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Digital cameras — Resolution and spatial frequency responses

Caméras numériques — Résolution et réponses en fréquence spatiale

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ISO copyright office
CP 401 • Ch. de Blandonnet 8
CH-1214 Vernier, Geneva
Phone: +41 22 749 01 11
Email: copyright@iso.org
Website: www.iso.org

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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 document 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).

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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 fifth edition cancels and replaces the fourth edition (ISO 12233:2023), which was revised.

The main changes are as follows:

— The subtitle of Annex D has been corrected to state that Annex D is normative (since it was erroneously listed as informative in the 4th edition), and the reference to Annex D in 6.1 has been clarified to state that Annex D shall be used to implement the e-SFR algorithm.

— In Annex D, the name of the function “OECF” in Formula (D.1) has been changed to “inverse OECF”, and the description of the equation has been clarified.

— The term “electronic still picture imaging” in the title and the term “electronic still-picture cameras” in the scope have been changed to “digital cameras”, to match current industry terminology.

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

0.1 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 [15]. This document defines terminology, test charts, and test methods for performing resolution measurements for digital cameras.

0.2 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 [2] and [4]). 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. In the fourth edition, the test chart used for the e-SFR measurement was updated, 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 a digital camera, such as the lens.

The measurements described in this document are performed using digital analysis techniques.

0.3 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. In the fourth edition, the edge feature was further modified 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 [15].

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 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 [19].

Digital cameras — Resolution and spatial frequency responses

1 Scope

This document specifies methods for measuring the resolution and the spatial frequency response (SFR) of digital cameras. It is applicable to the measurement of both monochrome and colour cameras which output digital data.

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:

— 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
digital camera
device which incorporates an *image sensor* (3.11) and produces a digital signal representing a picture

Note 1 to entry: A digital camera is typically a portable, hand-held device. The digital signal is usually recorded on a removable or an internal memory.

3.5
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

3.6
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.

3.7
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 logarithm (base 10) of 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 *digital cameras* (3.4) 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[4].

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[2]. Because *digital cameras* (3.4) 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.

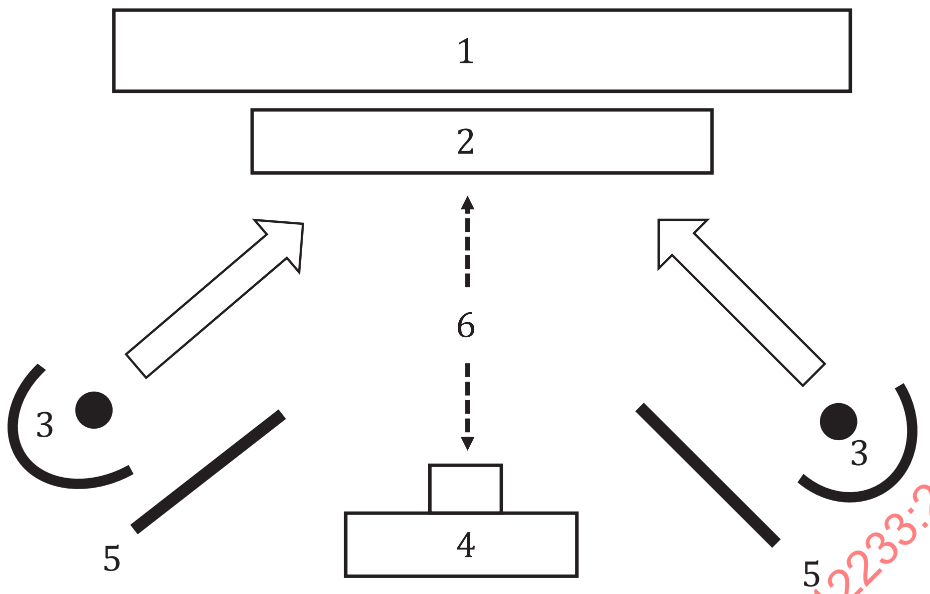
3.31
sampled imaging system
imaging system or device which generates an image signal by sampling an image at an array of discrete points, or along a set of discrete lines, rather than a continuum of points

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 digital 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 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 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.

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 a digital 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 may 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.

5.2.5 Test pattern modulation

For reflective charts, the ratio of the maximum chart reflectance, R_{max}, to the minimum chart reflectance, R_{min}, for large test pattern areas should be not less than 40:1 and not greater than 80:1 and shall be reported if it is outside this range. For transmissive charts, the ratio of the maximum chart transmittance, T_{max}, to the minimum chart transmittance, T_{min}, for a large test pattern should be not less than 40:1 and not greater than 80:1 and shall be reported if it is outside this range. For a paper base optical density of 0,10, these minimum and maximum numbers translate to optical densities of 1,7 and 2,0, respectively. Modulation ratios for the finer test chart features, relative to the ratio for large test pattern areas, should preferably be reported by the chart manufacturer for reference.

NOTE The decimal sign is a comma in ISO standards.

5.2.6 Positional tolerance

The position of any test chart feature shall be reproduced with a tolerance of ±1/1 000 picture heights (equivalent to ±1/10 % of the active test chart height). In addition, the width and duty cycle ratio of each feature (white or black line) of the wedge pattern shall be reproduced with a tolerance of ±5 % of the feature width.

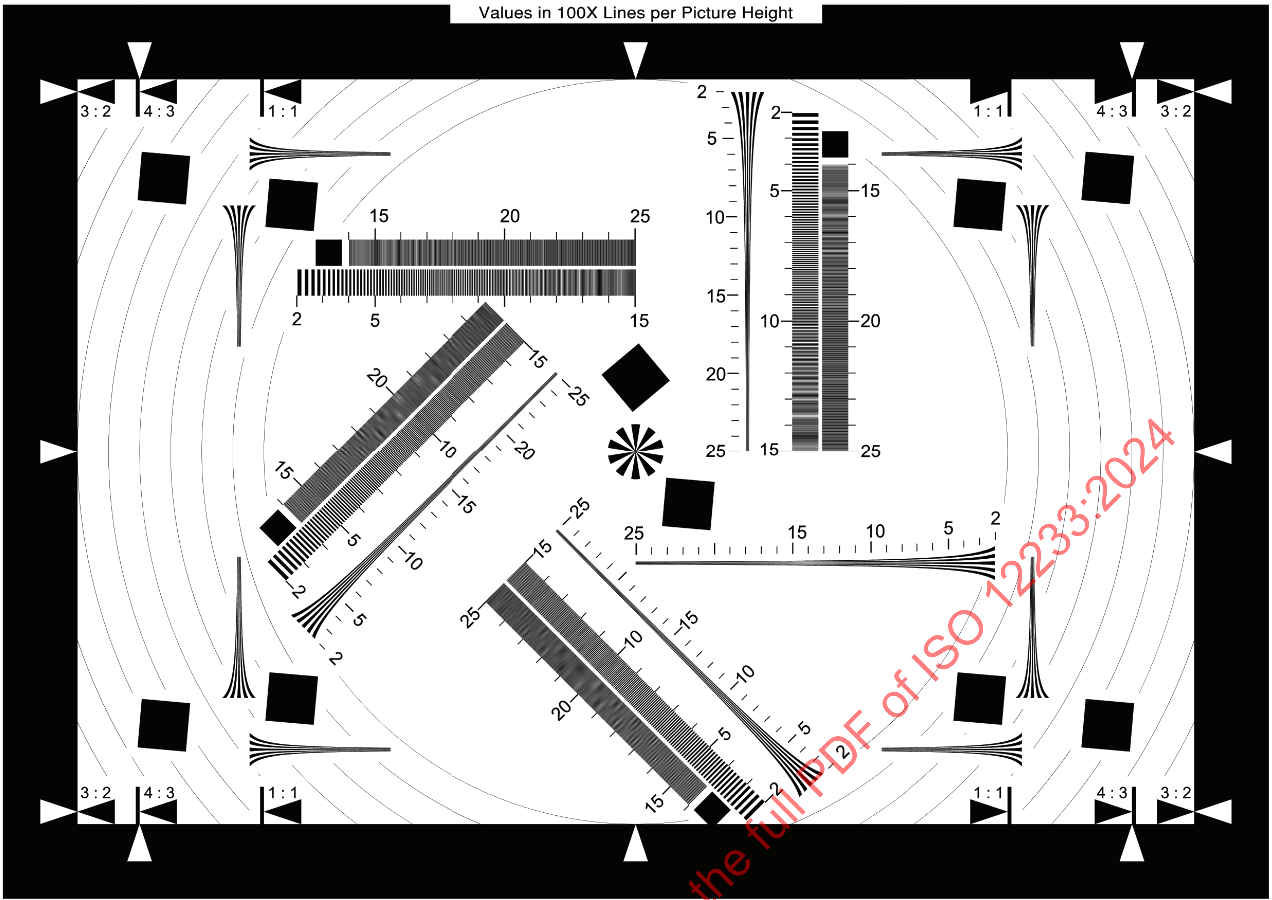


Figure 2 — CIPA resolution chart

5.3 Rules of judgement for visual observation

5.3.1 Rules of judgement

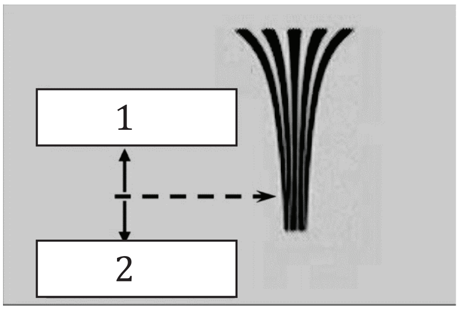
The viewer shall observe the following rules when judging the resolution value. These rules are intended to achieve a correct measurement value in the presence of unavoidable aliasing artefacts.

a) Beginning from the low frequency side, treat a spatial frequency as “Resolved” only when all lower spatial frequencies are also resolved. The resolution limit is achieved at the line just before the first occurrence of unresolved line features.

b) Treat a spatial frequency as “Not resolved” when the black and white lines appear to change polarity or lines are blurred together to produce a reduced number of lines, compared to the number in the test chart.

