. The images have been annotated using a stack system by a panel of experts in image quality. The annotator was asked to correctly classify the images to be evaluated among a stack of references (i.e. images that already had a texture score).

Tested on 517 images for each crop, the results are as follows:

Pearson correlation	0.94
Spearman correlation	0.92

Pearson correlation $r_{y\hat{y}}$ is the linear correlation and is computed through:

$$r_{y\hat{y}} = \frac{\sum_{i=1}^{n}\left(y_i - \bar{y}\right)\left(\hat{y}_i - \bar{\hat{y}}\right)}{\sqrt{\sum_{i=1}^{n}\left(y_i - \bar{y}\right)^2}\sqrt{\sum_{i=1}^{n}\left(\hat{y}_i - \bar{\hat{y}}\right)^2}}$$

Spearman correlation is the rank correlation and is equivalent to the computation for the Pearson correlation with the rank.

The repeatability of the detail preservation measurement dependents on several parameters:

- If autofocus or exposure are not repeatable, results may have low repeatability even for consecutive images taken under the same shooting conditions.
- For long focal lengths (≥ 100 mm, small vibrations on setup may induce variations in measurement results. Locking the camera mirror can increase measurement precision.

Over consecutive shots, the detail preservation metric has variations of ±1 % and the exposure measurement has variations of ±0.3 %. The detail preservation inter-operator variations are lower than 1.5 %, while the inter-laboratory variations are lower than 5 %.

37.10 Shooting Procedure

The DMC001 chart must be framed full field. It contains markers that help to best fit the usual output formats (4:3, 3:2, 16:9).

Framing examples:

3:2

4:3

37.11 Sidecar parameters

If automatic detection fails, you can set a text file that provides the position of the markers. The text file shall follow several characteristics:

- the text file of an image named "image.jpg" is named "image.txt"
- the text file is located in the same folder as the corresponding image
- the coordinates of markers are provided in the following way:

```
X1;Y1 // coordinates of the bottom-left marker
X2;Y2 // coordinates of the top-left marker
X3;Y3 // coordinates of the top-right marker
X4;Y4 // coordinates of the bottom-right marker
```

37.12 Run measurements

Measurement on DMC001 are only available through Workflow Manager. “DmcMeasure” is a class that launches the measurements on DMC setup. To get the inline user manual, the Python command line is:

```
from dxomark.core.measure.dmcmeasure import DmcMeasure
help(DmcMeasure)
```

To call the measurements, the inputs must be initialized. The mandatory inputs are:

- ImgList [list<string>]: list of every image path on which to do the measurement
- SequenceName [string]: name of the sequence on which measurements are done (only use for crop folder tree creation)
- CropsFolderPath [string]: path to the folder in which crops are generated

The measurement returns a dictionary the first key is the image name then it follows this structure:

- “Crops”
  - “Banknote”: path to the “Banknote” crop
  - “Cloth”: path to the “Cloth” crop
  - “Portrait”: path to the “Portrait” crop
  - “Rulers”: path to the “Rulers” crop
- “Detail preservation”
  - “Banknote”: detail preservation metric on banknote crop
  - “Cloth”: detail preservation metric on cloth crop
  - “Portrait”: detail preservation metric on portrait crop
- “Exposure”: Exposure measurement
- “Resolution”
  - “Rulers”
    - “Diagonal”: diagonal resolution measured in LP/mm
    - “Horizontal”: horizontal resolution measured in LP/mm
    - “Vertical”: vertical resolution measured in LP/mm

37.13 Setup parameters influencing the measurement

Detail preservation and Resolution

Following set up parameters may change the results of the detail preservation or resolution measurements:

- Digital zoom function: you must normally deactivate this unless it is the subject of the test.
- Resolution: set this to the highest available value to obtain accurate measurements.
- Framing of the image in 4:3, 16:9, etc.: take the photograph with maximum use of the sensor, unless it is the subject of the measurement.
- Special camera settings such as noise reduction filter, saturation filter, contrast enhancer, and so on should be deactivated.
- Exposure quality: the image must be neither over- nor under-exposed

Exposure

Following set up parameters may change the results of the exposure measurement:

- Deactivate the exposure correction (EV must be set to zero)

38 – VIDEO-COLOR: Video Exposure Convergence and Color Stability

38.1 Introduction

Video capture is becoming more and more widespread. The technical advances of consumer devices have led to improved video quality and to a variety of new use cases presented by social media and artificial intelligence applications. While quality standards and measurement protocols exist for still images, there is still a need of measurement protocols for video quality. All still image quality metrics can be adapted to individual video frames to provide a first estimation of the video quality from static scenes. An exhaustive video quality measurement protocol must also include the temporal aspects of video quality.

Workflow Manager proposes two temporal metrics: **exposure convergence** and **color stability**. These allow to test different lighting conditions representative of real use-cases (indoor, outdoor, low-light). Also, the measurements are done in auto mode and in the final user perspective, thus the measurement protocol includes the whole video acquisition and encoding pipeline (optics, sensor, ISP, codec).

Lighting transitions are a challenging occurrence for video quality that happen when either the lighting in the scene or the framing changes. They can occur when filming a show where the light changes constantly, when walking from outdoor to indoor or from indoor to outdoor, when driving in or out of a tunnel, when panning, etc. In auto mode, devices need to adapt the exposure and the white-balance to the change of lighting and the resulting transition can be unpleasant to the viewer. This chapter presents metrics to evaluate the performance of auto-exposure and auto-white-balance on lighting transitions.

T = 0.22s	T = 1.2s	T = 1.7s

Example of light transition with a car passing through a tunnel. Video frames before, during and after the transition.

38.2 Definitions

38.2.1 Luminance Steps

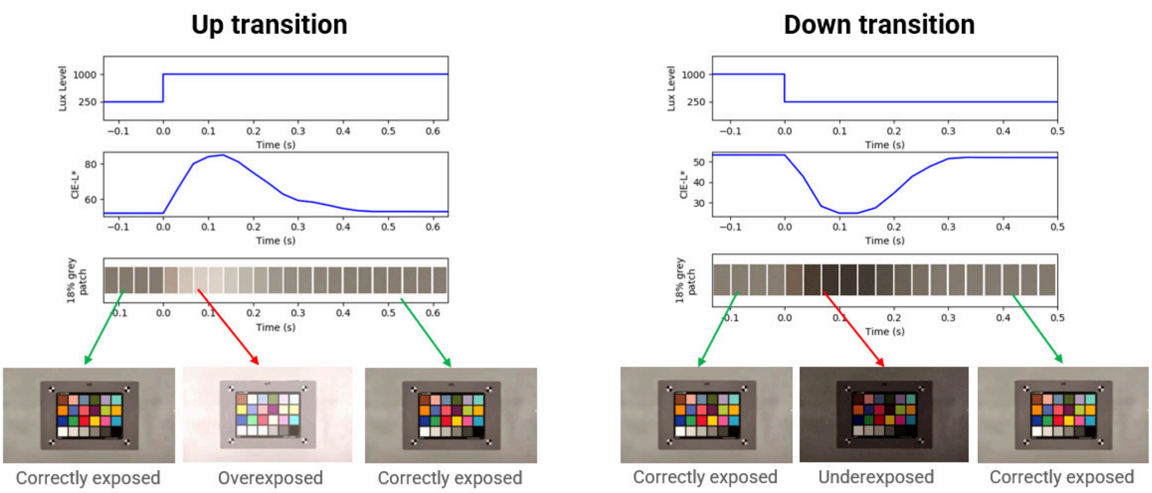
Luminance steps occur when the light changes abruptly in the scene, for example when filming a show in a dark room and the lights suddenly turns on. The device is presented with a very sudden change, and in auto-mode it has to respond to it.

There are two types of luminance steps:

Up transition from lower to brighter light (for example indoor to outdoor). The image is overexposed after the transition and the auto-exposure of the device has to adapt and converge to a new exposure.

Down transition from brighter to lower light (for example outdoor to indoor) The image is underexposed after the transition and the auto-exposure of the device has to adapt and converge to a new exposure.

When a device is submitted to a luminance step, the target exposure is changed: overexposed for up transitions, underexposed for down transitions. After a few frames, the exposure converges to a stable value again, ideally the same exposure value as before the luminance step.



Example of auto-exposure adaptation to up and down transitions

The following parameters allow to evaluate how fast, smoothly and accurately the exposure converges:

Convergence value The stable value the device converges to after the luminance step. The value is considered stable with respect to a threshold.

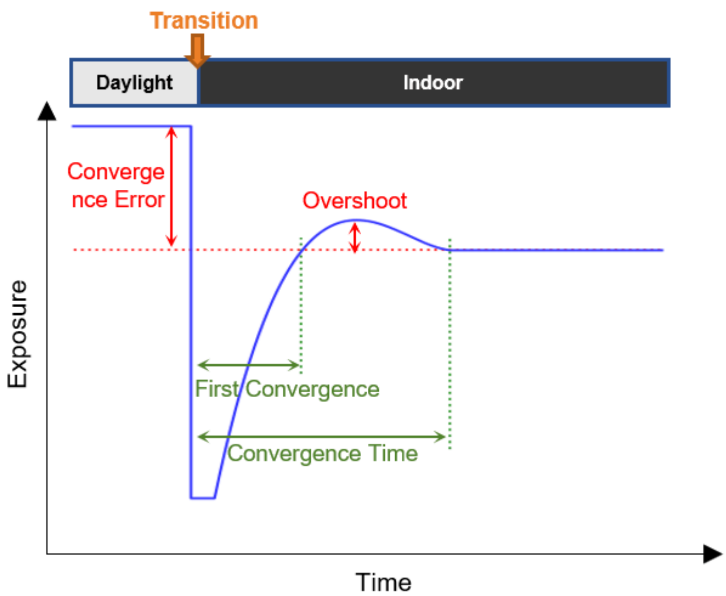
Convergence time The total time it takes to converge to the convergence value.

Convergence error The difference between the stable value before the transition and the stable value after the transition.

First convergence time The first time where the convergence value is reached.

Oscillation time The time it takes for the value to converge to a stable value after reaching the value at convergence for the first time.

Overshoot The maximum overshoot during oscillation.



Luminance step convergence: terms definition

38.2.2 Luminance and Color Temperature Ramps

Illuminant ramps occur when both the luminance and the color temperature vary over several seconds. These can occur when panning in a scene that contains several light sources, for example when walking in a room with both windows and artificial light sources. The difference with the luminance steps described in the previous section is that the changes between consecutive frames are relatively small. Some devices react smoothly and adapt to the transition, others adapt with a lag (which creates abrupt changes or oscillations later on), or do not adapt at all. The device adaptation can be evaluated with the following metrics:

Amplitude Amplitude variation of the luminance and color temperature during the transition.

