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Photography — Electronic still picture imaging — Resolution and spatial frequency responses

Photographie — Imagerie des prises de vues électroniques — Résolution et réponses en fréquence spatiale

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Contents

Page

Foreword

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The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular the different approval criteria needed for the different types of ISO documents should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see www.iso.org/directives).

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights. Details of any patent rights identified during the development of the document will be in the Introduction and/or on the ISO list of patent declarations received (see www.iso.org/patents).

Any trade name used in this document is information given for the convenience of users and does not constitute an endorsement.

For an explanation on the meaning of ISO specific terms and expressions related to conformity assessment, as well as information about ISO's adherence to the World Trade Organization (WTO) principles in the Technical Barriers to Trade (TBT) see the following URL: www.iso.org/iso/foreword.html.

The committee responsible for this document is ISO/TC 42, *Photography*.

This third edition cancels and replaces the second edition (ISO 12233:2014), of which it constitutes a minor revision with changes in Annex D.

Introduction

Purpose

The spatial resolution capability is an important attribute of an electronic still-picture camera. Resolution measurement standards allow users to compare and verify spatial resolution measurements. This document defines terminology, test charts, and test methods for performing resolution measurements for analogue and digital electronic still-picture cameras.

Technical background

For consumer digital cameras, the term *resolution* is often incorrectly interpreted as the number of addressable photoelements. While there are existing protocols for determining camera pixel counts, these are not to be confused with the interpretation of resolution as addressed in this document. Qualitatively, resolution is the ability of a camera to optically capture finely spaced detail, and is usually reported as a single valued metric. Spatial frequency response (SFR) is a multi-valued metric that measures contrast loss as a function of spatial frequency. Generally, contrast decreases as a function of spatial frequency to a level where detail is no longer visually resolved. This limiting frequency value is the resolution of the camera. A camera's resolution and its SFR are determined by a number of factors. These include, but are not limited to, the performance of the camera lens, the number of addressable photoelements in the optical imaging device, and the electrical circuits in the camera, which can include image compression and gamma correction functions.

While resolution and SFR are related metrics, their difference lies in their comprehensiveness and utility. As articulated in this document, resolution is a single frequency parameter that indicates whether the output signal contains a minimum threshold of detail information for visual detection. In other words, resolution is the highest spatial frequency that a candidate camera can usefully capture under cited conditions. It can be very valuable for rapid manufacturing testing, quality control monitoring, or for providing a simple metric that can be easily understood by end users. The algorithm used to determine resolution has been tested with visual experiments using human observers and correlates well with their estimation of high frequency detail loss.

SFR is a numerical description of how contrast is changed by a camera as a function of the spatial frequencies that describe the contrast. It is very beneficial for engineering, diagnostic, and image evaluation purposes and serves as an umbrella function from which such metrics as sharpness and acutance are derived. Often, practitioners will select the spatial frequency associated with a specified SFR level as a modified non-visual resolution value.

In a departure from the first edition of this document, two SFR measurements are described. Additionally, the first SFR metrology method, edge-based spatial frequency response, is identical to that described in the first edition, except that a lower contrast edge is used for the test chart. Regions of interest (ROI) near slanted vertical and horizontal edges are digitized and used to compute the SFR levels. The use of a slanted edge allows the edge gradient to be measured at many phases relative to the image sensor photoelements and to yield a phase-averaged SFR response.

A second sine wave-based SFR metrology technique is introduced in the second edition. Using a sine wave modulated target in a polar format (e.g. Siemens star), it is intended to provide an SFR response that is more resilient to ill-behaved spatial frequency signatures introduced by the image content driven processing of consumer digital cameras. In this sense, it is intended to enable easier interpretation of SFR levels from such camera sources. Comparing the results of the edge-based SFR and the sine-based SFR might indicate the extent to which nonlinear processing is used.

