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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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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).

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For an explanation of the voluntary nature of standards, 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 www.iso.org/iso/foreword.html.

This document was prepared by Technical Committee ISO/TC 42, *Photography*.

This fourth edition cancels and replaces the third edition (ISO 12233:2017), which has been technically revised.

The main changes are as follows:

— In Clause 6 and Annex C, the e-SFR test chart has been modified by replacing the “slanted square” features with four-cycle “slanted star” features, to enable diagonal measurements in addition to horizontal and vertical measurements.

— In Clause 6 and Annex D, the e-SFR algorithm has been modified by using a Tukey window, by using a 5th-order polynomial equation to fit the edge, and by correcting for the edge-angle sampling. As a result, the measurement results may be slightly different compared to the results obtained using the 3rd edition.

— Clause 6 and Annex D were updated to clarify the steps in the e-SFR algorithm.

— In Annex C, the reflectances of the surround and the light and dark patches were clarified.

— Annexes J, K, L, and M were added.

Any feedback or questions on this document should be directed to the user’s national standards body. A complete listing of these bodies can be found at www.iso.org/members.html.

Introduction

Purpose

The spatial resolution capability is an important attribute of a digital camera. Resolution measurement standards allow users to compare and verify spatial resolution measurements, as described in Reference [14]. This document defines terminology, test charts, and test methods for performing resolution measurements for analogue and digital cameras.

Technical background

Because digital cameras are sampled imaging systems, 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. SFR is similar to the optical transfer function (OTF) and the modulation transfer function (MTF) which are defined for linear systems (see References [1] and [3]). 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 several 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 camera image processing, which can include image sharpening, 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 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 spatial frequencies. 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 were described in the second edition. The first SFR metrology method, an edge-based spatial frequency response (e-SFR), was identical to that described in the first edition, except that a lower contrast edge was used for the test chart. The test chart used for the e-SFR measurement has been updated in this fourth edition, to enable measurements in diagonal directions. Regions of interest (ROIs) near slanted vertical, diagonal, and horizontal edges are digitized and used to compute the e-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 e-SFR response.

A second sine wave based SFR (s-SFR) metrology method was 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 some consumer digital cameras. In this sense, it is intended to enable easier interpretation of SFR levels from such cameras. 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 charts defined in this document have been designed specifically to evaluate digital cameras. They have 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.

The measurements described in this document are performed using digital analysis techniques. They are also applicable with 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 test chart. 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 using the constrained camera settings recommended in this document, these nonlinear operations can yield differing SFR results depending on the test chart. Naturally, this causes confusion on which test charts 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 test chart contrast edge features can be significantly different, especially with respect to their morphology. This is largely due to nonlinear image processing operations and would not occur for strictly linear imaging systems. To moderate this behaviour, in the second edition of ISO 12233, a lower contrast slanted edge feature was chosen to replace the higher contrast version of the first edition. The edge feature was further modified in this fourth edition, to enable measurements in diagonal directions. This “slanted star” 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. However, data clipping is still possible when using a test chart having a large edge reflectance ratio and/or when the captured image of the test chart is significantly overexposed. This data clipping can cause the measured e-SFR values to be overstated.

Sine wave features have long been the choice for directly calculating the MTF of analogue imaging systems and they are intuitively satisfying. They were introduced in 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. Using the sine wave starburst test pattern (see Figure 6) adopted in the second edition along 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.

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 settings 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 can be a good tool in assessing the contribution of spatial image processing in digital cameras. See Reference [14].

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 measurement is also provided in this fourth 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 several measurement methods and how they relate to each other. These results are provided in Reference [18].

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

1 Scope

This document specifies methods for measuring the resolution and the spatial frequency response (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 terminology databases for use in standardization at the following addresses:

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

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

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* (3.31) 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* (3.26) object

Note 1 to entry: Effectively spectrally neutral objects may have spectral reflectances or transmittances that vary with wavelength (are not constant) so long as they produce a neutral response using the specified imaging system. Objects that are effectively spectrally neutral with respect to one imaging system will not necessarily be so with respect to another imaging system.

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 (3.23) value(s) 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* (3.27) 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
L/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 L/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 *electronic still-picture cameras* (3.6) are *sampled imaging systems* (3.31) which use spatial colour sampling and typically include nonlinear processing, a meaningful MTF of the camera can only be approximated through the SFR. See ISO 15529:2010 (Reference [3]).

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 (Reference [1]). Because *electronic still-picture cameras* (3.6) are *sampled imaging systems* (3.31) which use spatial colour sampling and typically include nonlinear processing, a meaningful OTF of the camera can only be approximated through the SFR.

3.21
point spread function
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
reflectance
ratio of the luminous flux reflected from the surface of the chart to the luminous flux incident on the surface of the chart. The reflectance should be integrated over the range of wavelengths from at least 400 to 700 nm.