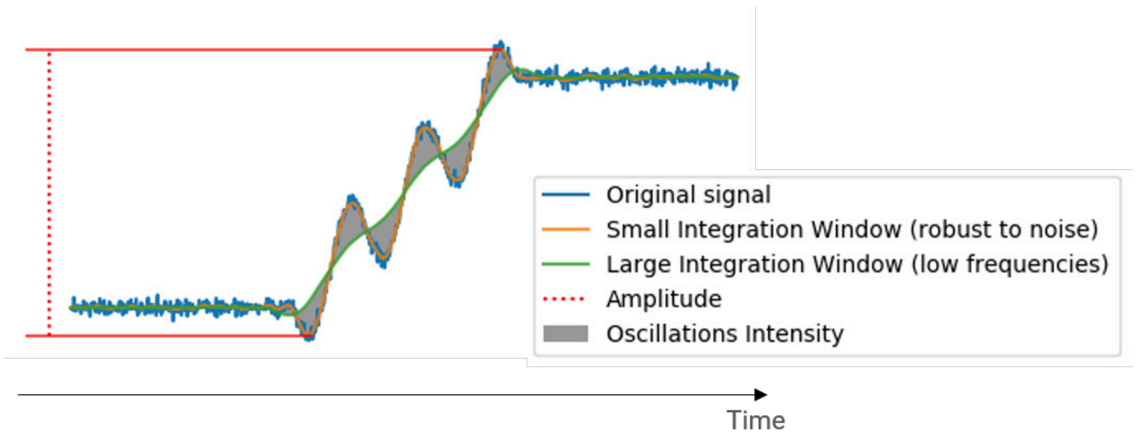
Oscillations intensity Robust estimator of signal variation over time. A constant signal has an oscillations intensity of 0; that intensity increases with the amount of oscillations in the signal. The oscillations intensity is the difference of moving averages on a large and a small integration window.

$$\frac{1}{T}\int_0^T \left|E_{T_S}[t,v] - E_{T_L}[t,v]\right| \,\mathrm{d}t,$$

where

$$E_T[t,v] = \frac{1}{T}\int_{t-T}^{t} v(\tau)\,\mathrm{d}\tau.$$

And v is the studied value, T is the duration of the video, and T_S and T_L are the small and large integration windows durations respectively.



38.3 Influencing factors

The Exposure and Color measurements are generally affected by several parameters of the device in video mode:

- the behavior of the Auto-Exposure (AE) and Auto-White Balance (AWB) algorithms, including:
  - exposure bias,
  - metering mode and/or exposure point in the field,
  - fixed custom settings (aperture, ISO, custom white balance,...),
  - tone mapping, color space, HDR and other enhancement algorithms;
- framerate or capture rate (e.g. fast- or slow-motion modes),
- choice of lens/filter, if applicable on the device under test,
- plus any other behavior of the Image Signal Processor (ISP) that affects exposure or color.

38.4 Measurement of exposure convergence and color stability

The measurements are performed using an X-rite ColorChecker Classic chart with a DXOMARK frame, reproduced in the figure below.

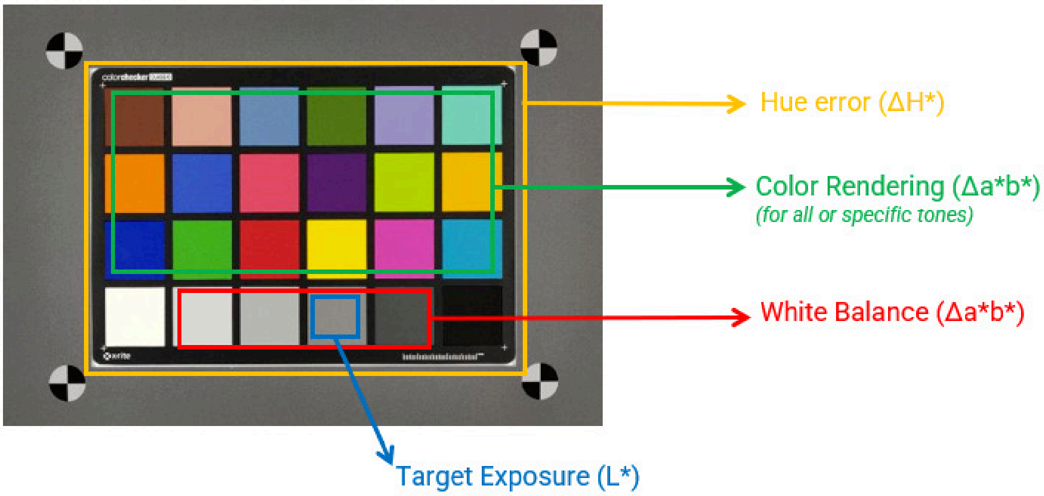
The metrics are computed in the CIELAB 1976 color space with the reference white point in D65. For each patch of the chart, the measurement computes the average L^*, Δa^*b^* and ΔH^* and aggregates them as follows:

Target exposure the L^* value on the 18 % grey patch,

White-balance average of the Δa^*b^* values on the 4 grey patches,

Hue error average of the ΔH^* values on the 18 colored patches,

Color rendering Δa^*b^* value on all or tone-specific (blue, green, skin tone, ...) colored patches.



X-rite ColorChecker Classic chart with DXOMARK frame

38.4.1 Exposure Convergence

The exposure convergence measure is performed on a video sequence that contains a luminance step. The measurement is performed as follows:

- Measure the target exposure (L^* value on the 18 % grey patch) on each frame of the video.
- Detect the transition with a threshold on the derivative value of L^*.
- Detect stable periods before and after the transition with a threshold on the standard deviation of the slope of L^* over a moving window.
- Compute the average L^* on the stable periods before (start luminance) and after (end luminance) the transition.
- Compute the convergence time as the duration between the start of the transition and the start of the stable period after the transition.
- Detect the first convergence and overshoot or oscillations with a thresholding on L^*. Compute the overshoot, first convergence time and oscillation time.

38.4.2 Color Stability

The color stability measure is performed on a video sequence that contains a luminance and color temperature ramps. The measurement is performed as follows:

- Measure the ΔH^* and Δa^*b^* on all patches on each frame of the video.
- Compute the White balance, Hue error and Color rendering as described above. Any of these values is called v in the rest of the paragraph.
- Compute the Amplitude variation as the difference between the 99th-percentile and the 1st-percentile of v.
- Compute the oscillation intensity:
  - Compute the moving average of v on a small integration window (0.5 second).
  - Compute the moving average of v on a large integration window (1.0 second).
  - Compute the oscillation intensity as explained in 38.2.2. The integration is done using the trapezoidal rule.

38.5 Measurement in raw format

As the exposure and color measurements are achieved after the raw conversion process, these measurements are not relevant for raw images, so it only makes sense for RGB images.

38.6 Workflow Manager output

The exposure convergence and color stability measurements are only available in the Workflow Manager python API and in the AZVideo measurement application. For more information about how to run the measurements with the Workflow Manager, please read the inline help of the function:

```
# import VideoExposureConvergenceMeasure
>>> from dxomark.core.videomeasure import VideoExposureConvergenceMeasure
>>> help(VideoExposureConvergenceMeasure)
# import VideoColorStabilityMeasure
>>> from dxomark.core.videomeasure import VideoColorStabilityMeasure
>>> help(VideoColorStabilityMeasure)
```

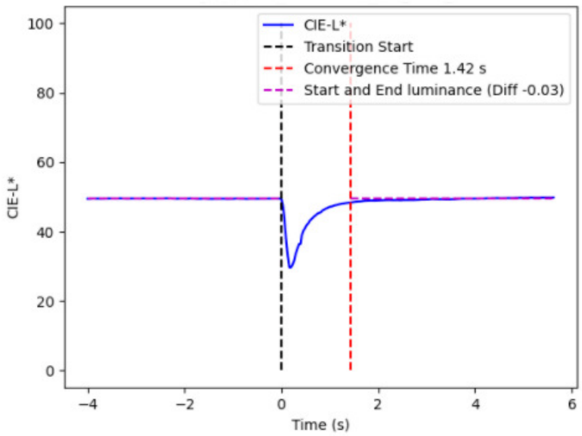
38.6.1 Exposure Convergence

Workflow Manager returns the following data:

- Start Transition Time: Timestamp in seconds of the exact moment the transition occurs.

- Convergence Time: Total time needed for the transition to converge, in seconds.
- First Convergence Time: Timestamp in seconds of the moment the transition gets to the convergence value for the first time.
- Oscillation Time: Duration in seconds of the oscillation.
- Luminance: For each frame, the value of the CIE-L^* value.
- Start Luminance: Initial value of the CIE-L^* value.
- Convergence Luminance: Final value of the CIE-L^* value.
- Luminance Difference: Difference between final and initial CIE-L^* value.
- Overshoot: Amplitude of the overshoot.

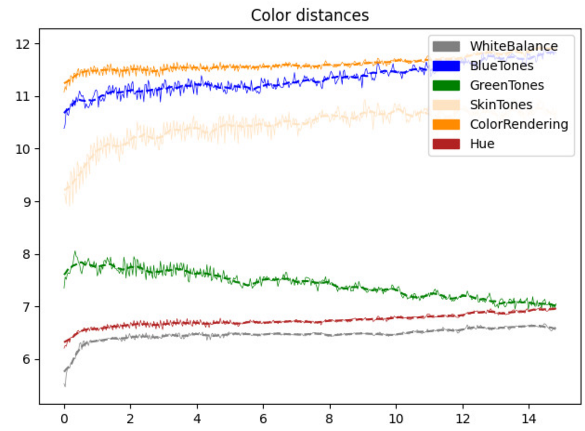
Here is an example of a graph generated from the Workflow Manager output data. This example is available in the demo-kit.



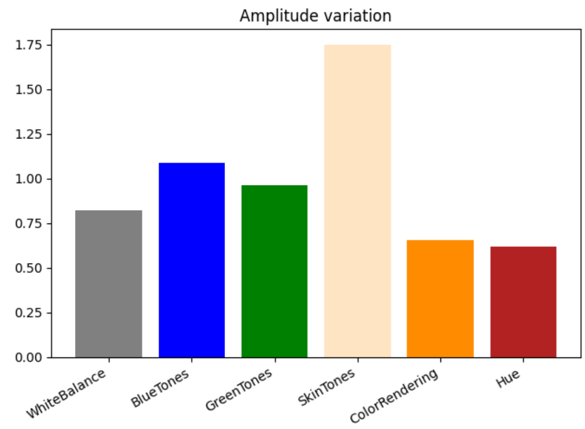
38.6.2 Color Stability

Workflow Manager returns the following data:

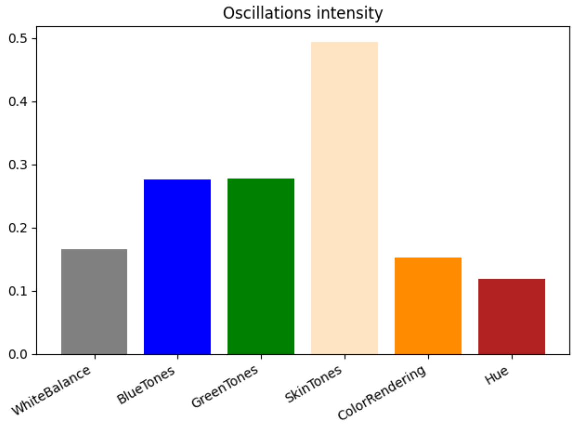
- Color distances graph illustrating averages of CIE-$\Delta a^* b^*$ or CIE-ΔH^*, for each group of patches over time.



- Amplitude variation histogram showing the total amplitude variation of CIE-Δa^*b^* or CIE-ΔH^* over the whole time range, for each group of patches.



- Oscillations Intensity histogram showing the intensity of the oscillations in (Δa^*b^*)/s or (ΔH^*)/s, for each group of patches.



38.7 Measurement accuracy

The per-frame measurement accuracy for CIE-Δa^*b^* and ΔH^* is described in the CF measurement (section 28).