The first step in determining visual resolution or SFR is to capture an image of a suitable test chart with the camera under test. The test chart should include features of sufficiently fine detail and frequency content such as edges, lines, square waves, or sine wave patterns. The test chart defined in this document has been designed specifically to evaluate electronic still-picture cameras. It has not necessarily been designed to evaluate other electronic imaging equipment such as input scanners, CRT displays, hard-copy printers, or electro-photographic copiers, nor individual components of an electronic still-picture camera, such as the lens.

Some of the measurements described in this document are performed using digital analysis techniques. They are also applicable with the analogue outputs of the camera by digitizing the analogue signals if there is adequate digitizing equipment.

Methods for measuring SFR and resolution — Selection rationale and guidance

This section is intended to provide more detailed rationale and guidance for the selection of the different resolution metrology methods presented in this document. While resolution metrology of analogue optical systems, by way of spatial frequency response, is well established and largely consistent between methodologies (e.g. sine waves, lines, edges), metrology data for such systems are normally captured under well-controlled conditions where the required data linearity and spatial isotropy assumptions hold. Generally, it is not safe to assume these conditions for files from many digital cameras, even under laboratory capture environments. Exposure and image content dependent image processing of the digital image file before it is provided as a finished file to the user prevents this. This processing yields different SFR responses depending on the features in the scene or in the case of this document, the target. For instance, in-camera edge detection algorithms might specifically operate on edge features and selectively enhance or blur them based on complex nonlinear decision rules. Depending on the intent, these algorithms might also be tuned differently for repetitive scene features such as those found in sine waves or bar pattern targets. Even for constrained camera settings recommended in this document, these nonlinear operators can yield differing SFR results depending on the target feature set. Naturally, this causes confusion on which targets to use, either alone or in combination. Guidelines for selection are offered below.

Edges are common features in naturally occurring scenes. They also tend to act as visual acuity cues by which image quality is judged and imaging artefacts are manifested. This logic prescribed their use for SFR metrology in the past and current editions of this document. It is also why edge features are prone to image processing in many consumer digital cameras; they are visually important. All other imaging conditions being equal, camera SFRs using different target contrast edge features can be significantly different, especially with respect to their morphology. This is largely due to nonlinear image processing operators and would not occur for strictly linear imaging systems. To moderate this behaviour, a lower contrast slanted edge feature (Figure C.1) was chosen to replace the higher contrast version of the first edition. This feature choice still allows for acuity-amenable SFR results beyond the half-sampling frequency and helps prevent nonlinear data clipping that can occur with high contrast target features. It is also a more reliable rendering of visually important contrast levels in naturally occurring scenes.

Sine wave features have long been the choice for directly calculating SFR of analogue imaging systems and they are intuitively satisfying. They have been introduced into the second edition based on experiences from the edge-based approach. Because sine waves transition more slowly than edges, they are not prone to being identified as edges in embedded camera processors. As such, the ambiguity that image processing imposes on the SFR can be largely avoided by their use. Alternatively, if the image processing is influenced by the absence of sharp features, more aggressive processing might be used by the camera. A sine wave starburst test pattern (Figure 6) is adopted in the second edition. With the appropriate analysis software, a sine wave-based SFR can be calculated up to the half-sampling frequency. For the same reasons stated above, the sine wave-based target is also of low contrast and consistent with that of the edge-based version. An added benefit of the target's design over other sine targets is its compactness and bi-directional features.

All experience suggests that there is no single SFR for today's digital cameras. Even under the strict capture constraints suggested in this document, the allowable feature sets that most digital cameras offer prevent such unique characterization. Confusion can be reduced through complete documentation of the capture conditions and camera setting for which the SFR was calculated. It has been suggested that comparing edge-based and sine wave-based SFR results under the same capture conditions could be a good tool in assessing the contribution of spatial image processing in digital cameras.

Finally, at times, a full SFR characterization is simply not required, such as in end of line camera assembly testing. Alternately, SFR might be an intimidating obstacle to those not trained in its utility. For those in need of a simple and intuitive space domain approach to resolution using repeating line patterns, a visual resolution metric is also provided in this third edition of this document.