5.3.2 Example of a correct visual judgement

As shown in Figure 3, the boundary between the resolved (Key item 1) and not resolved (Key item 2) regions is indicated by a dashed arrow, which corresponds to resolution value to be measured.



Key

1 five black lines

2 less lines

Figure 3 — Correct application of the wedge feature interpretation

6 Edge-based spatial frequency response (e-SFR)

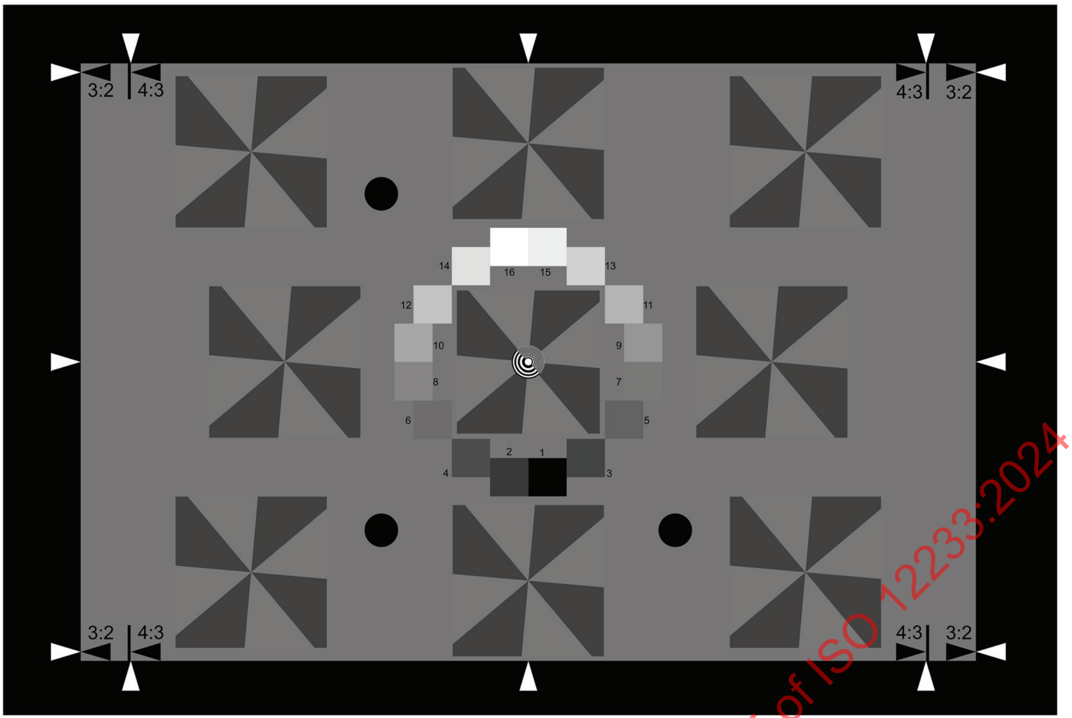
6.1 General

The edge-based spatial frequency response (e-SFR) of a digital camera is measured by analysing the camera data near slanted low contrast neutral edges, using a test chart having four-cycle “slanted star” test patterns. The “slanted star” test patterns permit the e-SFR to be measured in the vertical, horizontal, and diagonal directions.

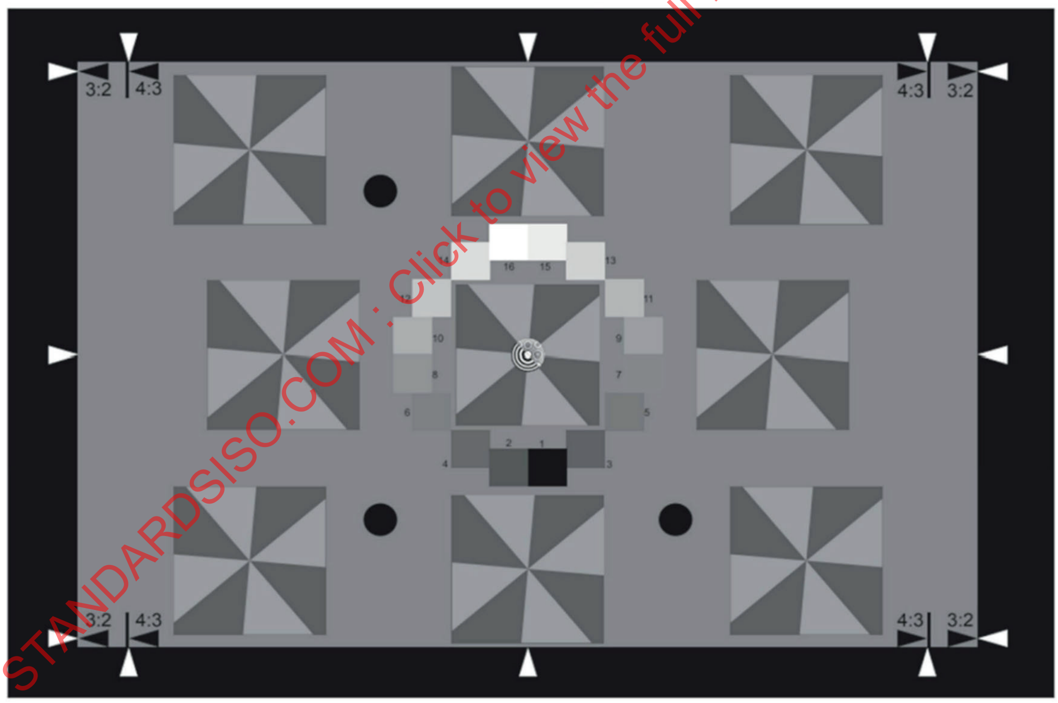
The preferred test chart for measuring e-SFR is shown in Figure 4 a) and specified in Annex C. It includes four-cycle “slanted star” test patterns having a 4:1 reflectance ratio between the bright and dark portions, with the bright portions having the same reflectance as the test chart background. As a result, the slanted edges used to perform the measurements have the same 4:1 reflectance ratio (and reflectance values) as the slanted squares used in the 2nd and 3rd editions of ISO 12233. This allows the measurements performed using this 4th edition to be directly compared to the results from these earlier editions.

The e-SFR measurements may optionally be performed using a test chart with “slanted star” test patterns having a reflectance ratio which is greater than 4:1, but less than or equal to 10:1. Figure 4 b) is an example of such a test chart, and depicts a reflectance ratio of approximately 6:1. The larger reflectance ratio can reduce the influence of noise on the e-SFR measurement, but is more likely to be influenced by non-linear signal processing in the camera. When e-SFR measurements are performed using a test chart having a reflectance ratio greater than 4:1, the reflectance ratio shall be reported along with the test results.

NOTE Attention is drawn to the possibility of overstating the measured e-SFR values due to data clipping when using a test chart having a large reflectance ratio and/or when the captured image of the test chart is significantly overexposed. See the Introduction for additional information.