Note that the measurement results are also often affected by device repeatability when AE/AWB behavior is not stable. The measurement accuracy of other aggregated metrics depends on the accuracy of the influencing setup and device parameters describe in the other sections

38.8 Measurement scale

38.8.1 Exposure Convergence

In the human eye, the reaction to a light transition is initially driven by an automatic contraction (in an "up" transition) or dilatation (in a "down" transition) of the pupil aperture, called the "Pupil Light Reflex", with a reaction time commonly ranging from approximately 200ms (start of reaction) to 1s (final convergence time)[9].

While other biophysical mechanisms then adapt the sensitivity of the eye to match the new conditions in larger timeframes (from a few minutes to a few hours depending on the stimulus), in general the visibility

[9] "Latency of the Pupil Light Reflex: Sample Rate, Stimulus Intensity, and Variation in Normal Subjects", *Investigative Ophthalmology & Visual Science* April 2003, Vol.44, 1546-1554.

and viewer impression on a transition depend on the initial response time, linked to the convergence time metric:

Convergence time	Viewer impression	Frames at 30fps
Under 200 ms	Transition is very quick and may feel invisible or unnatural in some conditions. It may also bring instability by changing too often.	< 6
500 ms	Transition is visible and quick.	15
1 second	Transition is visible.	30
Above 2 seconds	Transition is long and likely presents overshoot and oscillations.	> 60

The ideal exposure convergence time will depend on the application requirements:

- for computer vision, the transition needs to lose as little information as possible. The ideal transition is instantaneous, and information about the state of the camera (ISO, exposure time, aperture,...) can be used to recover information about the scene if necessary.
- for consumer videos, the transition needs to be smooth and pleasing to the viewer. The ideal transition mimics the behavior of an human eye and usually lasts for around 500ms[10], with longer durations corresponding to larger changes in light intensity, and no oscillations and overshoot. An instantaneous transition would not convey an accurate impression of the scene.

The oscillation time metric is strictly lower than the total convergence time and follows the same scale. In case of oscillations, the overshoot metric is a CIE-L^* difference:

[10] S. Oh, C. Passmore, B. Gold, T. Skilling, S. Pieper, T. Kim, and M. Belska. A framework for auto-exposure subjective comparison. Electronic Imaging, 2017(12):202–208, 2017.

CIE-ΔL^*	Impression
< 1	Difference is not visible.
< 2.3	Difference is not visible for saturated colors but might be visible in neutral greys.
> 10	Difference is very visible.

38.8.2 Color Stability

The main indicator of Color Stability during a lighting ramp is the oscillation intensity described above. It has the same unit as the metric it is based on, for example for White Balance and Color Rendering oscillation intensities:

WB/CR oscillation intensity (CIE-$\Delta a^* b^*$)	Impression
< 1	Oscillations are not visible.
< 2.3	Oscillations slightly visible under some conditions.
< 5	Oscillations are visible.
> 5	Strong oscillations.

Similarly, amplitude metrics follow the same scales as the metrics explained for the CF measure (section 28).

38.9 Setup parameters influencing the measurement

The following setup parameters may change the results of the measurements or cause the device to react differently to the measurement conditions:

- Illuminant type (spectrum/color temperature, stability).
- Intensity, amplitude and speed of illuminant transitions.
- Presence of dust on either the lens or the sensor.
- Lighting uniformity on the test chart.
- Position of the test chart in relation to the camera/photographer's optical axis (orthofrontality).
- Size of the test target in the image (shooting distance).
- Background around the chart (grey frame, and any other visible lab structures around it).

38.10 Measurement validity

Exposure Convergence and Color Stability measurements results are meaningful only if the influencing information are specified at the same time.

At minimum, the illuminant transition type must be specified; for example, it is not meaningful to say that the White Balance Oscillation Intensity is 1.5, but it is meaningful to say that during an illuminant transition from D65 (with a color temperature of 6500K) at 1000 lux to 10 lux, the observed oscillations intensity for a given device was 1.5.

38.10.1 Exposure Convergence

The video sequence should starts at most 20 seconds before the transition and should end at least 5 seconds after transitions.

Ideally, at least 5 seconds before the transition and 20 seconds after the transition allow the measurement to be relevant and accurate.

Moreover, the measurement is not valid if the exposure converges to a value of CIE-L^* lower than 25.

38.10.2 Color Stability

In order for the color stability measure to work correctly, the measurement period should start at the beginning of the ramp and finish 5 seconds after the end of the ramp.

The measurement also depends on the overall exposure of the video sequence that can neither be highly underexposed or overexposed.

38.11 Comparing two cameras

You can compare measurements if lighting conditions and chart positions are similar, in order to have the same illuminant uniformity on the chart. And ideally, the framing of the chart must be identical.

38.12 Shooting

a) Install the appropriate X-Rite ColorChecker® classic (see Section 4.12). We strongly recommend using the frame with markers that facilitate automatic detection.

b) Decide on the important parameters, if applicable:

   - A good value for the X-Rite ColorChecker® classic white patch (80 % of the dynamic in raw format, use of an unsaturated video in RGB format).
   - Resolution.
   - To avoid vignetting effects, the X-Rite ColorChecker® classic target should not fill more than 2/3 of the image field.

c) Special conditions for framing the photograph (see also Section 5). To correctly detect and measure the test target in the image, ensure that:

   - There is no dust on either the lens or the sensor.
   - The test target is correctly oriented, with the text at the bottom of the produced image.
   - The edges of the test target are parallel to the edges of the image.
   - The test target is correctly exposed and uniformly lit.
   - There are at least 64 × 64 pixels visible for each patch in the digital image.

d) Setup lighting scenarios:

   - For Color Stability, illuminant ramps should be as smooth as possible.
   - For Exposure Convergence, illuminant transitions must be sharp.
   - Ideally, use the Dynamic Lighting System (DLS), which has been designed for such scenarios. The Automatic Lighting System (ALS) is not suitable for sharp illuminant transitions, and only supports illuminant ramps for fluorescent tubes (D65, TL84, TL83).

39 – Wide-Angle Measurements

39.1 Introduction

The Wide-Angle Distortion Measurement is a new measurement available in Workflow Manager, with the aim of providing a comprehensive distortion measurement and modeling for a larger range of wide-angle cameras for field of views ranging from 80 to 170 degrees.

39.1.1 What is a wide-angle camera?

In traditional photography, wide-angle lenses are defined as having a larger field of view than normal lenses, and a smaller focal length for a given sensor size, as explained in detail for the EFL measurement.

Colloquially, the term wide-angle is however relatively loosely-defined. For example, the equivalent focal length of the main camera in most smartphones is between 24 mm and 30 mm, which while technically wide-angle is seldom advertised as such. Similarly, the "wide-angle" camera in high-end smartphones is closer to traditional ultra wide-angle lenses with a diagonal field of view larger than 80°.

The following chapter as well as the rest of this manual uses the conventions from traditional photography. In general, we can distinguish the following types of cameras:

Type of lens/camera	Typical characteristics		
	Field of view	Eq. focal length	Type of distortion
Telephoto	<50°	>50 mm	Pincushion
Normal	≈50°	≈50 mm	-
Wide-angle	≈50-80°	≈24-50 mm	-
Ultra wide-angle	>80°	<24 mm [1]	Barrel
Fish-eye	≈100-180°	<24 mm [1]	Barrel / Other [2]
Omni-directional	>180°	<24 mm [1]	Other [2]

[1] Focal lengths are typically measured in the center, but they provide little information about the actual field of view when in presence of significant distortion or non-perspective lens types.

[2] Omni-directional cameras and some fish-eye lenses are not modeled after the pinhole camera model and exhibit distortion types

Note that some camera devices artifically distort the output image in a controlled way depending on software configuration (e.g. simple distortion/perspective correction, crop/aspect setting on the device, anamorphosis correction in group portraits, etc).

Therefore, while the absolute focal length is an optical property of the lens, the field of view, equivalent focal length and distortion are properties of the entire camera device (lens, sensor and software processing).

39.1.2 Wide-angle and distortion

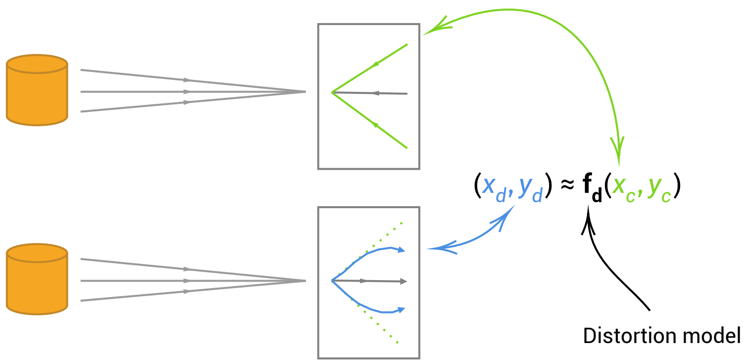
Distortion (see chapter on the DC measure) often manifests itself more strongly in wide-angle lenses, usually from the fact that it makes optical design more straightforward. The effect of distortion (curved lines) becomes therefore more visible as the field of view increases.

39.1.2.1 Modeling distortion

A very common model for an ideal perspective camera is the pinhole model, described in more details for the DC measure.

This being an ideal model, most cameras follow it approximately, and it is often useful to consider distortion as being a small difference in pixel coordinates of an object, between this ideal model and the real behavior of the camera.

An estimation of this difference is computed as the distortion model, a mathematical function transforming distorted coordinates to non-distorted ones.

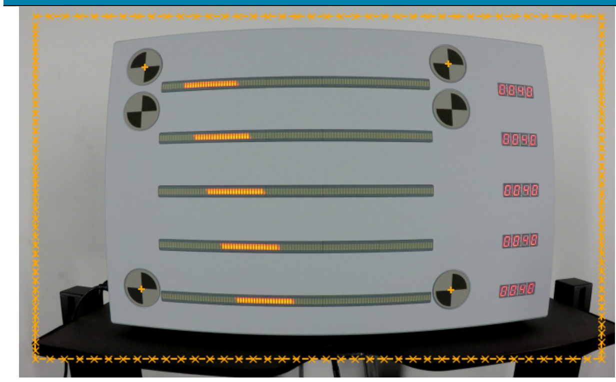


Simplified representation of light rays emitted from an object towards an ideal pinhole camera (top, in green) and a real camera with distortion (bottom, in blue)

different from traditional lenses.

39.1.2.2 Correcting distortion

Using this distortion model, one can do a mapping between ideal pixel coordinates without distortion and real coordinates on the sensor, with distortion. This is the basis for distortion correction.

Original image	Corrected image
	

When measuring metrics on a camera with a wide field of view exhibiting significant distortion, Analyzer and Workflow Manager measures require a distortion measurement in order to precisely position chart elements.

39.1.2.3 Accuracy of the distortion model

The model being an approximation of the real distortion, an indicator of model accuracy is the model error in the field for each pixel on the sensor, defined as the difference between the real distorted positions and the ones approximated by the model:

$$\epsilon(x_{d,px}, y_{d,px}) = \left\| f_{d,px}(x_{c,px}, y_{c,px}) - \begin{bmatrix} x_{d,px} \\ y_{d,px} \end{bmatrix} \right\|$$

While this is valid on the entire field of view, ϵ is estimated using the detected positions on the chart.

That per-pixel error is often aggregated in the Root Mean Square Error (RMSE) for N points:

$$\text{RMSE} = \frac{1}{N}\sum_{x,y}\epsilon(x,y)^2$$

Higher-level indicators of model quality are the Maximum Valid Radius and Maximum Valid Crop Factor.