With such a variety of methods available for measuring resolution, there are bound to be differences in measured resolution results. To benchmark the likely variations, the committee has published the results of a pilot study using all of the proposed techniques and how they relate to each other. These results are provided in Reference [20].

Photography — Electronic still picture imaging — Resolution and spatial frequency responses

1 Scope

This document specifies methods for measuring the resolution and the SFR of electronic still-picture cameras. It is applicable to the measurement of both monochrome and colour cameras which output digital data or analogue video signals.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 14524, *Photography — Electronic still-picture cameras — Methods for measuring opto-electronic conversion functions (OECFs)*

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

— IEC Electropedia: available at http://www.electropedia.org/

— ISO Online browsing platform: available at http://www.iso.org/obp

3.1
addressable photoelements
number of active photoelements in an *image sensor* (3.11)

Note 1 to entry: This equals the product of the number of active photoelement lines and the number of active photoelements per line.

3.2
aliasing
output image artefacts that occur in a *sampled imaging system* (3.23) due to insufficient sampling

Note 1 to entry: These artefacts usually manifest themselves as moiré patterns in repetitive image features or as jagged stair-stepping at edge transitions.

3.3
cycles per millimetre
cy/mm
spatial frequency unit defined as the number of spatial periods per millimetre

3.4
edge spread function
ESF
normalized spatial signal distribution in the *linearized* (3.15) output of an imaging system resulting from imaging a theoretical infinitely sharp edge

3.5
effectively spectrally neutral
having spectral characteristics which result in a specific imaging system producing the same output as for a *spectrally neutral* (3.25) object

3.6
electronic still-picture camera
camera incorporating an *image sensor* (3.11) that outputs an analogue or digital signal representing a still picture

Note 1 to entry: This camera may also record or store an analogue or digital signal representing a still picture on a removable media, such as a memory card or magnetic disc.

3.7
gamma correction
signal processing operation that changes the relative signal levels

Note 1 to entry: Gamma correction is performed, in part, to correct for the nonlinear light output versus signal input characteristics of the display. The relationship between the light input level and the output signal level, called the camera opto-electronic conversion function (OECF), provides the gamma correction curve shape for an image capture device.

Note 2 to entry: The gamma correction is usually an algorithm, lookup table, or circuit which operates separately on each colour component of an image.

3.8
horizontal resolution

resolution (3.22) value measured in the longer image dimension, corresponding to the horizontal direction for a “landscape” image orientation, typically using a vertical or near vertical oriented test-chart feature

3.9
image aspect ratio
ratio of the image width to the image height

3.10
image compression
process that alters the way digital image data are encoded to reduce the size of an image file

3.11
image sensor
electronic device that converts incident electromagnetic radiation into an electronic signal

EXAMPLE Charge coupled device (CCD) array, complementary metal-oxide semiconductor (CMOS) array.

3.12
line pairs per millimetre
lp/mm
spatial frequency unit defined as the number of equal width black and white line pairs per millimetre

3.13
line spread function
LSF
normalized spatial signal distribution in the *linearized* (3.15) output of an imaging system resulting from imaging a theoretical infinitely thin line

3.14
line widths per picture height
LW/PH
spatial frequency unit for specifying the width of a feature on a *test chart* (3.26) relative to the height of the active area of the chart

Note 1 to entry: The value in LW/PH indicates the total number of lines of the same width which can be placed edge to edge within the height of a test target or within the vertical field of view of a camera.

Note 2 to entry: This unit is used whatever the orientation of the "feature" (e.g. line). Specifically, it applies to horizontal, vertical, and diagonal lines.

EXAMPLE If the height of the active area of the chart equals 20 cm, a black line of 1 000 LW/PH has a width equal to 20/1 000 cm.