a) e-SFR test chart with 4:1 edge reflectance ratio

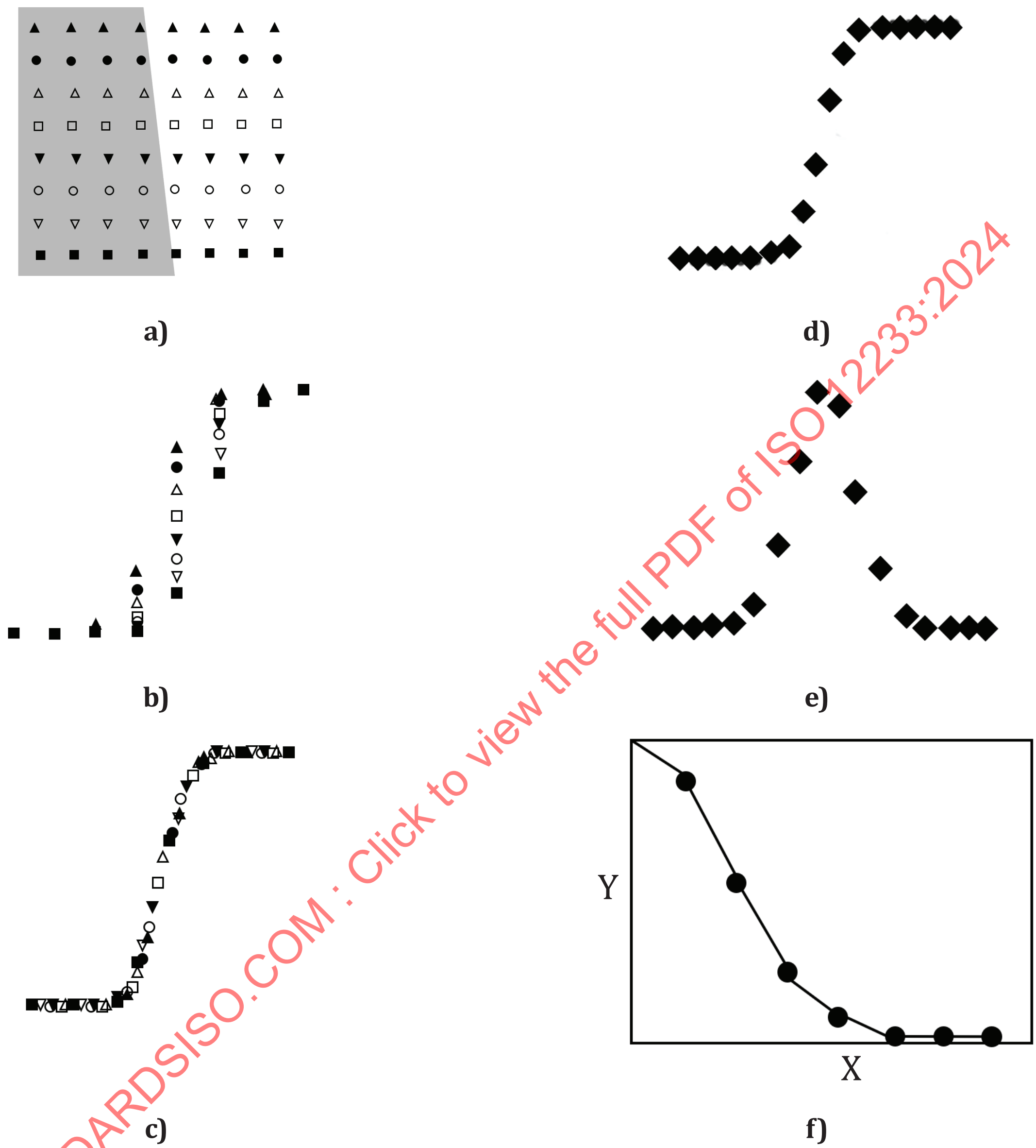


b) e-SFR test chart with 6:1 edge reflectance ratio

Figure 4 — e-SFR test charts

The e-SFR measurement includes the capture of a digital image of the test chart and analysis of the contents of the image file by a software program. This software can be accessed from www.iso.org/12233. The e-SFR algorithm shall be implemented as described in Annex D, and example source code for computing the e-SFR is provided in Annex M.

A diagram depicting some of the key aspects of the current e-SFR algorithm is shown in Figure 5 a) to f). See Reference [16]. Figure 5 a) shows how the pixel values of a small region of interest (ROI) window containing a slanted edge are sampled by the image sensor. The slight slant in the edge causes the position of the edge to be displaced slightly between each row of image samples. Figure 5 b) shows the resulting edge profiles of each row.



Key

X spatial frequency

Y e-SFR values

Figure 5 — Key aspects of the e-SFR algorithm

The ROI shall be square or rectangular (i.e., having vertically and horizontally oriented sides, not slanted sides) and should have between 100 pixels and 400 pixels on a side. Other sizes may be used, in which case the size of the ROI shall be reported.

The location of the edge is then estimated for each row in the window, and these locations are used to estimate the edge direction and position using a polynomial fit to the edge. The positions of each row of samples are adjusted using this polynomial fit, to compensate for the position of the edge for each row, yielding an oversampled edge profile, as shown in Figure 5 c). A 5th order polynomial should be used, although any other lower order polynomial (e.g. a 1st order linear fit) may be used instead, in which case the polynomial order shall be reported along with the measurement results.

NOTE Earlier versions of ISO 12233 used a linear fit to the edge. Tests have shown that in cases of significant geometric distortion, a higher order polynomial fit provides better results than a linear fit for typical ROI (region of interest) sizes, by compensating for this distortion. See Reference [10].

The oversampled edge profile is then "binned", by averaging the edge values within ¼ pixel size bins, to provide a 4x super-sampled edge profile, as shown in Figure 5 d). See Reference [17].

The derivative of this super-sampled edge is calculated using a finite difference filter to obtain the line spread function, as shown in Figure 5 e). The discrete Fourier transform of the line spread function is calculated, and the e-SFR value (Key item Y) at each spatial frequency (Key item X) is equal to the absolute value of the transform after correcting for the frequency response of the finite difference filter, as shown in Figure 5 f).

6.2 Methodology

The algorithm defined in Annex D can automatically compute the e-SFR, using image data from a user-defined rectangular region of the image which represents a near-vertically, near-diagonally, or near-horizontally oriented dark to light or light to dark edge.

The algorithm is described assuming a near-vertical edge. To measure near-horizontal edges, the selected edge image data are rotated 90° before performing the calculation. Note that a near vertical edge is used to measure a horizontal e-SFR, since the e-SFR is a measure of the image transition across the edge, rather than along it. Likewise, a near horizontal edge is used to measure the vertical e-SFR. Near diagonal edges are used to measure the diagonal e-SFR.

As an additional option, the effects of non-uniformity due to illumination shading or lens vignetting can be compensated using the method described in Annex J. However, the e-SFR results without non-uniformity compensation shall also be reported, along with the e-SFR results obtained using non-uniformity correction.

See References [6], [8] and [9] for supplementary information on the e-SFR method.

7 Sinewave-based spatial frequency response (s-SFR) measurement

The sinewave-based spatial frequency response (s-SFR) of a digital camera is measured by analysing the camera image taken of a sine wave-modulated starburst pattern, as described in Reference [13]. The test chart for measuring the s-SFR is shown in Figure 6 and is specified in normative Annex E.

An executable version of software has been developed to perform measurements using this test chart. The software, which was created using Matlab®[1)], can be accessed from www.iso.org/12233.

The software can report the results from a single image or can average the results from numerous images. The star is divided into a user-selected number of segments (typically eight segments) for analysis. The user selects the area of the captured image that contains the chart. The Siemens star is surrounded by 16 grey patches used to linearize the image code values by inverting the opto-electronic conversion function (OECF) of the camera. The posted software requires the lightest patch to be in the upper right corner. The result shows the modulation versus frequency [in line pairs/picture height (LP/PH)] for each of the segments.

The s-SFR algorithm that shall be used to perform the s-SFR measurements is specified in Annex F.

1) Matlab is an example of a suitable product available commercially. This information is given for the convenience of users of this document and does not constitute an endorsement by ISO of this product.

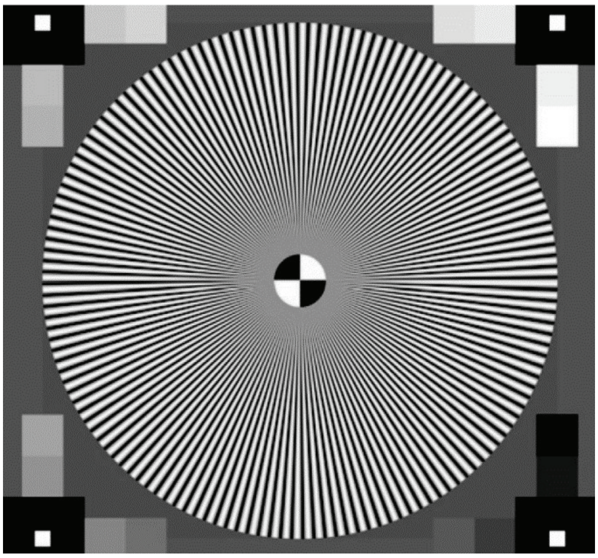


Figure 6 — Sine-based SFR test chart

8 Presentation of results

8.1 General

The results of the resolution and SFR measurements shall be reported as described below. The following information should be reported along with the measurement results:

a) the values of all camera settings that might affect the results of the measurement, including the sharpness setting, lens focal length and aperture, and resolution or compression mode (if adjustable);

b) whether dark-field and/or flat-field correction was used;

c) the illuminating source colour temperature and illumination level;

d) for cameras equipped with interchangeable lenses, the type and characteristics of the lens used in the tests.

If the effect of the lens and the test target can be mathematically removed by using their modulation data (*i.e.*, if the calculated response data is the same for any interchangeable lens), the calculated camera SFR measurements without a lens may also be reported.

The calculation of an acutance value from the e-SFR or the s-SFR data is described in Annex L. This acutance value can also be reported.

NOTE 1 Conversion between commonly used units is described in informative Annex H.

NOTE 2 While reporting all of the above conditions is important for full technical reports, it can make the data collection and reporting complex. Abridged reporting of the capture conditions is acceptable and often preferable for catalogue or casual user information.

8.2 Resolution

8.2.1 General

The resolution values acquired using the visual resolution measurement shall be reported as spatial frequency values, in LW/PH.

The SFR10 frequency value derived from the SFR as the spatial frequency value for a given (i.e. 10 %) modulation level (see 8.3.1) may also be used as the summary resolution metric, as long as it is consistent with the visual resolution.

The resolution value shall be measured for at least the four basic directions of horizontal, vertical, +45°, and −45° for the presentation of results, and the manner of presentation shall be selected as follows.

8.2.2 Basic presentation

The resolution value of each measuring direction shall be reported with its direction for all measured directions.

8.2.3 Representative presentation

The minimum resolution value for all measured directions shall be reported without its direction.

The average resolution value may be reported as a representative value additionally if each of the minimum (with its direction, mentioned above) and average is clearly specified.