39.1.2.4 Distortion model

The Wide-Angle Distortion Measure implements different distortion models.

39.1.2.4.1 The Brown-Conrady distortion model

The Wide-Angle Distortion Measure implements what is known as the Brown-Conrady[11] model, which is an extended version of the polynomial radial model considered in the EFL measure in Section 14.4 ("Measurement of 3D geometry").

The distortion function uses 5 parameters $(k_1, k_2, p_1, p_2, k_3)$, with (x_d, y_d) the normalized coordinates in the original distorted image, (x_c, y_c) the normalized coordinates in the corrected image, and $r^2 = x_c^2 + y_c^2$:

$$\begin{bmatrix} x_d \\ y_d \end{bmatrix} = f_d(x_c, y_c) = \begin{bmatrix} x_c\left(1 + k_1 r^2 + k_2 r^4 + k_3 r^6\right) + 2p_1 x_c y_c + p_2(r^2 + 2x_c^2) \\ y_c\left(1 + k_1 r^2 + k_2 r^4 + k_3 r^6\right) + 2p_1(r^2 + 2y_c^2) + p_2 x_c y_c \end{bmatrix}$$

The normalized coordinates are then converted to pixel coordinates using a projection matrix K, with (f_x, f_y) being the focal length, and (c_x, c_y) the position of the optical center, up to a constant λ:

$$\begin{bmatrix} x_{d,px} \\ y_{d,px} \\ 1 \end{bmatrix} = K \begin{bmatrix} x_d \\ y_d \\ 1 \end{bmatrix} = \lambda \begin{bmatrix} f_x & 0 & c_x \\ 0 & f_y & c_y \\ 0 & 0 & 1 \end{bmatrix} \times \begin{bmatrix} x_d \\ y_d \\ 1 \end{bmatrix}$$

Similarly, we have, with α a scaling factor applied when correcting distortion:

$$\begin{bmatrix} x_{c,px} \\ y_{c,px} \\ 1 \end{bmatrix} = K' \begin{bmatrix} x_c \\ y_c \\ 1 \end{bmatrix} = \alpha\lambda \begin{bmatrix} f_x & 0 & c_x \\ 0 & f_y & c_y \\ 0 & 0 & 1 \end{bmatrix} \times \begin{bmatrix} x_c \\ y_c \\ 1 \end{bmatrix}$$

[11] Brown, Duane C. (May 1966). "Decentering distortion of lenses". Photogrammetric Engineering. 32 (3): 444–462

The value of α is determined automatically so all pixels where the model is known and accurate are present in the corrected image.

The value of λ is not necessary to correct distortion, but can be determined by adding additional information on the size and position of the chart relative to the camera device. This lets the projection matrix be also usable for estimating camera pose (translation and rotation).

Real lenses usually have some distortion, mostly radial distortion, and slight tangential distortion. So, the above model can be extended to 12 parameters:

$$\begin{bmatrix} x_d \\ y_d \end{bmatrix} = f_d(x_c, y_c) = \begin{bmatrix} x_c \frac{1+k_1 r^2+k_2 r^4+k_3 r^6}{1+k_4 r^2+k_5 r^4+k_6 r^6} + 2p_1 x_c y_c + p_2(r^2 + 2x_c^2) + s_1 r^2 + s_2 r^4 \\ y_c \frac{1+k_1 r^2+k_2 r^4+k_3 r^6}{1+k_4 r^2+k_5 r^4+k_6 r^6} + 2p_1(r^2 + 2y_c^2) + p_2 x_c y_c + s_3 r^2 + s_4 r^4 \end{bmatrix}$$

The distortion parameters are the radial coefficients k_1, k_2, k_3, k_4, k_5, and k_6 , p_1 and p_2 are the tangential distortion coefficients, and s_1, s_2, s_3, and s_4, are the thin prism distortion coefficients.

39.1.2.4.2 Non Radial distortion model

The Brown-Conrady method supports well the distortion with mostly radial components. Some devices with non-radial distortion require a more complex distortion model.

Analyzer uses a degree-14 2D polynomial distortion model in the DC measure. This model is more complex to estimate but it supports well non-radial distortion.

39.1.2.5 Model Selection heuristics

Which model to use depends on the device and its geometrical characteristics. A "good" model needs to balance the following traits:

- Simplicity (less coefficients, easier to optimize)
- Lower point error
- As much of the field of view is valid as possible

It is better to select a simpler model if several models perform similarly. Indeed it is easier to compute, and it has less variability or edge cases when calibrating.

The Wide-Angle Distortion Measure uses the following heuristic to choose the best distortion model:

- Compute accuracy metrics for all models
- Among them, keep the models within 30% of the best maximum valid crop factor "distorted"
- Among them, keep the models within 30% of the best RMSE inside that maximum valid crop factor
- Among the remaining models, select the simplest model, in that order:

  OpenCV Distortion model with 5 coefficients, the simplest model.

  OpenCV12 Distortion model with 12 coefficients, more complex to optimize but necessary for some very wide angle devices.

  PolyXY Analyzer Polynomial distortion model. This is the most complex distortion model. It is only picked as a last option for non-radial devices that do not fit OpenCV models well.

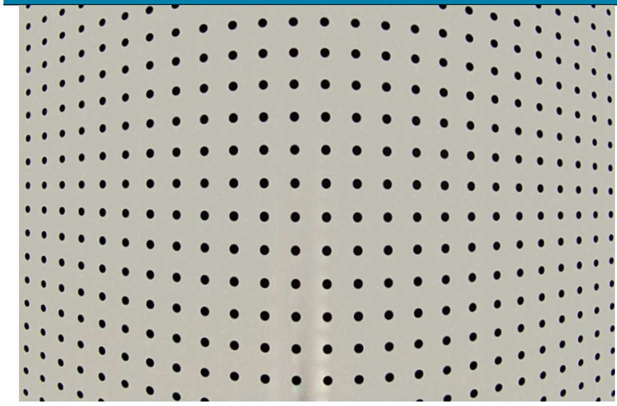
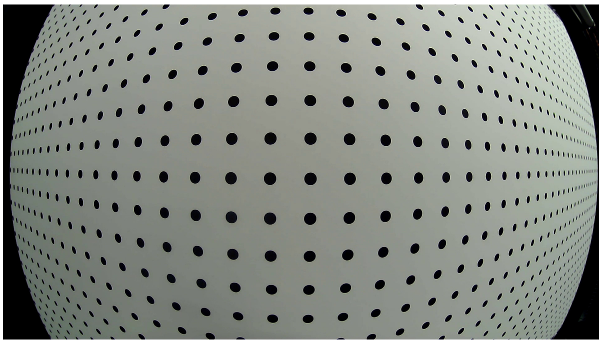
39.2 Performing distortion measurements on wide angle images/videos

39.2.1 Requirements

The traditional DC and EFL measures support all distortion types up to a maximum amount of distortion, usually reached with a field of view of approximately 110-120 degrees.

The wide-angle distortion measure introduced in this chapter keeps supporting the same devices, but adds support to an extended range of wide-angle camera devices, with the following limitations:

- up to **170 degree** diagonal field of view,
- at least **720p** (1280 x 720 pixels) resolution,
- all distortion types are supported, including devices with a strong **non-radial** distortion (non-perspective projection types e.g. cylindrical, anamorphic lenses,...) or non-rectilinear **circular fish-eye** lenses.

Non-radial distortion	Non-rectilinear circular fisheye
	

Examples of supported devices

39.2.2 Shooting

The Wide-Angle Distortion Measurement uses a Dots chart. For a successful measurement on wide-angle devices, it is recommended to:

a **Determine the influencing parameters**: The following parameters can influence the geometric properties of the device under test, and should be fixed and known as much as possible:

- aspect, crop ratio and resolution,
- focus distance (on autofocus lenses),
- focal length (on zoom lenses),
- video or photo mode (crop or aspect settings are often different between photo and video),
- stabilization mode (video stabilization often coincides with cropping or perspective corrections),
- as well as other settings that may influence the results: distortion correction, anamorphosis, etc.

b **Determine shooting conditions**:

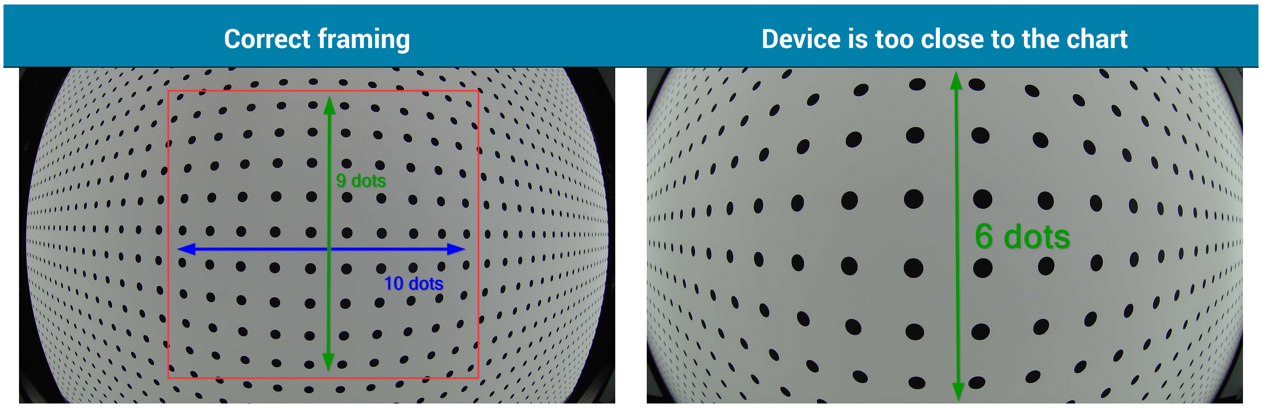
- The image should be correctly exposed, following the same conditions as the DC measure.
- In order to minimize noise, use the lowest ISO with appropriate lighting conditions.
- Strict uniformity of the light on the chart is not required, but the average intensity in the corners should be no more than 25% of the intensity at the center, including lens shading.

c **Frame the chart correctly**, so that:

- The image should contain at least 10 dots horizontally and 9 vertically.

- The dots should cover at least 50% of the horizontal field and 75% of the vertical field.
- If possible, frame the chart so it fills the image entirely. If not, the chart should fill the image as much as possible while still showing enough dots.
- If the chart does not fill the image entirely, the background outside of the chart should be as uniform and dark as possible, following recommendations in the Laboratory Setup chapter.
- The device should be as orthofrontal as possible to the chart.

d (Optionally) **Record the distance between the device and the chart**, for example using a distance meter, in order to compute field of view and focal length metrics.



39.2.3 Running the measurement

The Wide-Angle Distortion Measurement can be run using Workflow Manager, like this:

```
# Import the needed modules
from dxomark.core.measure import WideAngleDistortionMeasure

# Compute the distortion model from a Dots chart image
obj = WideAngleDistortionMeasure()
obj.Inputs({ "Img": r"C:\Path\To\DotsImage" })
obj.Process()
out = obj.Outputs()
```

If available, you can also provide the `DotSpacing` (distance between dots of the Dots chart, in mm) and `ChartDistance` (distance from the center of the device to the chart, in mm) in order to get additional outputs from the "Field of View" section below.

```
# Compute the distortion model from a Dots chart image
obj = WideAngleDistortionMeasure()
```

```
obj.Inputs({
    "Img": r"C:\Path\To\DotsImage",
    "DotSpacing": 26,
    "ChartDistance": 526,
})
obj.Process()
out = obj.Outputs()
```

When run on a video, the measure can be run on one of the frames, extracted as an image.