3.15
linearized
digital signal conversion performed to invert the camera opto-electronic conversion function (OECF) to focal plane exposure or scene luminance

3.16
lines per millimetre
lines/mm
spatial frequency unit defined as the number of equal width black and white lines per millimetre

Note 1 to entry: One line pair per millimetre (lp/mm) is equal to 2 lines/mm.

3.17
modulation
normalized amplitude of signal levels

Note 1 to entry: This is the difference between the minimum and maximum signal levels divided by the average signal level.

3.18
modulation transfer function
MTF
modulus of the *optical transfer function* (3.20)

Note 1 to entry: For the MTF to have significance, it is necessary that the imaging system be operating in an isoplanatic region and in its linear range. Because most *electronic still-picture cameras* (3.6) provide spatial colour sampling and nonlinear processing, a meaningful MTF of the camera can only be approximated through the SFR. See ISO 15529:2010.

3.19
normalized spatial frequency
spatial frequency unit for specifying resolution characteristics of an imaging system in terms of cycles per pixel rather than in cycles/millimetre or any other unit of length

3.20
optical transfer function
OTF
two-dimensional Fourier transform of the imaging system's *point spread function* (3.21)

Note 1 to entry: For the OTF to have significance, it is necessary that the imaging system be operating in an isoplanatic region and in its linear range. The OTF is a complex function whose modulus has unity value at zero spatial frequency (see ISO 9334). Because most *electronic still-picture cameras* (3.6) provide spatial colour sampling and nonlinear processing, a meaningful OTF of the camera can only be approximated through the SFR.

3.21
point spread function
PSF
normalized spatial signal distribution in the *linearized* (3.15) output of an imaging system resulting from imaging a theoretical infinitely small point source

3.22
resolution
measure of the ability of a camera system, or a component of a camera system, to depict picture detail

3.23
sampled imaging system
imaging system or device which generates an image signal by sampling an image at an array of discrete points, or along a set of discrete lines, rather than a continuum of points

Note 1 to entry: The sampling at each point is done using a finite-size sampling aperture or area.

3.24
spatial frequency response
SFR
relative amplitude response of an imaging system as a function of input spatial frequency

Note 1 to entry: The SFR is normally represented by a curve of the output response to an input sinusoidal spatial luminance distribution of unit amplitude, over a range of spatial frequencies. The SFR is divided by its value at the spatial frequency of 0 as normalization to yield a value of 1,0 at a spatial frequency of 0.

3.24.1
edge-based spatial frequency response
e-SFR
measured amplitude response of an imaging system to a slanted-edge input

Note 1 to entry: Measurement of e-SFR is as defined in Clause 6.

3.24.2
sine wave-based spatial frequency response
s-SFR
measured amplitude response of an imaging system to a range of sine wave inputs

Note 1 to entry: Measurement of s-SFR is as defined in Clause 7.

3.25
spectrally neutral
exhibiting reflective or transmissive characteristics which are constant over the wavelength range of interest

3.26
test chart
arrangement of *test patterns* (3.27) designed to test particular aspects of an imaging system

3.27
test pattern
specified arrangement of spectral reflectance or transmittance characteristics used in measuring an image quality attribute

3.27.1
bi-tonal pattern
pattern that is *spectrally neutral* (3.25) or *effectively spectrally neutral* (3.5), and consists exclusively of two reflectance or transmittance values in a prescribed spatial arrangement

Note 1 to entry: Bi-tonal patterns are typically used to measure *resolution* (3.22) by visual resolution method.

3.27.2
hyperbolic wedge test pattern
bi-tonal pattern (3.27.1) that varies continuously and linearly with spatial frequency

Note 1 to entry: A bi-tonal hyperbolic wedge test pattern is used to measure *resolution* (3.22) by the visual resolution method in this document.

3.28
vertical resolution
resolution (3.22) value measured in the shorter image dimension, corresponding to the vertical direction for a "landscape" image orientation, typically using a horizontal or near horizontal oriented test-chart feature

3.29
visual resolution
spatial frequency at which all of the individual black and white lines of a test pattern frequency can no longer be distinguished by a human observer

Note 1 to entry: This presumes the features are reproduced on a display or print.