8.3 Spatial frequency response (SFR)

8.3.1 General

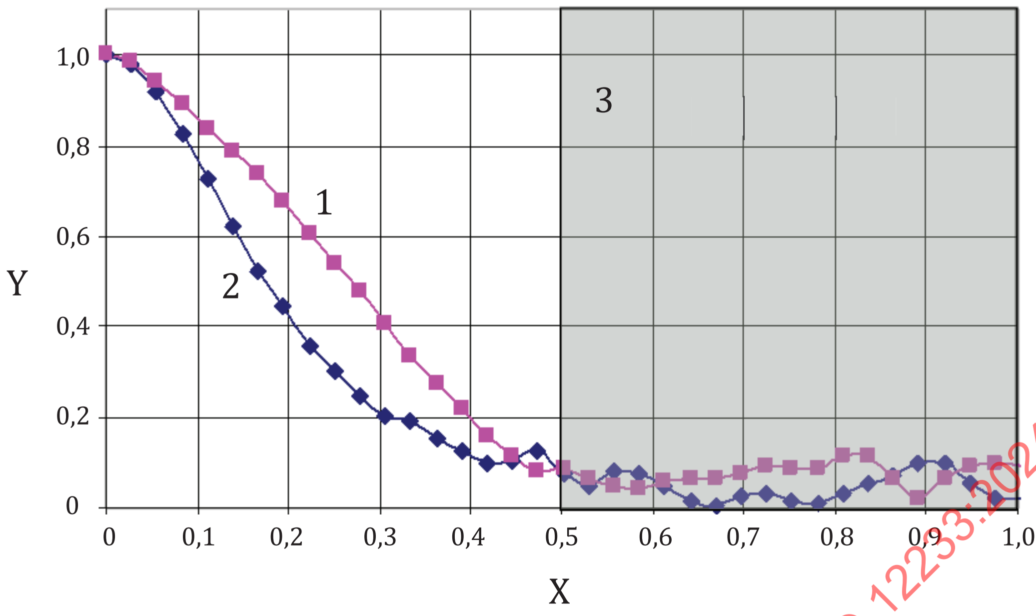
The SFR result is reported as the modulation level of each spatial frequency. It may also be reported as the frequency value associated with a given modulation level. It shall be reported using a graph plot as shown in Figure 7 or using a chart diagram.

Summary resolution metrics derived from the SFR may also be reported. Depending on the use case, the spatial frequency associated with selected SFR response levels (ordinate value) may also be reported. The SFR criterion levels and SFR methodology used shall also be reported in this case. See References [15] and [19] for comparisons of SFR results between the two methods.

8.3.2 Spatial frequency response

The SFR results shall be reported using a graph plotting the modulation level (having a value of 1 at 0 spatial frequency) versus spatial frequency, or in a list of SFR values versus spatial frequency. The SFR values shall be reported separately for the horizontal, diagonal, and vertical directions. The values shall be the average of four replicate SFR measurements of a low contrast slanted edge. The spatial frequency axis should preferably be labelled with one of three units: frequency relative to the sensor sampling frequency (cycles/pixel), line widths per picture height (LW/PH), or cy/mm on the sensor, or with Formulas representing the relationship between these units. There shall be a minimum of 32 equally spaced measurement values for spatial frequencies between 0 and the sensor sampling frequency. The camera half-sampling frequency shall be reported. Values between 1/2 and 1 times the sampling frequency shall be marked to indicate the area of potential aliasing. Figure 7 demonstrates one suitable method of graphically reporting SFR values.

The SFR at angles other than horizontal and vertical positions should also be measured. Typically, tangential and radial direction SFRs are necessary for understanding the influence of the optics on the combined optical and sensor SFR behaviour.



Key

X normalized spatial frequency (cycles/pixel)

Y edge spatial frequency response (e-SFR)

1 horizontal e-SFR

2 vertical e-SFR

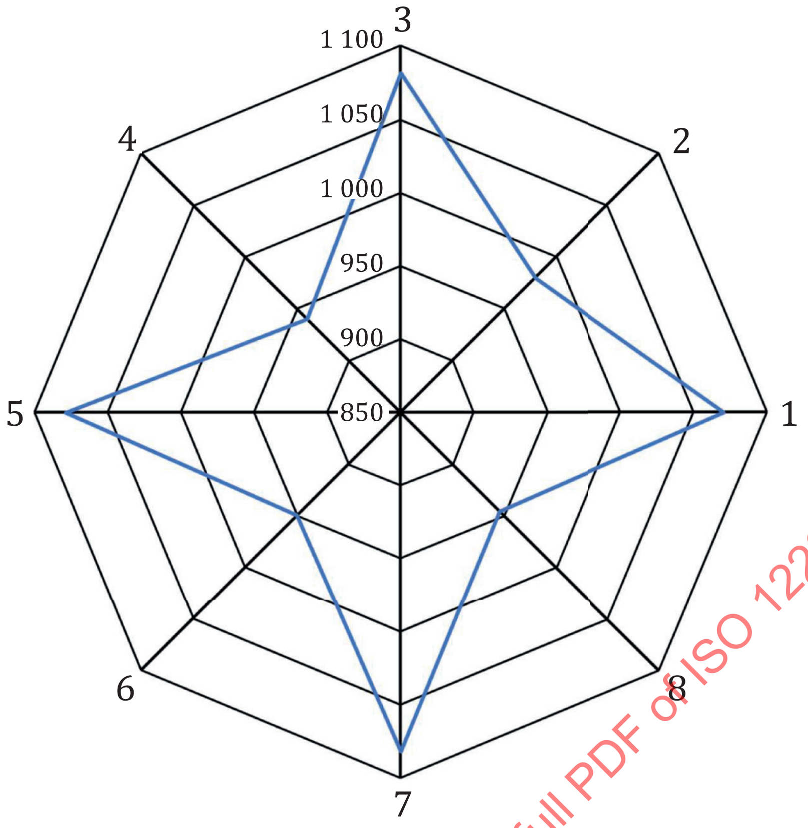
3 aliased region

Figure 7 — Digital camera SFR example plot

NOTE The decimal sign is a comma in ISO standards.

8.3.3 Report of resolution value derived from the s-SFR

The s-SFR values should be reported separately for each measured direction. If the resolution is determined for more than horizontal and vertical orientations, a radar chart diagram is a recommended way to present it. Figure 8 shows an example of a suitable method for reporting the frequency values corresponding to certain modulation levels (e.g. 10 %) in any direction. It indicates the resolution behaviour as a function of angular orientation. Multiple plots may also be graphed on the same chart to show the relationship of differing SFR modulations to one another.



Key

1-8 segment number

Values 850 to 1 100 represent spatial frequency (LW/PH).

NOTE Measurement conditions: lens focal length = 55 mm, lens aperture = f/4, camera compression = off, white balance setting = daylight, dark-field and flat-field correction were not used, 2 000 lx daylight illumination.

Figure 8 — Resolution value derived from the *s-SFR* (e.g. 10 % modulation) measured for different angular orientations

Annex A
(informative)

CIPA resolution chart

A.1 Features of the CIPA resolution chart

The CIPA resolution chart includes the features listed in Table A.1, which are located as shown in Figures A.1 to A.5.

Table A.1 — Description of CIPA resolution chart features

Code	Characteristics and application
A	Black border with inner edge which defines active target area
B	White framing arrows used to frame target vertically
C	Centre pattern used to set focus
D	Framing lines and arrows that define 1:1, 4:3, and 3:2 image aspect ratios
J	200 LW/PH to 2 500 LW/PH hyperbolic zone plates used to measure visual resolution
L	Slightly slanted (~5° or 50°) small black squares used to measure e-SFR
P	200 LW/PH to 2 500 LW/PH square wave sweep
Q	Hyberbolic wedges, used for checking whether the peripheral portions are in focus
S	Concentric circles for reference when other patterns are added

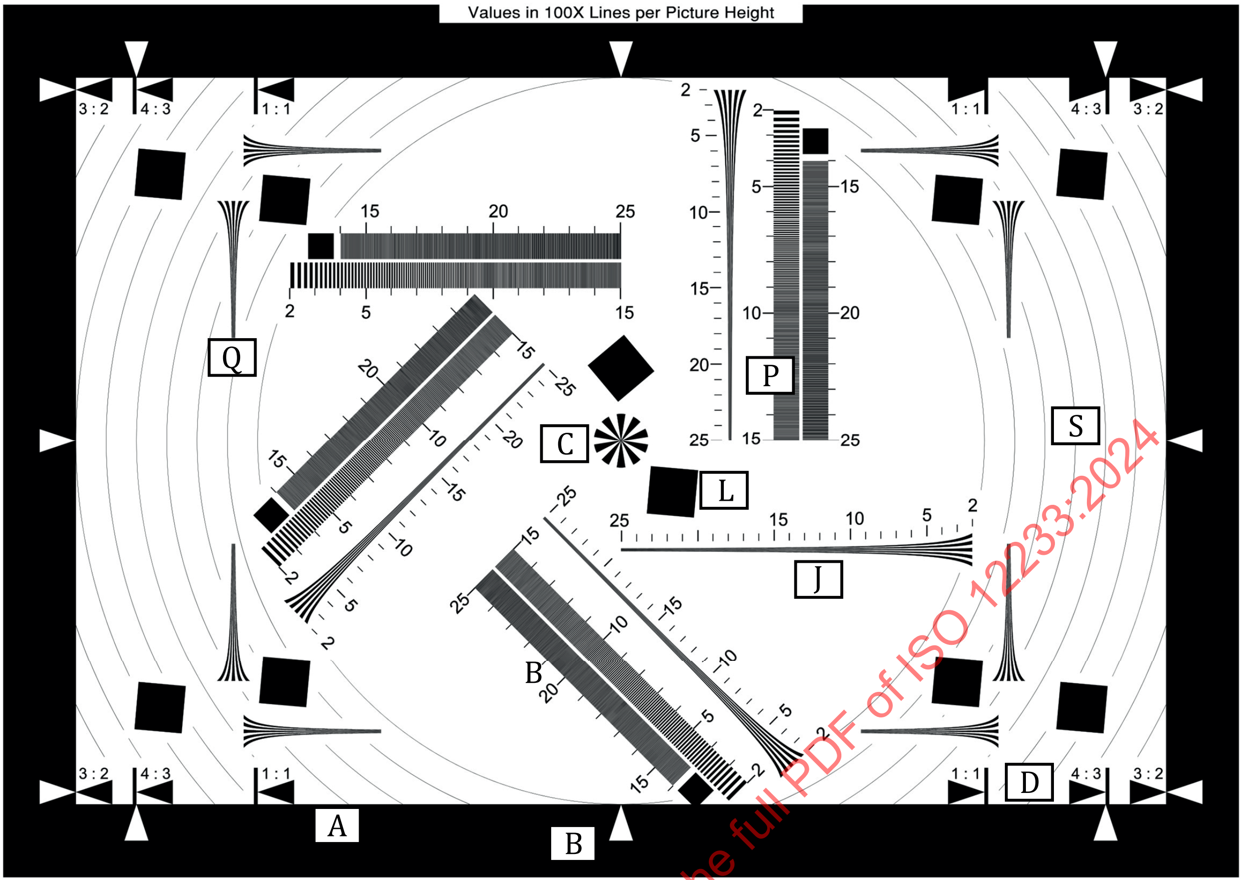


Figure A.1 — Characteristics of the CIPA resolution chart

A.2 Tolerance of the CIPA resolution chart

This chart satisfies the following requirements.

a) The ratio of the maximum chart reflectance, R_{max}, and the minimum chart reflectance R_{min} for large test pattern areas should not be less than 40:1 or greater than 80:1 and shall be reported if it is outside this range.

b) The positional tolerance of the test patterns shall be within 0,2 mm of the specified location (±0,1 % of the image height).

c) The line width tolerance shall be within ±5 %.

d) The reflectance ratio, R_{max}/R_{min}, for the finest features of the hyperbolic patterns J and Q should be 18 or greater.