39.2.4 Workflow Manager outputs

The Wide-Angle Distortion Measurement returns the following outputs:

- distortion model coefficients and measurement accuracy metrics,
- distortion metrics (like the DC measure),
- focal length and field of view metrics (like the EFL measure),

The graphs in this section are provided as an indication of how to present the results from the Workflow Manager API, and their implementation can be found in the Wide-Angle Distortion Measure demokit distributed with Workflow Manager.

39.2.4.1 Distortion model

The computed distortion model is available in the `Model` key from the output dictionary. Under that key is a dictionary containing the model coefficients:

- `ModelType` contains the type of distortion model. The supported models are:
  - `OpenCV`: default OpenCV distortion model with 5 parameters
  - `OpenCV12`: more complex OpenCV distortion model with 12 parameters
  - `PolyXY`: complex non-radial polynomial distortion model
- `ImageSize` contains a list of $[w, h]$ corresponding to the width and height (in pixels) of the image used to generate the distortion model.
- For `OpenCV` and `OpenCV12` distortion models:
  - `ProjectionMatrix` contains the K 3x3 matrix,

- `DistortionCoefficients` contains a list of distortion coefficients:
  - $[k_1, k_2, p_1, p_2, k_3]$ for the 5 parameters distortion model
  - $[k_1, k_2, p_1, p_2, k_3, k_4, k_5, k_6, s_1, s_2, s_3, s_4]$ for the 12 parameters distortion model

- For the `PolyXY` distortion model:
  - Polynomials:
    - `DistortedToUndistortedPolynomials` contains keys `X` and `Y`, corresponding to polynomials describing the distorted to undistorted transformation.
    - `UndistortedToDistortedPolynomials` contains keys `X` and `Y`, corresponding to polynomials describing the undistorted to distorted transformation.

    Each polynomial is an array `c` so that `c[i, ...]` is the coefficients for the polynomial exponent `(i, ...)`. This array can be used by NumPy functions like `numpy.polyval2d`.
  - Homography matrices:
    - `Homography` contains the homography matrix between detected positions and orthofrontality.
    - `HomographyInverse` contains the homography matrix between orthofrontality and detected positions.

In addition to that, several accuracy metrics are available in the `ModelAccuracy` key.

The term crop factor refers to the width k of a rectangular area (crop rectangle) expressed as a ratio of the sensor width w, centered and having the same aspect ratio as the sensor.

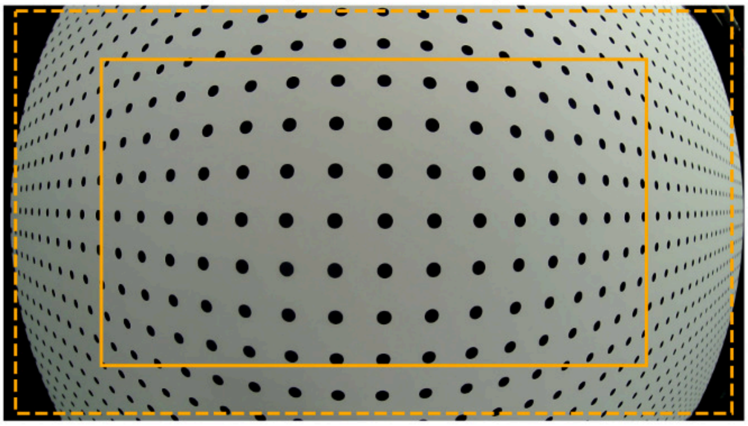
The term radius r of a pixel refers to the distance to the center of the image $O(x_O, y_O)$, expressed as a ratio of the diagonal of the image d.

The Maximum Valid Radius is the value r_{lim} such that the model error is below a limit $\epsilon(x, y) < \epsilon_{lim}$ for all pixels x, y whose radius is less than r_{lim}.

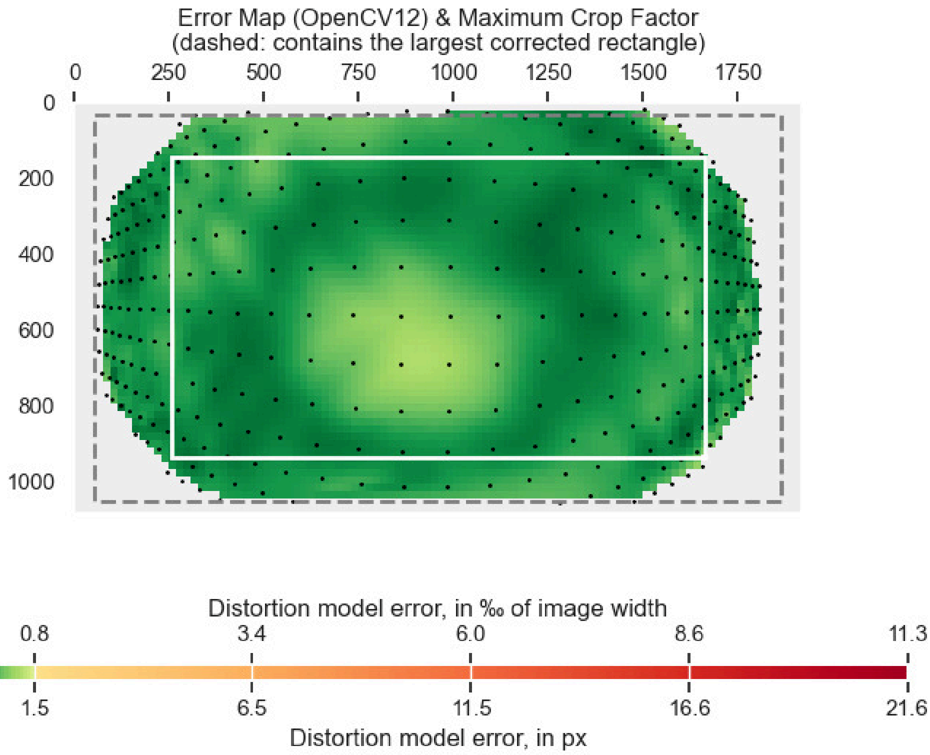
The Maximum Valid Crop Factor is the value k_{lim} such that the model error is below a limit $\epsilon(x, y) < \epsilon_{lim}$ for all pixels in the crop rectangle defined by k_{lim}.

The Error Map is a map of the distance between positions predicted by the model and real positions. It can be displayed in pixels or in permille of the image width.

See Measurement Accuracy for more details on the accuracy metrics.



The solid line represents the maximum crop factor. The dashed line represents the maximum crop factor such that all pixels from the corrected image come from within the maximum crop factor in the original image.



Error Map with scale bar both in pixels and in permille.

39.2.4.2 Distortion metrics

The same distortion metrics as the traditional DC measurement are available in the Wide-Angle Distortion Measurement, namely:

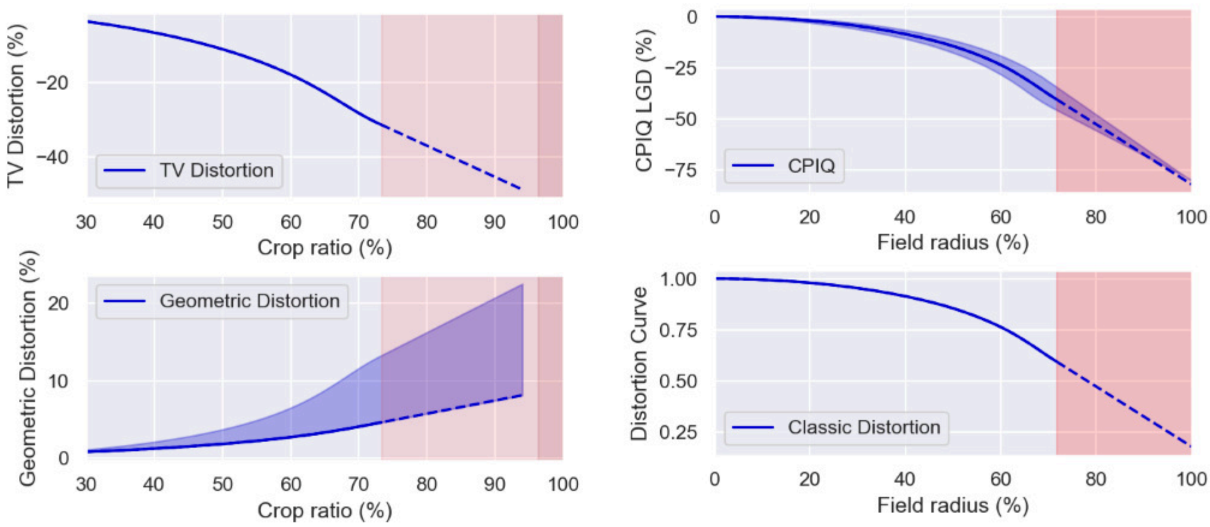
- TV Distortion
- Maximum/mean geometric distortion
- Maximum CPIQ LGD (in % and JND)

	Results
TV Distortion	-20.68 %
Geometric Distortion (Avg)	+5.26 %
Geometric Distortion (Max)	+18.55 %
CPIQ LGD (Max)	-47.78 %
CPIQ LGD (JND)	-15.17

Example of metrics in the Wide-Angle Distortion Measure

The measurement outputs also contains graphs of several metrics as function of either the radius or the crop factor.

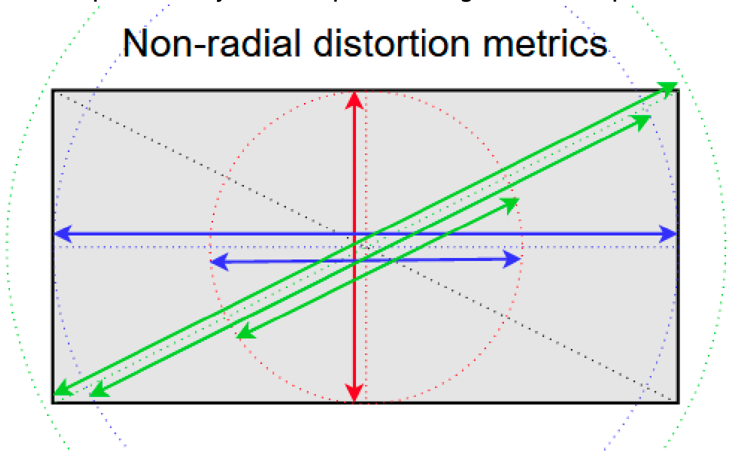
All distortion metrics are by default extrapolated to the image edges, so that the results can be compared between cameras as well as with other results from the DC measure.



Example of profiles present in the Wide-Angle Distortion Measure, with extrapolated regions outside of the Maximum Valid Radius/Crop Factor in red and extrapolated values as dashed lines. The shaded blue region corresponds to values between the average and maximum for each crop ratio or radius.