4 Test conditions

4.1 Test chart illumination

The luminance of the test chart shall be sufficient to provide an acceptable camera output signal level. The test chart shall be uniformly illuminated as shown in Figure 1, so that the illuminance at the chart is within ±10 % of the illuminance in the centre of the chart at any position within the chart. The illumination sources should be baffled to prevent direct illumination of the camera lens by the illumination sources. The area surrounding the test chart should be of low reflectance to minimize flare light. The chart should be shielded from any reflected light. The illuminated test chart shall be effectively spectrally neutral within the visible wavelengths.

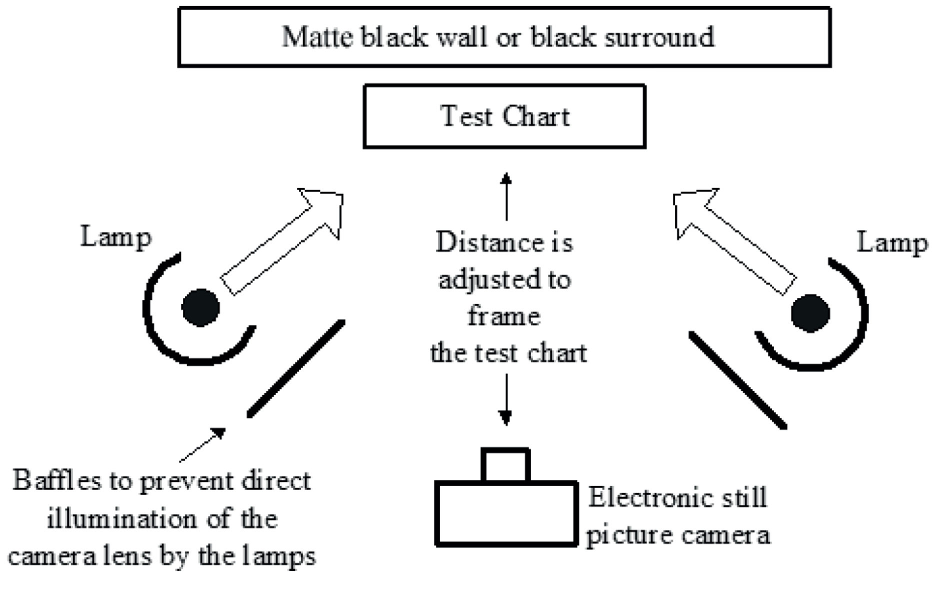

Figure 1 — Test chart illumination method

4.2 Camera framing and lens focal length setting

The camera shall be positioned to properly frame the test target. The vertical framing arrows are used to adjust the magnification and the horizontal arrows are used to centre the target horizontally. The tips of the centre vertical black framing arrows should be fully visible and the tips of the centre white framing arrows should not be visible. The target shall be oriented so that the horizontal edge of the chart is approximately parallel to the horizontal camera frame line. The approximate distance between the camera and the test chart should be reported along with the measurement results.

4.3 Camera focusing

The camera focus should be set either by using the camera autofocusing system, or by performing a series of image captures at varying focus settings, and selecting the focus setting that provides the highest average modulation level at a spatial frequency approximately 1/4 the camera Nyquist frequency. (In the case of a colour camera, the Nyquist frequency is of the conceptual monochrome image sensor without colour filter array). Auto focus accuracy is often limited and this limitation might have an impact on the results.

4.4 Camera settings

The camera lens aperture (if adjustable) and the exposure time should be adjusted to provide a near maximum signal level from the white test target areas. The settings shall not result in signal clipping in either the white or black areas of the test chart, or regions of edge transitions.