A.3 Dimensional specification of the CIPA resolution chart

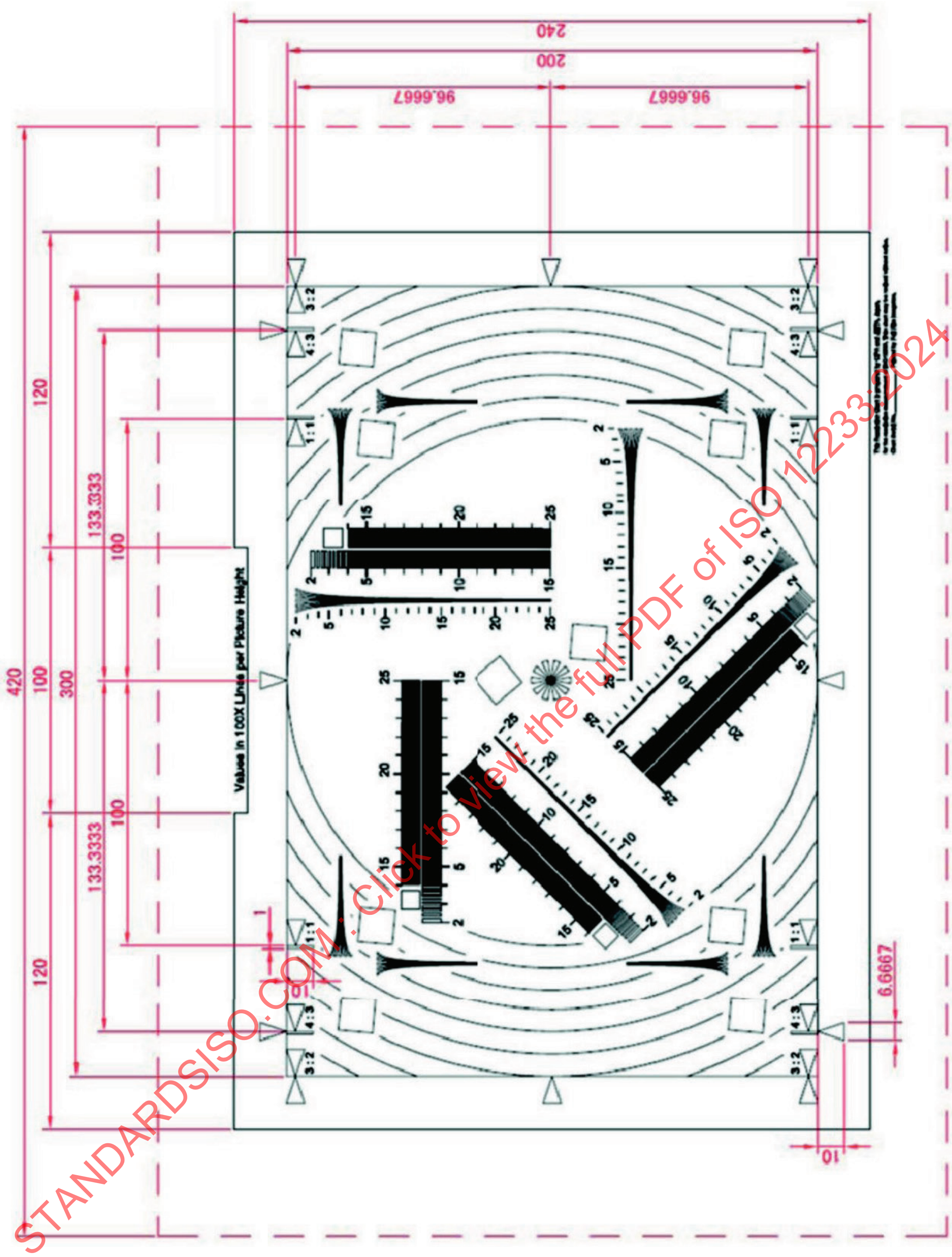


Figure A.2 — Dimensional drawing “A” for CIPA resolution chart

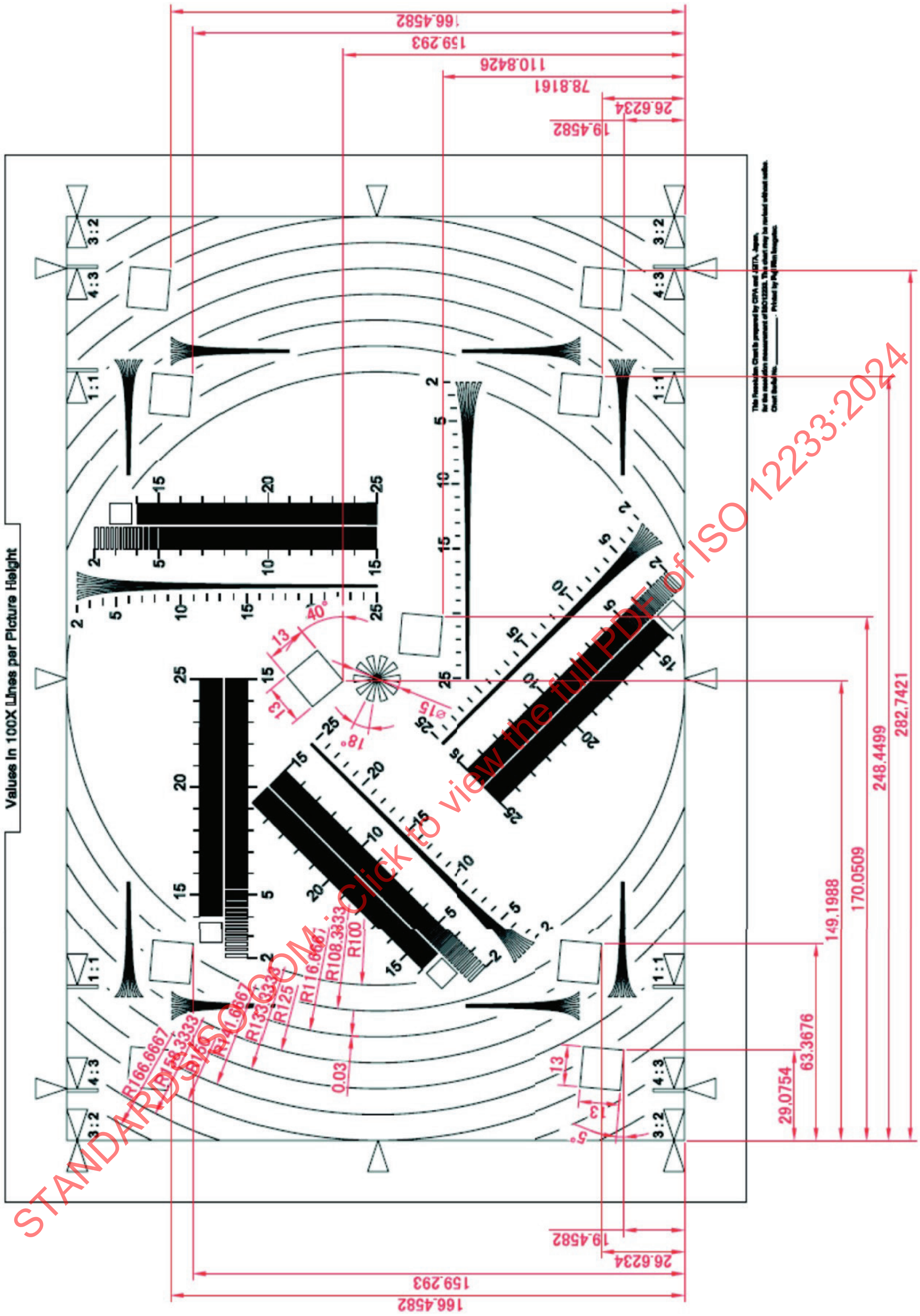


Figure A.3 — Dimensional drawing "B" for CIPA resolution chart

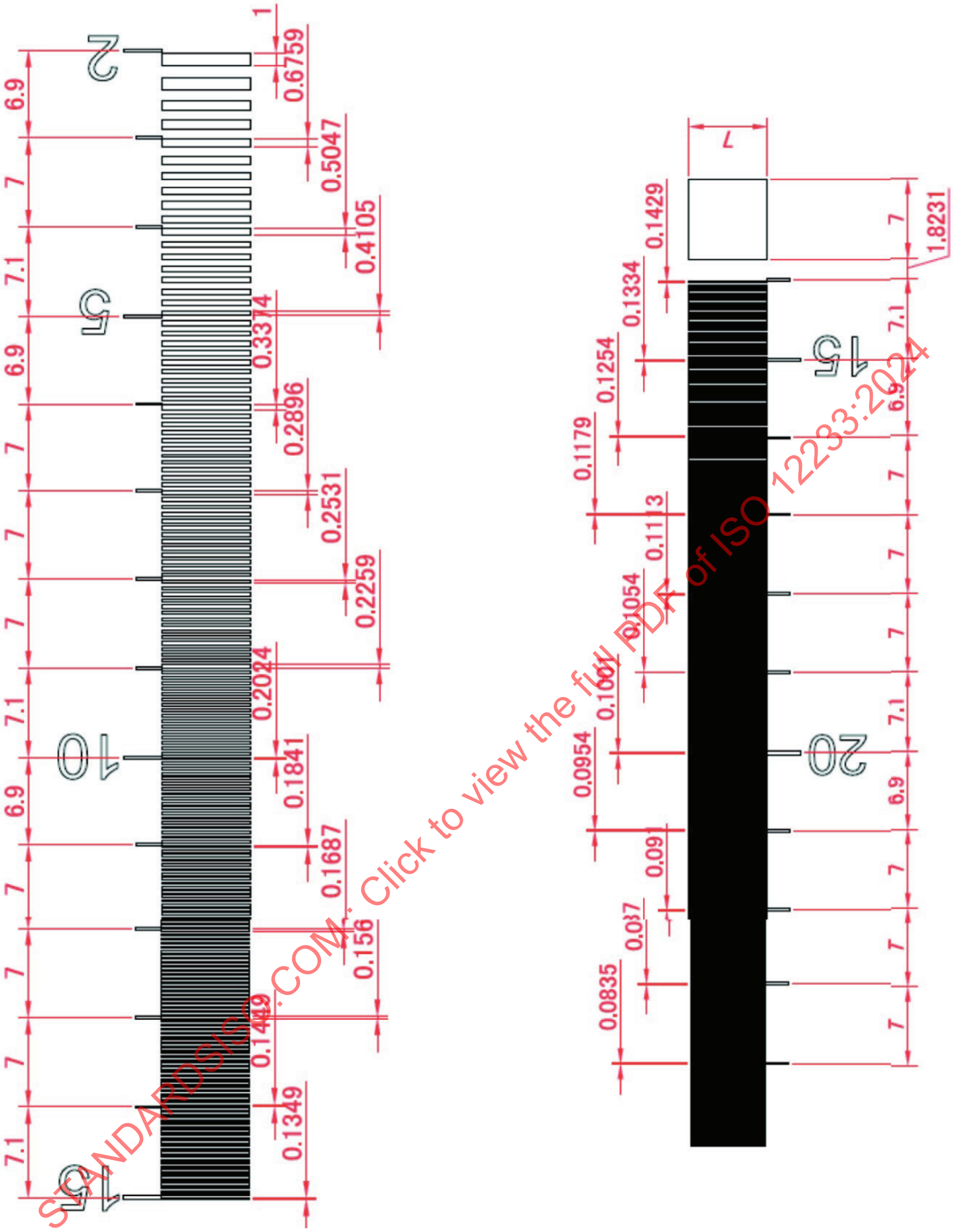


Figure A.4 — Detail drawing for linear frequency sweep

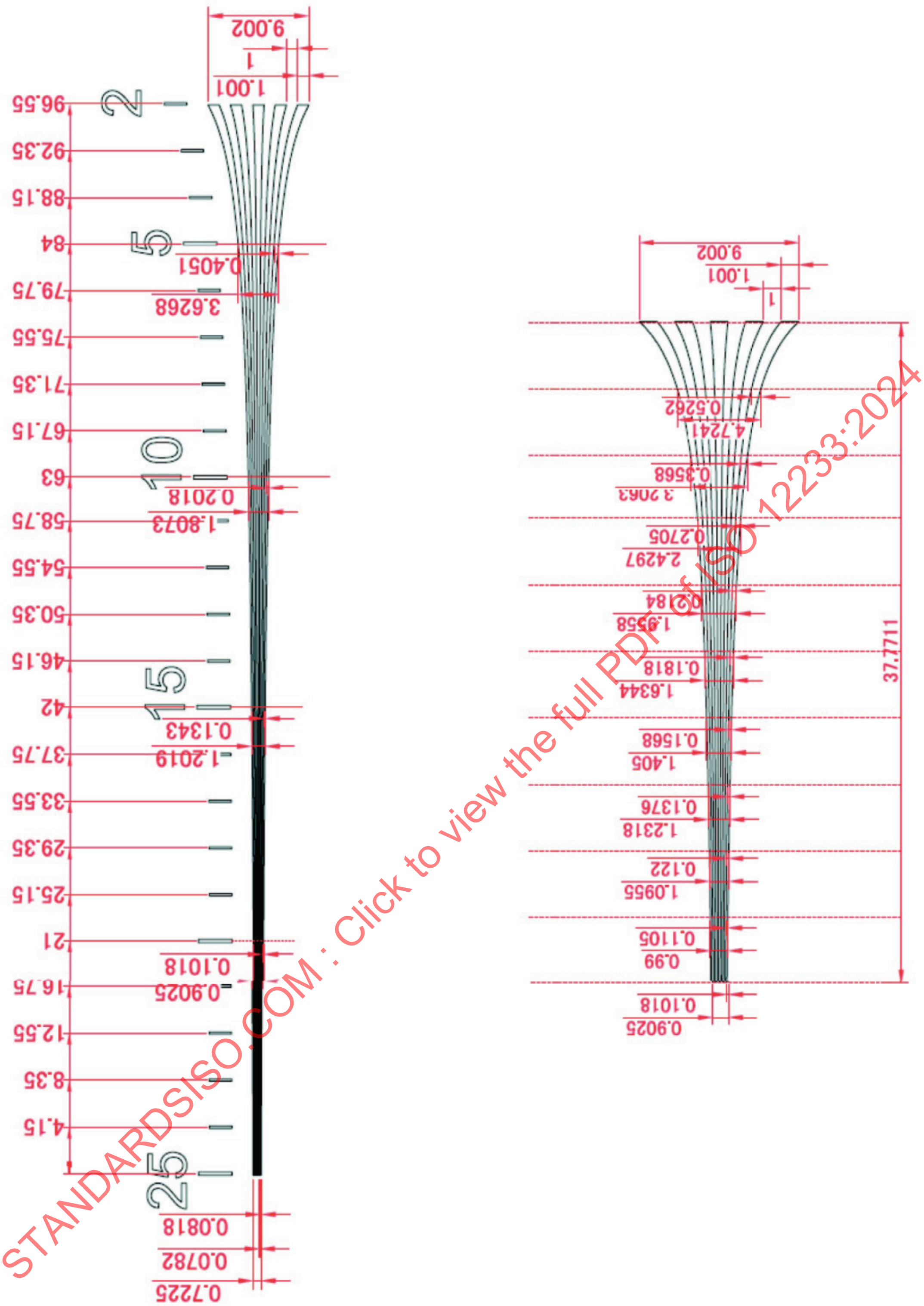


Figure A.5 — Detail drawing for five-line hyperbolic wedge pattern

Annex B
(informative)

Visual resolution measurement software

B.1 Background and purpose

This annex describes the "HYRes"[2] measurement software, which provides measurement results that correlate well with visual resolution measurements, while avoiding some of the problems of using visual observations. It is also automatic, highly repeatable, and does not depend on an image display device. It supports both JPEG and BMP image file formats. HYRes is available only in the English language.

HYRes also avoids visual observation errors due to aliasing, by determining when the number of lines in the captured image of a resolution wedge decreases below that in the test chart. Once this condition occurs, the spatial frequency is considered to be "not resolved". In other words, the measurement software uses the same judging rules as described in 5.3 to remove the influence of artefacts.

HYRes was upgraded to HYRes IV (integrated version) for the 4th edition of this document. Each newer version of HYRes has some additional functions and/or user interface improvements, but the measurement algorithm has not been changed in any way. Therefore, each version provides the same measurement results.

In this annex, when HYRes is described without specifying a specific version, the description applies to all HYRes versions, including HYRes IV and all earlier versions.

B.2 Downloading the software

HYRes software that performs this measurement can be downloaded (at no cost) from the following URL:

https://www.cipa.jp/dcs/hyres/hyres_dl_e.html

Reference [5], "CIPA DC-003-Translation-2020 Resolution Measurement Methods for Digital Cameras", contains a more detailed description of the HYRes software algorithm, and can be downloaded (at no cost) from the following URL:

https://www.cipa.jp/e/std/std-sec.html

CIPA DC-003 includes several annexes describing HYRes (specifically, HYRes3.1, which was the first publicly released version of HYRes) and includes a flowchart that completely describes the corresponding source code. There is also an annex that describes the experiment and results used to validate HYRes. The objective results provided by the HYRes software were in good agreement with judged visual resolution by human observers.