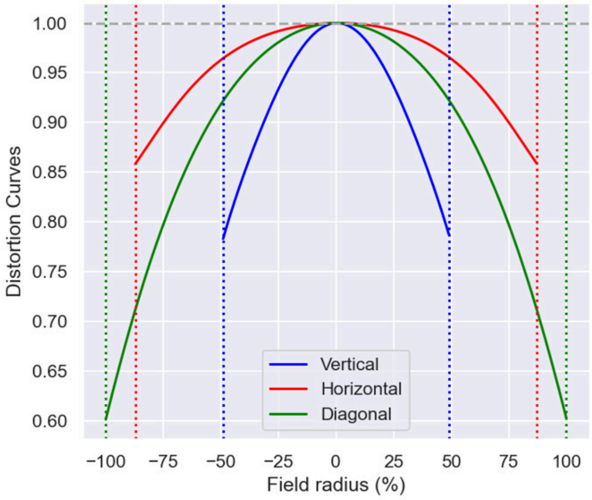
39.2.4.3 Non-radial distortion metrics

For devices with non-radial distortion it is interesting to look at the distortion profiles along each direction: vertical, horizontal and diagonal. The non-radial distortion profiles are computed the same way as the classic distortion curve, except that they are computed along the lines represented in the following figure:



Vertical, Horizontal and Diagonal lines used to compute the non-radial distortion metrics

The measurement outputs contains graphs of distortion profiles along the three directions. It also contains the maximum distortion value for the three directions, and the maximum distortion value for the three directions in the equivalent maximum field radius for each direction, for example the maximum horizontal distortion in the equivalent vertical field radius.



Example of non-radial distortion profiles present in the Wide-Angle Distortion Measure.

Field Radius	49%	87%	100%
Vertical Distortion Max	0.78	-	-
Horizontal Distortion Max	0.96	0.86	-
Diagonal Distortion Max	0.92	0.71	0.60

Example of non-radial distortion metrics

39.2.4.4 Field of view

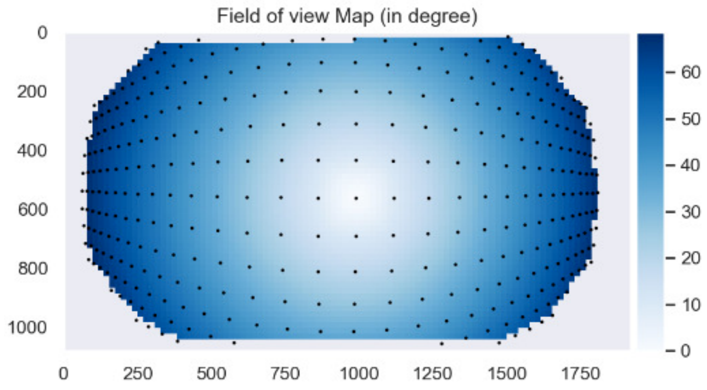
It is possible to compute the field of view of a wide angle camera in the three directions: vertically, horizontally and diagonally. The computation is the same as the one explained in the EFL measure.

The distortion measurement computes the field of views of the lenses when it has the two additional following inputs:

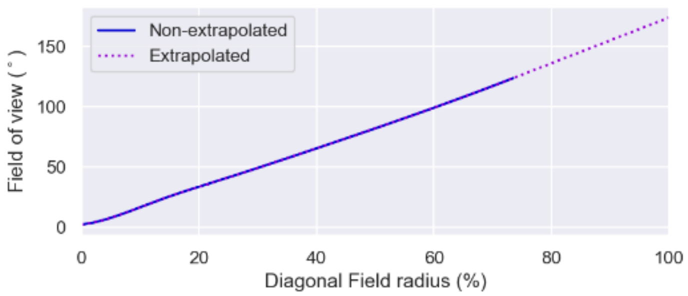
- `DotSpacing`: the distance between two dots of the Dot chart in mm
- `ChartDistance`: the distance between the chart and the lens in mm

If the measurement succeeds, we have these following data:

- The field of view map that illustrate the angle between each dots detected and the center dot of the image.



- The field of view map shows the value of the field of view occupied by a disk centered on the image center and whose radius is a varying proportion of the image size in the three directions.



- The Summary table contains results related to the horizontal, vertical and diagonal field of view. Measurement points are obtained in the validity area of the detected dots then extrapolated to the field of view at 100% of the image size. The measurement also provides the orthofrontality angles.

	Horizontal Field of View	Vertical Field of View	Diagonal Field of View
Non-extrapolated	129.39 °	74.06 °	123.76 °
Extrapolated	150.2 °	80.97 °	173.99 °
	Tilt	Pan	
Orthofrontality angles	2.18 °	-0.01 °	

39.2.5 Measurement accuracy

39.2.5.1 Distortion model

The distortion model accuracy, in pixels, is automatically estimated and reported as an error map, radial profile and RMSE values.

The allowed error ϵ_{lim} is set to 2% of the image height, and used when computing the maximum valid crop factor and maximum valid radius.

39.2.5.2 Distortion metrics

Devices with lower RMSE or model error will have better measurement accuracy. For RMSE < 1 pixel, the same accuracy guarantees as the DC measurement apply.

Inside the maximum valid crop factor and radius, the variation of TV Distortion and Geometric Distortion percentages is limited to ±1% (meaning that the ground truth of a TV Distortion estimate of 25% will be between at most 24 and 26%). This is also the case for the non-extrapolated metrics and profiles.

Outside of the maximum valid crop factor, the extrapolated metrics are robust indicators of the true device distortion but may have larger estimation errors. In general for barrel distortion the extrapolation underestimates the true values.

39.2.5.3 Equivalent focal length and field of view

The measurement accuracy explained in the EFL measurement 16.8 can be applied for non-extrapolated values. However, the accuracy for the extrapolated results is not guaranteed because these are estimated values.

The repeatability accuracy is ±1°, and above all, it depends on the following characteristics that can affect the accuracy:

- The framing of the image that is processed (check the right shooting conditions 39.2.2).
- The orthofrontality angle is too high (more than 1°).

39.2.6 Comparing two cameras

39.2.6.1 Distortion model

The distortion model coefficients are only comparable between different cameras if the `DotSpacing` and `ChartDistance` parameters are present.

39.2.6.2 Distortion metrics

The extrapolated metrics are comparable between cameras.

The non-extrapolated metrics are only comparable at the same crop factor or radius.

39.2.6.3 Equivalent focal length and field of view

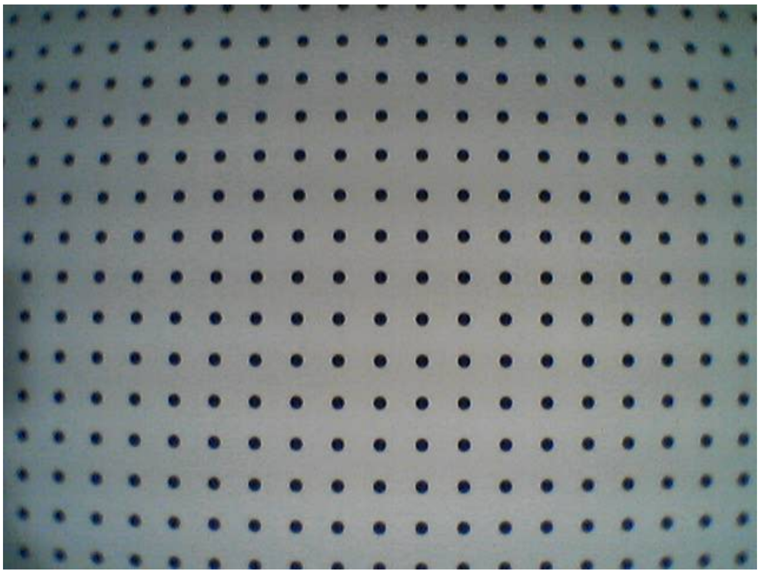
The focal length and field of view measurements are comparable between different cameras.

39.3 Performing measurements on highly distorted images/videos using the distortion model

39.3.1 Computing the device-specific distortion model

To perform a measurement on a wide angle image or video, one needs to first compute the distortion model corresponding to the device under test. This model will be used to undistort images/frames and then perform a standard measurement on it.

In order to compute the model, you will need to make shoots of the Dots chart with the same camera parameters as the ones used to shoot your wide angle image/videos:



Distorted Dots chart used to retrieve the distortion model of the camera.

The resolution of the Dots chart image has to be the same as the resolution of the wide angle image/video. You can use Workflow Manager to compute the distortion model, as done in the following example:

```
# Import the needed modules
from dxomark.core.videomeasure import VideoStream, VideoFlickerMeasure
from dxomark.core.measure import WideAngleDistortionMeasure

# Compute the distortion model from a Dots chart image
obj = WideAngleDistortionMeasure()
obj.Inputs({ "ImgObj": r"C:\Path\To\DotsImage" })
obj.Process()
out = obj.Outputs()
distModel = out["Model"]
```

39.3.2 Running video measurements

For video measures, inputs require a VideoStream instance as well as the previously computed distortion model:

```
# Load the video
vs = VideoStream()
vs.SetDistortionModel(out["Model"])
vs.LoadFile(r"C:\Path\To\video.mp4")
```

You can then perform the measurement as usual, using this VideoStream instance as well as the other required arguments. If you have a doubt on what is needed, please call help(<measure_name>).

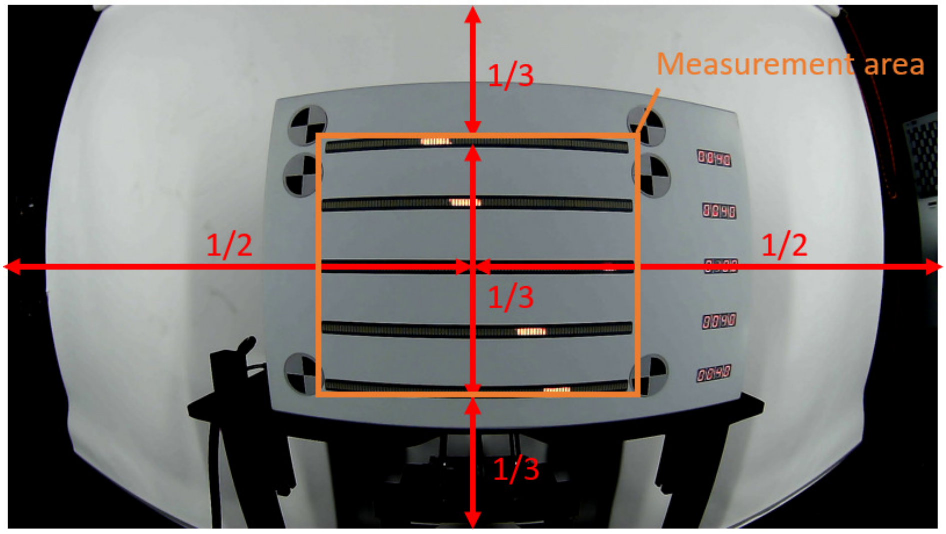
39.4 FLICKER: Flickering

39.4.1 Optimal framing for wide-angle lenses

The correct shooting protocol for the Flickering measurement is described in the Flickering manual. In addition to following those guidelines, in order to maximize the measurement accuracy despite the distortion, the framing of the LED Universal Timer mk II should present the following characteristics:

- The center of the picture should coincide with the central LED of the middle line of the LED Universal Timer mk II;
- The measurement area should cover approximatively one-third of the horizontal field of view.

An example of a correctly framed picture is given in the figure below.



Framing guidelines.

39.4.2 Running the flickering measure on a video

In order to run the Flickering measure on a video, and for more information about it, please refer to the Flickering User Manual. Be careful to set a distortion model in the VideoStream object as detailed in 39.3.