Note 1 to entry: If the camera under test is sensitive to an extended spectral range (e.g. near Infrared wavelengths), the spectral range over which the reflectance is integrated needs to include this extended spectral range.

3.23
resolution
measure of the ability of a camera system, or a component of a camera system, to depict picture detail

Note 1 to entry: The limiting resolution, visual resolution, e-SFR and s-SFR are examples of resolution measurements.

3.24
SFR10 frequency
Spatial frequency where the SFR value drops to 10 %

3.25
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.

3.25.1
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.

3.25.2
sinewave-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.

3.26
spectrally neutral
exhibiting reflective or transmissive characteristics which are constant over the wavelength range of interest

3.27
test chart
arrangement of *test patterns* (3.28) designed to test particular aspects of an imaging system

3.28
test pattern
specified arrangement of spectral reflectance or transmittance characteristics used in measuring an image quality attribute

3.28.1
bi-tonal pattern
pattern that is *spectrally neutral* (3.26) 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* (3.23) by using the visual resolution method.

3.28.2
hyperbolic wedge test pattern
bi-tonal pattern (3.28.1) that varies continuously and linearly with spatial frequency

Note 1 to entry: A bi-tonal hyperbolic wedge test pattern is used to measure *resolution* (3.23) by using the visual resolution method in this document.

3.29
vertical resolution
resolution (3.23) 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

3.30
visual resolution
spatial frequency at which all of the individual black and white lines of a *test pattern* (3.28) 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.

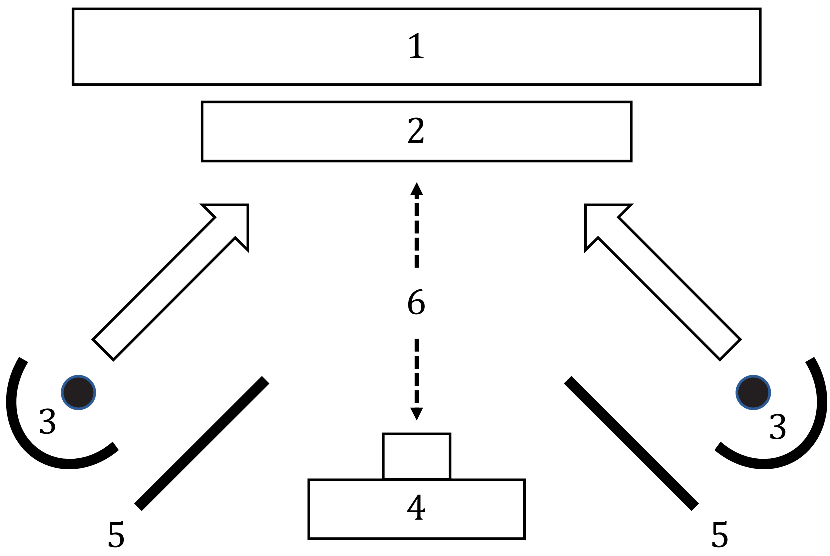
3.31
sampled imaging system
imaging system or device which generates an image signal by sampling an image at an array of discrete points, or along a set of discrete lines, rather than a continuum of points

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

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 (Key item 2) shall be uniformly illuminated as shown in Figure 1, so that the illuminance at any position within the chart is within ±10 % of the illuminance in the centre of the chart. The illumination sources (Key item 3) should be baffled (Key item 5) to prevent direct illumination of the camera lens by the illumination sources. The area surrounding the test chart (Key item 1) should be of low reflectance to minimize flare light. The test chart should be shielded from any reflected light. The illuminated test chart shall be effectively spectrally neutral within the visible wavelengths.



Key

1 matte black wall or black surround
2 test chart
3 illumination sources
4 electronic still picture camera
5 baffles to prevent direct illumination of the camera lens
6 distance is adjusted to frame test chart

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 test chart 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.

Most cameras 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 settings 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.

Some cameras include adaptive tone mapping, which means that different parts of the image may have different OECFs (opto-electronic conversion functions). Because the use of adaptive tone mapping might affect resolution measurements, it should be turned off, if possible, when performing resolution measurements. Since adaptive tone mapping is often used when the camera operates in HDR (high dynamic range) mode, the HDR mode should be turned off, if possible, when performing resolution measurements.

Multiple SFR measurements may 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. See ISO 12232 (Reference [2]) for the luminance signal calculation. Colour-filtered resolution measurements can be performed as described in informative Annex G.

4.7 Gamma correction

The signal representing the image from the 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 might 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 formula. The measurement of the OECF shall be as specified in ISO 14524, using OECF patches integrated on the resolution test chart (as shown in Figures 4a, 4b, and 6) or using the standard reflection camera OECF test chart specified in ISO 14524.

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 described 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.