B.3 Measurement procedure

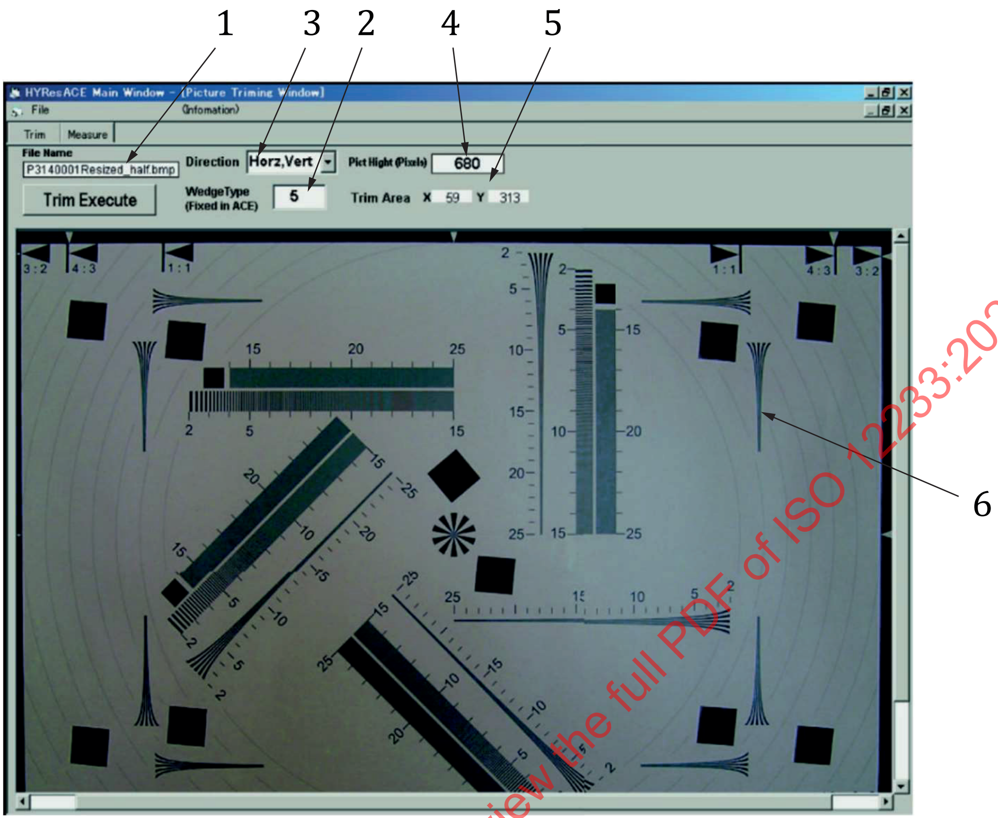
The following is a step-by-step description of the visual resolution measurement procedure.

The description in this subclause, and Figures B.1 to B.3 below, depict HYRes ACE, which is the previous version of HYRes. HYRes IV is the integrated version with several operating modes, including a mode that is equivalent to HYRes ACE.

a) Capture a digital image of the visual resolution test chart shown in Figure 1 under the test conditions specified in Clause 4.

2) HYRes is an example of a suitable product available commercially. This information is given for the convenience of users of this document and does not constitute an endorsement by ISO of this product.

b) Read in the image file to the HYResACE software in the image trimming mode. Manually select the type of wedge (the black line number of the wedge, etc.) to be measured. Then, define the rectangular region of interest (ROI) which includes the wedge pattern from this test chart image by using the image trimming function of HYResACE, as shown in Figure B.1.



Key

1 file name

2 wedge type

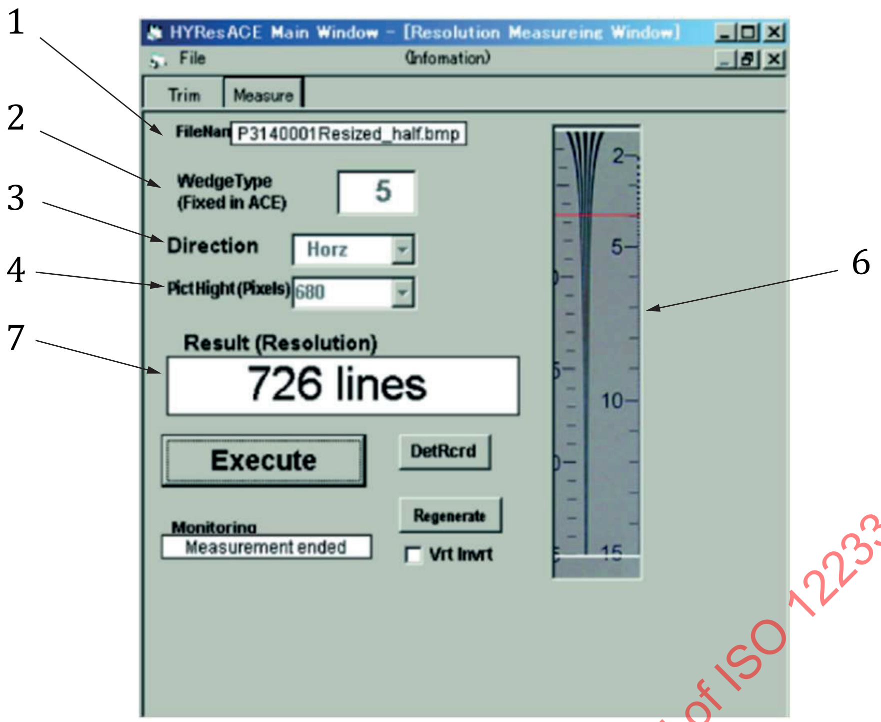
3 direction

4 picture height (pixels)

5 trim area (defines region of interest)

6 wedge measured

Figure B.1 — Trimming window of HYResACE



Key

1 file name
2 wedge type
3 direction
4 picture height (pixels)
6 wedge measured
7 result (visual resolution)

Figure B.2 — Measuring window of HYResACE

c) HYResACE automatically opens the “Measuring window”, which is a mode for calculating the visual resolution, and displays the selected ROI. The visual resolution limit is then calculated, and the measured value is displayed when the operator clicks the “Execute” button, as shown in Figure B.2.

d) HYResACE measures the visual resolution in four directions: horizontal, vertical, +45°, and −45°. The user only needs to specify the direction of the wedge when executing the image trimming process, as shown in Figure B.3.

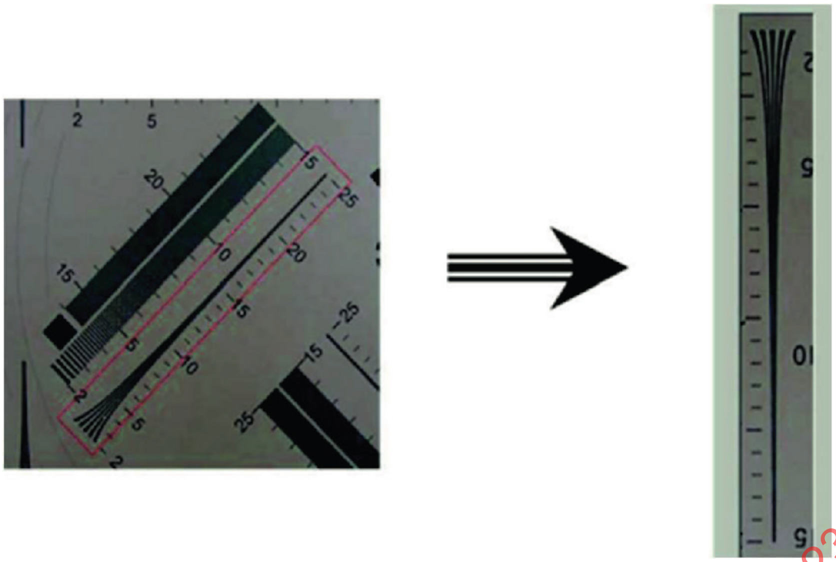


Figure B.3 — Example of automatic rotation (the case of 45° multiple rotation)

B.4 The outline of the software processing

B.4.1 Main process

HYRes detects the length of the wedge from the selected ROI and the position of the visual resolution limit line on the wedge in integer pixel units. To find these, a subprocess named "black line detection", described below, is applied to each scan line sequentially. "Black line detection" is a process which simulates human visual perception of the wedge pattern.

NOTE This "line" is a horizontal raster scan line, not a black or white line of the wedge.

The reported visual resolution is easily calculated by taking the ratio of the calculated position of the resolution limit line to the overall wedge length. The correct absolute value is calculated by correcting the ratio to the actual magnification by using the wedge length and the image height (vertical pixel number) data of the original image before trimming. In this way, the magnification of the process is not required.

B.4.2 Black line detection

One's ability to visually distinguish white spaces from the black lines of the hyperbolic resolution wedges in Figure B.1 relies on sophisticated and complex processing in the visual cortex. This processing accommodates and adapts to low frequency luminance differences and treats them as though they are effectively uniform. For example, in the high frequency regions of the wedge, near the visual resolution limit, the signal amplitude becomes very small, and any local amplitude change in luminance at the black/white lines can be smaller than the changes in luminance at lower frequencies across the entire wedge due to the spatial frequency behaviours of the camera and/or light shading and falloff. In such cases, there is a possibility that the minimum luminance value of a pixel on a black line is greater than the value of a pixel on a white line. This could be due to either stochastic noise or shading effects. Regardless, human vision will still distinguish the black and white lines of the wedge in response to their actual line luminance changes without being affected by changes unrelated to the line detection task at hand.

Also, in the low frequency range of the wedge, sharpening effects can often introduce "ringing" near the black/white edges that are interpreted as luminance changes. Often, such localized changes in luminance are much larger than the amplitude of the wedge image near the high frequency portion where the visual resolution limit is measured. In such cases, as long as the amplitude due to ringing is sufficiently small compared to the luminance amplitude of the wedge image at the low frequencies, human perception will filter and ignore it. In addition, human vision often ignores other noise sources (e.g. stochastic noise, etc.) in the image when they are sufficiently small. In summary, human vision often ignores luminance changes due to low and high frequency noise when a particular task, like line detection, is required. It is as though a spatially matched filter is imposed that allows the viewer to ignore absolute luminance changes that are irrelevant to the task at hand, namely line detection. The black line detection algorithm is able to simulate this process.