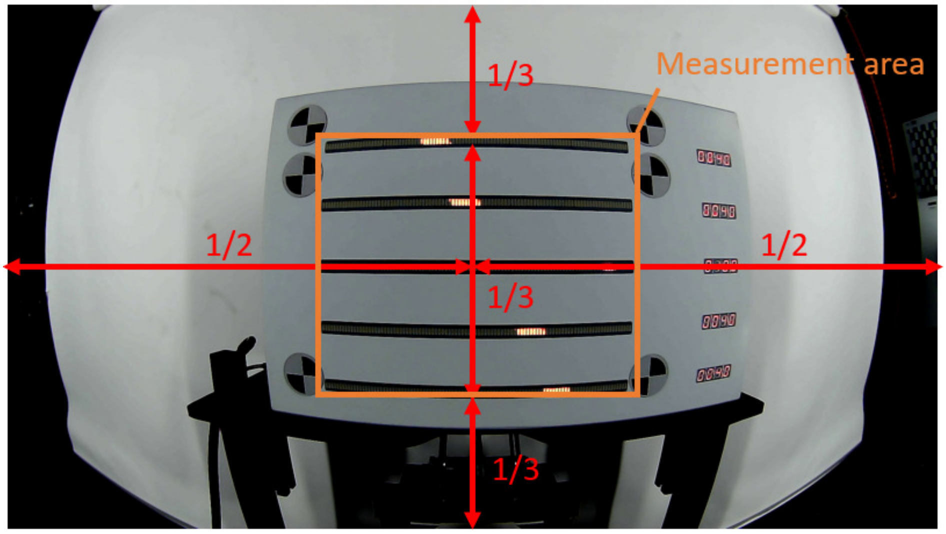
39.5 TMR: Timing

39.5.1 Optimal framing for wide-angle lenses

The correct shooting protocol for the Timing measurement is described in Chapter 31. In addition to following those guidelines, in order to maximize the measurement accuracy despite the distortion, the framing of the LED Universal Timer should present the following characteristics:

- The center of the picture should coincide with the central LED of the middle line of the LED Universal Timer;
- The measurement area should cover approximatively one-third of the horizontal field of view.

An example of a correctly framed picture is given in the figure below.



Framing guidelines.

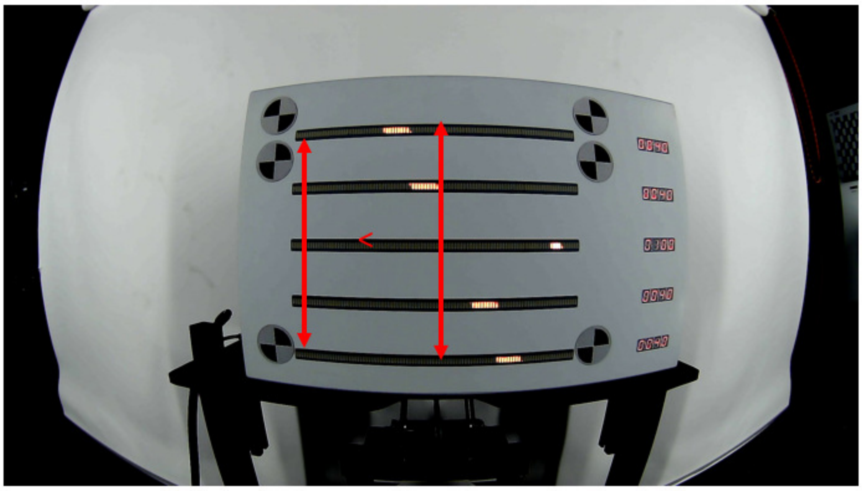
39.5.2 Impact of distortion on measurement accuracy

As detailed in Chapter 31, the measurement accuracy for an undistorted image is of ±1 LED, with the corresponding value in milliseconds depending on the LED Universal Timer calibration.

However, a noticeably distorted image, such as it can be expected in a Wide-Angle setup, could be affected by a larger measurement error.

A distorted line that may reduce measurement accuracy.

In particular, there is a combination of effects between the image distortion and the rolling shutter: one LED line is imaged over several pixel rows, which results in a delay between the moments two LEDs on the same line are read, because of the Rolling Shutter. This introduces a measurement error for both Exposure Time and Rolling Shutter.



Incertitude on the horizontal position of the LED lines.

For Exposure Time, the measurement error will depend on the value of the Rolling Shutter, the amount of distortion, and the true value of the Exposure Time being measured.

In particular:

- When the value of the Rolling Shutter increases, the measurement error increases;

- When the measured Exposure Time increases, the measurement error decreases;
- When the amount of distortion increases, the measurement error increases.

In order to have an estimation, one can make reference to the following table. This gives the approximate expected accuracy of the Exposure Time measurement as a function of two factors:

- The ratio between the nominal Rolling Shutter time and the nominal Exposure Time
- The distortion, expressed in terms of measured TV distortion.

TV[%]	RS/ET [%]										
	25	50	75	100	150	200	250	300	400	500	600
10	<1%	<1%	<1%	<1%	1%	1%	1%	1%	1%	2%	2%
20	1%	1%	2%	2%	3%	4%	6%	7%	9%	11%	13%
30	1%	2%	2%	3%	5%	7%	8%	10%	13%	16%	20%
40	1%	2%	3%	4%	5%	7%	9%	11%	14%	18%	21%
50	1%	2%	4%	5%	7%	10%	12%	15%	19%	24%	29%
60	1%	3%	4%	6%	9%	12%	15%	17%	23%	29%	35%

Impact of distortion on the Exposure Time measurement accuracy depending on nominal Rolling Shutter and Exposure Times.

Section 13.4.1 explains what TV distortion is and how to measure it.

Example of usage

Let us consider a device with a nominal Rolling Shutter of 15 ms and a TV distortion of 30 %. If the nominal Exposure Time we want to measure is 1/30 s, then the ratio RS/ET is 45 %. According to the table, the measurement error on the Exposure Time will thus be between 1 and 2 %, which is in the same order of magnitude as the error on an undistorted image.

If instead we consider a nominal Exposure Time of 1/250 s, with a corresponding RS/ET ratio of 375 %, the error will be between 11 and 13 %. This error could be too large for some applications. In this case, assuming the resolution of the device is high enough, it is recommended to increase the distance between the device and the LED Universal Timer in order to reduce the distortion of the measurement area.

39.6 VVN: Visual Video Noise

39.6.1 Measuring noise

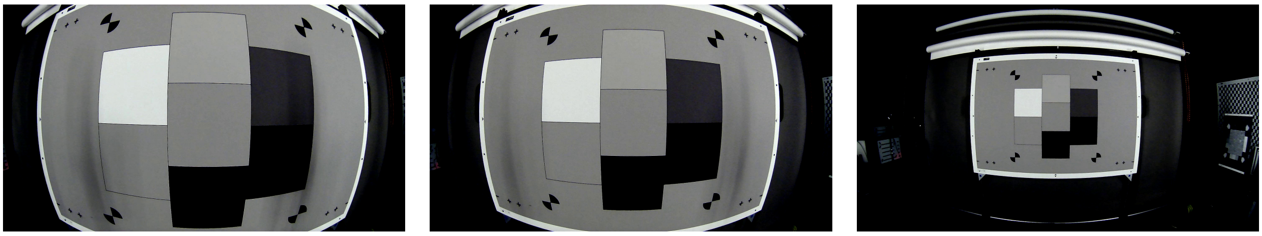
Distortion does not per se affect noise or the way it is measured. However, it does present an inconvenience in that the target chart is deformed so the uniform patches are no longer squared. The measurement only uses the distortion model given as input in order to determine where in the image uniform patches can be located, upon which the noise measurements can be performed. It is not however used to undistort the image nor for any other operation that might alter the measurement results.

39.6.2 Optimal framing for wide-angle lenses

The correct shooting protocol for the Visual Video Noise measurement is described in Chapter 21. In addition to following those guidelines, in order to maximize the measurement accuracy despite the distortion, the framing of the Visual Noise chart should present the following characteristics:

- The framing should not be too large. Because of distortion it may not be possible to only frame the target, the sides of the target are then visible in the image. This can change the exposure if the auto-exposure of the device takes the background into account. Using a white or gray background can help the auto-exposure (though the backgrounds could not be wide enough for some fisheye devices);
- The framing should not be too close. The distortion correction can crop out a part of the image. For wide-angle lenses if the markers are too close to the edges of the image they can be cropped out by the distortion correction.

An example of a correctly framed picture is given in the figure below.



Left: Wrong framing – Framing is too close: the markers would be cropped out by the distortion correction. Also, shadows are visible on the grey patches.
Middle: Right framing.
Right: Wrong framing – Framing is too far, to much of the background is visible in the frame which would alter exposure.

40 – Glossary

A

Angle of view (or of field)

This is the maximum angle formed by the rays of light that penetrate the lens to form the edge of the circular image which contains the exact shape of the sensor. It is expressed in degrees. As the focal length increases, the angle of view decreases.

Autofocus

An automatic focusing device that combines a software program, analyzing the image that is received by the sensor, and a motor driving a group of elements in the lens.

B

Barrel distortion

Barrel distortion occurs when the image of a rectangular grid is output by the sensor with the shape of a barrel (the peripheral lines are curved out).

Bit

Binary data unit. It is used to encode data. A bit may take only two values: 0 or 1.

Bits per pixel

This unit indicates the number of different levels (therefore the number of colors) that a point may take, in a digital image. For example, an image defined with one bit per pixel is only capable of reproducing black and white, without grey levels. An image defined with 8 bits per pixel and per color channel gives a 24 bit RGB image capable of reproducing 16.7 million different colors.

C

Calibration

Calibration consists in describing mathematically the deviation behavior of a camera, display or print with respect to a standard system used as a sample (typically an ideal camera).

CCD Sensor

(CCD = Charge Coupled Device). A device that transfers the sensor charge. It was invented by researchers at Bell Laboratories in 1969. Photons that reach the photosites of the sensor are accumulated in silicon cups that constitute each of them. The excitation of silicon electrons produces an electrical signal that will be interpreted by the DSP (Digital Signal Processor) to form the image pixels.

Chromatic aberration

There are generally three types of chromatic aberration:

- Axial: the different color components of white light do not all focus in the same plane (blue is closer to the lens and red is further away), so they produce a colored spreading of the blur spot.
- Lateral: depending on whether they pass through the lens at its edge or at its center, light rays do not focus at the same point as a function of their wavelength; this phenomenon adds to the offset caused by the sensor's demosaicing software.
- "Purple fringing": this is a photonic chromatic aberration that appears at the edge of strongly contrasted areas.

CMOS Sensor

CMOS = Complementary Metal Oxide Semiconductor: A transistor is associated with each photosite, which allows the output signal (expressed as the contrast of the produced image) to reach a dynamic that is several hundred times greater than the one obtained by using CCD technology.

Collimated

A collimated light is a light whose rays are parallel, which means that the wave front is planar. Such a light is sometimes called "focused at infinity." Some optical devices (called collimators) enable operators to filter out light rays to obtain a collimated light.

Color temperature

Expresses the quality of the light produced by a so-called "black body" or "standard illuminant" when it is heated to a temperature measured in degrees kelvin (°K). A black body produces a spectrum of light that is always the same for a given temperature. Thus the sun has an average color temperature of 5,500 K (a value which varies with the season and the time of day).

Compression

An algorithm that reduces the size of a data file. There are two types of compression: destructive and non-destructive.