Electronic still-picture cameras might include image compression, to reduce the size of the image files and allow more images to be stored. The use of image compression can significantly affect resolution measurements. Some cameras have switches that allow the camera to operate in various compression or resolution modes. The values of all camera settings that might affect the results of the measurement, including lens focal length, aperture and image quality (i.e. recording pixel number or compression) mode (if adjustable), shall be reported along with the measurement results.

Multiple SFR measurements can be reported for different camera settings, including a setting that uses the maximum lens aperture size (minimum *f*-number) and maximum camera gain.

4.5 White balance

For a colour camera, the camera white balance should be adjusted, if possible, to provide proper white balance [equal red, green, and blue (RGB) signal levels] for the illumination light source, as specified in ISO 14524.

4.6 Luminance and colour measurements

Resolution measurements are normally performed on the camera luminance signal. For colour cameras that do not provide a luminance output signal, a luminance signal should be formed from an appropriate combination of the colour records, rather than from a single channel such as green. The reader is referred to ISO 12232 for the luminance signal calculation. Colour-filtered resolution measurements can be performed as described in Annex G.

4.7 Gamma correction

The signal representing the image from an electronic still-picture camera will probably be a nonlinear function of the scene luminance values. Since the SFR measurement is defined on a linearized output signal and such a nonlinear response can affect SFR values, the signal shall be linearized before the data analysis is performed. Linearization is accomplished by applying the inverse of the camera OECF to the output signal via a lookup table or appropriate equation. The measurement of the OECF shall be as specified in ISO 14524, using the standard reflection camera OECF test chart or using an integrated OECF/resolution chart.

5 Visual resolution measurement

5.1 General

The visual resolution is the maximum value of the spatial frequency in LW/PH within a test pattern that is able to be visually distinguished. A black and white hyperbolic wedge is used as the test pattern.

Because of aliasing artefacts in the high frequencies, actual resolution judgements can be ambiguous. The objective visual resolution method cited herein using a hyperbolic wedge test pattern gives more stable results by adopting the visual judgement rules described in 5.3 which have been used by a highly skilled observer.

It can be measured analytically using computer analysis of captured images, as defined in Annex B. The computer analysis method is intended to correlate with the subjective judgement of visual resolution made by a skilled observer but is likely to yield a more consistent and objective result compared to actual visual judgements. However, if there is a discrepancy between the results of the computer analysis method and the judgement of a human observer, the judgement of the human observer takes priority.

5.2 Test chart

5.2.1 General

The preferred test chart for measuring the visual resolution is the CIPA resolution chart, which is shown in Figure 2 and specified in Annex A.

The chart shown in Figure 2 is designed to measure cameras having a resolution of less than 2 500 LW/PH. Nevertheless, it is possible to use the chart to measure the resolution of an electronic still camera having a resolution greater than 2 500 LW/PH. This is accomplished by adjusting the camera to target distance, or the focal length of the camera lens, so that the test chart active area fills only a portion of the vertical image height of the camera. This fraction is then measured in the digital image, by dividing the number of image lines in the camera image by the number of lines in the active chart area. The values of all test chart features, in LW/PH, printed on the chart or specified in this document, are multiplied by this fraction, to obtain their correct values. For example, if the chart fills 1/2 of the vertical image height of the camera, then the multiplication factor is equal to 2 and a feature labelled as 2 000 LW/PH on the chart corresponds to 4 000 LW/PH using this chart framing.

NOTE Figure 2 includes an improved version of the test chart features originally defined in ISO 12233:2000. This original test chart defined in ISO 12233:2000 is described in Annex I.

5.2.2 Material

The test chart can be either a transparency that is rear illuminated or a reflection test card that is front illuminated. A reflection chart shall have an approximately Lambertian base material. A transparency chart shall be rear illuminated by a diffuse source.

5.2.3 Size

The active height of reflection test charts should be no less than 20 cm. The active height of transparencies shall be not less than 10 cm.

5.2.4 Test patterns

The test chart shall have bi-tonal patterns and should be spectrally neutral.

NOTE Bi-tonal test charts are easily manufactured and minimize the cost of producing the chart.