Destructive compression involves a loss of data. In this case, the goal is to use the highest compression rate that produces invisible, or very slightly visible, destruction of the image. JPEG is an example of destructive compression.

Non-destructive compression does not cause any data loss. An image can be recorded many times in a row with no quality deterioration. TIFF LZW is an example of non-destructive compression.

Contrast

Contrast is characterized by the slope of the transfer function of an image. The more vertical the slope, the higher the contrast, and the fewer output grey levels the image contains for the corresponding portion of the curve. Contrast can be expressed separately for each channel of an image as RGB or HSL (Hue, Saturation, Luminosity).

D

Definition of an image

This is the size of a digital image, or the total number of pixels. For example, a camera may produce a 3.2 million-pixel image, or a 6 million-pixel image. The definition of an image may also be given by the number of pixels in its width and height; for example, 1160×1737 pixels is equivalent to 2 million pixels. This term should not be confused with “resolution".

Depth of field

The area in the image where all the objects are sharp, from the nearest to the furthest. The depth of field is small when the focusing distance is close, the diaphragm is open, and the lens has a long focal length.

Diaphragm

Mechanical device with sliding blades fitted in a lens that modifies the lens aperture. The numerical description of the aperture indicates the quantity of light that the lens-diaphragm assembly transmits to the sensor. Thus a f/1 diaphragm passes all the light it receives. The standard aperture scale is f/1.4, 2, 2.8, 4, 5.6, 8, 11, 16, 22. When the aperture number is large, very little light reaches the sensor. Light decreases by one-half when the aperture graduation increases by one stop.

Digital zoom

The zoom effect produced by over-sampling and framing of the image received by the sensor. An identical effect can be produced by the use of image-processing software.

Dynamic range

Defines the range of tones, from the densest to the lightest areas, that an acquisition, display, or printing peripheral is capable of analyzing or reproducing exactly. It is generally expressed in bits per pixel.

DPI

DPI = Digital Points per Inch: Unit of measurement for the number of pixels per linear inch in an image.

E

EXIF

EXIF = EXchangeable Image file Format: In the header of a graphical file, this contains information about the image, under a standard known format. It includes the dimensions of the image, shooting date, model of the camera, technical settings, and so on.

Exposure meter

Instrument for measuring the quantity of light falling on, or reflected by the subject, in order to determine the shutter speed and aperture settings required to obtain the correct exposure of an image.

Exposure (time)

Expressed in fractions of a second, this term describes the exposure time of a shot. The exposure time is generally associated with the value of the aperture and therefore defines the quantity of light that reaches the sensor.

F

File format

Description of the structure and coding of a file, marked by an extension (.TIF or .JPG, for example) and sometimes by a special icon.

Focal length

This is the distance between the plane of the sensor and the optical center of the lens, when the lens is focused on infinity. This value is always expressed in millimeters. The “normal"focal length (which produces an image comparable to human vision) is essentially equal to the value of the diagonal of the sensor. Long focal lengths correspond to long-focus lenses (which gives the impression of being closer to the photographed subject), and short focal lengths to wide-angle lenses (which makes the photographed subject appear farther away). A zoom, or lens with variable focal length, is described by two values that indicate the shortest and longest focal lengths it is able to reach. A focal length equivalent to 24×36 is sometimes used in the documentation of digital cameras to provide a comparable value that is independent of the size of the installed sensor.

Focal plane

An imaginary plane on which the lens forms a sharp image when the focus is correctly set.

Focal point

There are two focal points: one in front of the lens and the other behind it. They are both located on the optical axis of the lens. All the rays of light coming from the subject to form an image on the focal plane converge at the focal points.

Focusing

Device for adjusting a lens with either manual or automatic controls. It ensures the sharpness of the image according to the distance of the subject.

G

Gamma

Gamma is the measurement of image contrast in the mean grey levels. The gamma is represented by a curve whose output grey levels are the abscissa, and the input values are the ordinates. It is measured by a decimal number that expresses the slope of this curve.

Gamut

The gamut of a system is the set of colors it can reproduce, detect, or represent. The human eye has its own gamut, which is often taken as a reference. Each color space (sRGB, Adobe RGB and so on) and each sensor has its own gamut.

Geometrical distortion

A perfect optical system would project the image of a regular grid onto the sensor without distortion. In practice, either barrel or pincushion distortion appears, depending on the optical formulation of the lens.

H

Histogram

A diagram consisting of a series of vertical bars. Each bar represents one value of grey level (between 0 and 255 for an 8-bit image). The height of a bar is proportional to the number of pixels in the image whose grey level it represents. An image has a unique histogram for each RGB channel. The histogram of a correctly-exposed image must contain pixels for each grey level.

I

IEEE 1394 (FireWire)

A standard high-speed communication protocol for data transmission between a central unit and its peripherals. Peripherals connected in this way to a computer constitute a bus that can appear as a continuous chain or as a tree structure. The IEEE 1394 protocol accepts a long length of cable (4.5 m) between each peripheral, and allows connection and disconnection of peripherals without switching off the computer.

IL - Exposure index

The exposure index is a value that is independent of sensor sensitivity, and that defines a quantity of light reaching the sensor for a given combination of aperture and shutter speed. In practice, a change of +1 IL indicates that the quantity of light reaching the sensor is doubled.

ISO

ISO = International Standards Organization: An international standard unit expressing the sensitivity of a photographic film or, similarly, a sensor. This value is sometimes expressed as an ASA number, an old standard that is identical to ISO. The higher the value, the more sensitive the sensor, and the better images it produces under low lighting conditions. The sensitivity of the sensor is directly proportional to the ISO rating. Therefore a value of 200 ISO indicates that the sensitivity is twice that of 100 ISO. It should be noted that sensors have a unique nominal sensitivity and that other sensitivities are obtained by processing the produced signal.

J

JPEG

(JPEG = Joint Photographic Experts Group) A process of bitmap image compression that has become a standard for image coding. The JPEG compression algorithm is destructive, that is to say, part of the information in the file is lost each time the image is recorded. However, it is very effective and significantly reduces the size of a processed file. A low compression ratio and a small number of successive recordings produce no visible effect in the image. On the contrary, a high compression ratio gives rise to artifacts at the boundaries of significant color variations.

L

Lens

An optical device containing several lens elements combined in a mechanical assembly that is capable of achieving focus, among other things. The lens projects an image of the subject onto the sensor. A lens is characterized by its focal length (or its minimum and maximum focal lengths, in the case of a zoom), its widest aperture and its minimum focusing distance. The most recent lenses may also include automatic focusing, and image stabilization systems (for long focal lengths).

Line spread function (LSF)

The theoretical response of an imaging system to an infinitely thin line. The Fourier transform of the LSF in the direction normal to the line is the modulation transfer function (MTF).

M

Mask

In silver halide photography, a mask is a red "non-actinic" film that protects the sensitive surface from luminous radiation. It can be shaped as required so as to protect only selected areas. By analogy, in digital photography, a mask is a layer added to an image to protect part of it with a ratio between 0% and 100%. This lets you apply corrections selectively or to achieve complex combinations of images. This type of mask is also known as an "alpha layer."

N

Neutrality

A characteristic of an image that reproduces the colors of the subject without modifying them. You can obtain this result by correctly setting the color temperature, the exposure, and any contrast and saturation settings, so long as the camera is capable of rendering colors without modifying them.

Noise

Random granulation in the image, particularly visible in areas that are homogeneous (such as blue sky). The origin of the noise may be photonic, thermal, or caused by imperfections in photosites; caused by the charge-transfer process; by analog-to-digital conversion data; or by demosaicing and compression processing.

O

Optical zoom

A lens that can be used at all intermediate focal lengths between the longest and shortest available.

Orthofrontal

A planar chart is orthofrontal to a camera if its plane is parallel to the focal plane, or in other words, normal to the optical axis. Therefore, a view of a target in orthofrontal position is free of perspective defects.

Over-exposure

A sensor produces an over-exposed image when it has received too much light, which makes the image appear too bright in comparison with the human visual perception of reality.

P

Photonics

Dealing with photons, thus with light, as opposed to electrons. For example, photonic noise is different from electronic noise, but their effects are similar.

Photosite

The elementary photosensitive cell of a sensor. The terms photosite (on the sensor) and pixel (in the image) are often confused, as they relate to very similar objects.

Pincushion distortion

Pincushion distortion occurs when the sensor outputs an image of a rectangular grid whose peripheral lines are not straight, but are curved inward.

Pixel

The smallest element of a digital image. Pixel is an abbreviation of the English expression "picture element." A pixel does not have a predefined size. It depends directly on the dimensions and resolution of the acquisition, display, or printing peripheral that is used. The number of pixels defines the image.

R

Resolution

The number of pixels within a linear inch (dpi, for dots per inch) or a centimeter (ppc, for points per centimeter). A file of a given weight or definition may have many different resolutions (72 dpi, 300 dpi, etc.). This term should not be confused with "definition".

RGB

Stands for red, green, blue, the primary colors of additive synthesis. It also indicates a means of color representation based on an International Lighting Committee (ILC) standard. This system is used in digital photography and computer screens. It is the opposite of the subtractive method of synthesis, CMYK (cyan, magenta, yellow, black), that is used in printing and with color printers.

S

Sampling

The measurement, at regular intervals, of the amplitude of a varying analog signal, in order to convert it to a digital form. The sample obtained may be processed by digital software.

Saturation

Expresses the purity of a color, or the lack of white in its components for maximum luminosity. A saturated color can be only a primary RGB color, or a color composed of only two primary colors. The addition of a third color implies the presence of white.

Sensor

Physical device capable of digitizing an image projected onto a rectangular surface.

Shutter

A mechanical or electromechanical assembly with two states, open or closed. It controls the quantity of light that reaches the sensor. The time of shutter opening is expressed in seconds or fractions of a second: an exposure of $1/500^{th}$ allows half as much light to pass compared to an exposure of $1/250^{th}$. It should be noted that a number of photoscopes no longer have a shutter, so the exposure time is obtained by the duration of energizing the sensor.

SMIA

Standard Mobile Imaging Architecture. The SMIA standard was created in 2003 by Nokia Corporation and ST Microelectronics to standardize the characterization and specifications of camera modules in mobile applications.

T

Target exposure

A reference grey level in an image. The target exposure aims to represent the most important subject of interest in an image. It is typically chosen right in the middle of the dynamic range of the output color space. It is used for digital camera auto-exposure algorithms to control the exposure gain; typically, the mean value of the image is constrained to be close to the target exposure.

TIFF or TIF

TIFF = Tagged Image File Format: a Bitmap file format created by Aldus, now part of Adobe. This format allows non-destructive compression using the LZW method. The labels (tags) include records such as the file resolution in x and y, the size of the image in x and y, the number of bits per pixel, the compression mode, the ICC profile, the predisplay thumbnail, and so on.

U

Under-exposure

A sensor produces an under-exposed image when it has not received a sufficient quantity of light, making the image appear too dense in comparison with our visual perception of reality.

V

Vignetting

Vignetting is the darkening of the image in its corners. Vignetting appears if (a) the lens does not cover the sensor completely; (b) if the incidence angle of the light reaching the edges of the object is reduced; or (c) if you use certain accessories, such as a too-narrow lens hood.

W

WB-auto

(White-Black automatic) Automatic white balance.

White balance

The white balance corresponds to the emission of a signal at the same level in the highlights for the RGB channels. The white balance may be manually set for a particular color temperature, or by an automatic system embedded in the camera.

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