It does so in two important ways.

a) Detection of a black line at a locally minimum point in the scanning line is done by inflection point detection through analysis of neighbouring point differences.

b) Significant signal differences are judged based on a variable threshold technique that is line frequency adaptive.

At the start of the algorithm's line scanning process, a suitably high threshold level is chosen to accommodate the relatively large signal levels of the low frequency portions of the wedge. This threshold is decremented as higher frequency lines are probed in an attempt to detect the specified number of black lines (i.e. five). After the specified number of black lines is detected, the process continues onto the next scan lines until all five lines can no longer be detected using the same threshold level. At this point, the threshold level is decremented and the scan line under consideration is again analysed with the new threshold. If all five lines can still not be detected with this new threshold, the processing ceases and the visual resolution limit is reached.

B.4.3 Image rotation process

HYRes operates on the data assuming that the main scanning direction crosses a hyperbolic wedge perpendicularly. In other words, the basic measurement process operates on the horizontal resolution wedge. The vertical resolution and 45° slanted resolution measurements are performed by rotating the captured wedge images before performing the measurement.

The 90° rotation is a simple coordinate change and does not apply interpolation to generate new pixel values. Nearest neighbour interpolation is applied to fill vacant pixels with existing pixel values without creating new numerical values for the 45° (or its multiple) rotation. This is shown in Figures B.4 and B.5.

Because a 45° rotation increases the relative size of the image (as shown in Figure B.5), compensation for this factor is necessary in calculating resolution. HYRes automatically compensates for this factor as required.

5	10	15	20	25
4	9	14	19	24
3	8	13	18	23
3	7	12	17	22
1	6	11	16	21

Figure B.4 — Arrangement before 45° rotation

				5				
			4	5	10			
		3	4	9	10	15		
	2	3	8	9	14	15	20	
1	2	7	8	13	14	19	20	25
1	6	7	12	13	18	19	24	25
	6	11	12	17	18	23	24	
		11	16	17	22	23		
			16	21	22			
				21				

Figure B.5 — Pixel arrangement after a 45° clockwise rotation of Figure B.4

Annex C
(informative)

Edge SFR test chart

The features of the e-SFR test chart are shown in Figure C.1 and defined in Table C.1. The e-SFR test chart is a grey scale test chart which includes low modulation "four-cycle slanted star" test patterns, which replace the low modulation "slanted square" test patterns used in ISO 12233:2014 and ISO 12233:2017. The origin of this "slanted star" test pattern is described in Reference [14]. The test chart also includes grey scale patches which are used to determine the OECF. While the example test chart in Figure C.1 uses 16 OECF test patches, a 20-patch version described in ISO 14524 may be used instead.

This lower contrast SFR test chart design is based on experiences with the ISO 12233:2000 test chart shown in Figure I.1. The high contrast edges of the ISO 12233:2000 test chart often yielded clipped count values in the final image file, especially for highly processed image files. This led to corrupted or variable SFR results. The lack of OECF patches in the original test chart also made it inconvenient to account for the OECF response without a separate image capture using an OECF test chart.

NOTE Figure C.1 depicts a test chart with "slanted star" test patterns having a reflectance ratio of approximately 6:1, in order to show the bright portions of the "slanted star" test patterns. However, for the preferred test chart the bright portion of the "slanted star" test patterns has the same reflectance as the background, and the chart appears as shown in Figure 4 a).

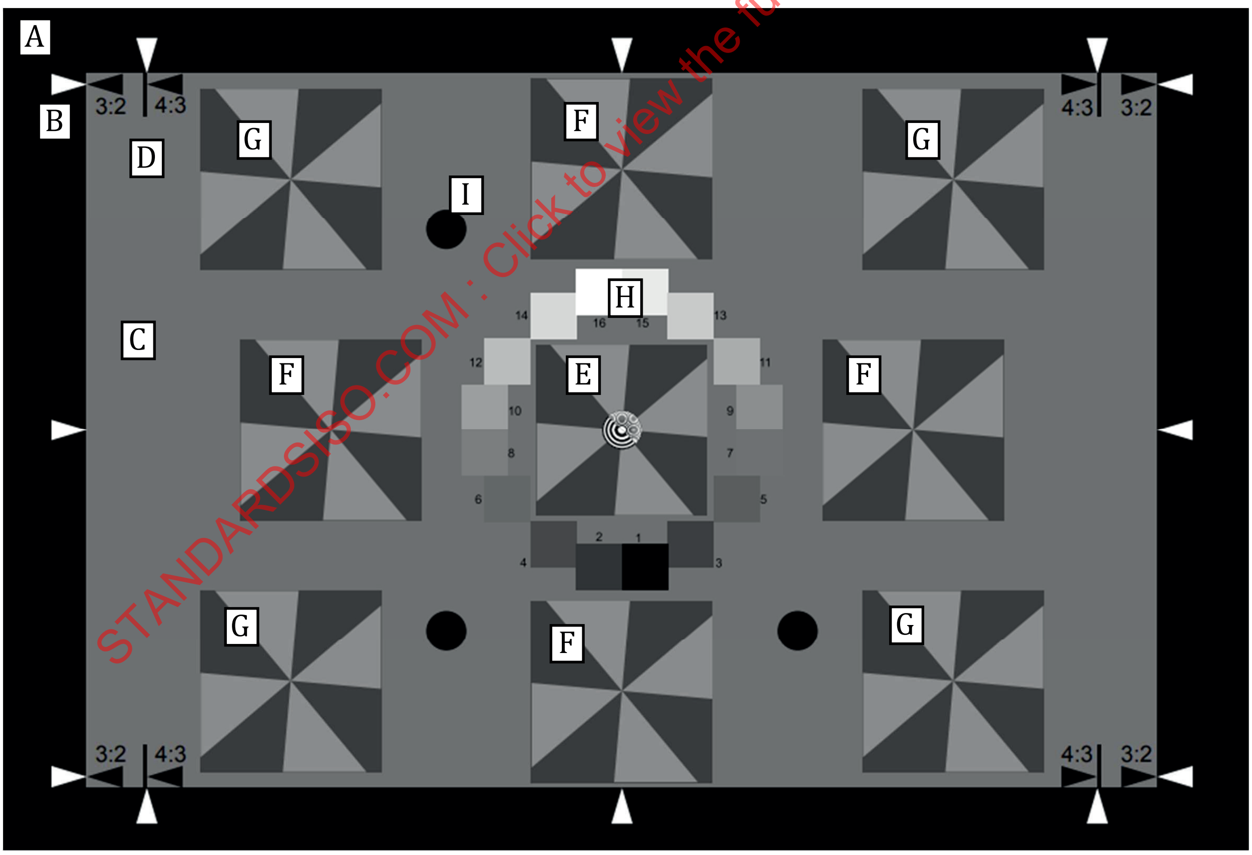


Figure C.1 — e-SFR test chart

Table C.1 — Details and requirements of the e-SFR test chart in Figure C.1

Code	Characteristics and application
A	Black border with inner edge which defines active test chart area
B	White framing arrows used to frame target horizontally or vertically
C	Active test chart area. The reflectance of the grey background should be 0,20 +/-0,02 (e.g., approximately 20 % reflectance).
D	Framing lines and arrows that define 4:3 and 3:2 image aspect ratios
E	Centre four-cycle "slanted star", centred within the active area. The structure starts with a dark edge originating in the centre toward the upper edge which is tilted to an angle of 5° clockwise from the vertical. This dark area ends at an angle of 50°. A bright area starts at this position until 95°. These areas continue in 45° sections until the full circle is covered and a total of 4 cycles of bright and dark areas are formed. The size of each of these squared structures corresponds to 25 % of the height of the active area of the test chart. The reflectance of the dark portions of the slanted wedges should be 0,05 +/-0,005 (e.g. approximately 5 % reflectance). For the preferred e-SFR test chart (4:1 reflectance ratio), the reflectance of the bright areas of the slanted wedges should be equal to the reflectance of the grey background. For optional e-SFR test charts having a larger reflectance ratio (up to a 10:1 reflectance ratio), the reflectance of the bright portions of the slanted wedges should equal the reflectance ratio times 0,05 +/-0,005 (e.g., approximately 30 % reflectance for a 6:1 ratio and 50 % reflectance for a 10:1 ratio). In the centre, a dual-frequency zone plate may be included and used to set focus
F	Four-cycle "slanted star" used to measure e-SFR at 50 % horizontal and 45 % vertical field positions for a 4:3 image aspect ratio. The chart includes four of these test patterns, two centred horizontally and two centred vertically on either side of the centre "slanted star" E. A 5 % positional tolerance relative to the 50 % and 45 % field positions is allowed. Each of these "slanted star" test patterns has the same structure as described in row E.
G	Four-cycle "slanted star" used to measure e-SFR at 70 % field position for a 4:3 image aspect ratio. The chart includes four of these test patterns positioned along the active area diagonals as shown in Figure C.1. A 5 % positional tolerance relative to the 70 % field position is allowed. Each of these "slanted star" test patterns has the same structure as described in row E.
H	OECF patches whose reflectance, circular symmetry, and geometric order are consistent with the requirements in ISO 14524. Due to space limitations, the patch sizes should be scaled to fit within the active area without interfering with the "slanted star" test patterns. The OECF patches should be numbered as indicated in Figure C.1.
I	Asymmetric features for automatic target detection. These features should be placed within the 4:3 active area image aspect ratio, but may be placed in various locations for convenience as dictated by use cases.

Annex D
(normative)

Edge spatial frequency response (e-SFR) algorithm

A flowchart of the e-SFR measurement algorithm is shown in Figure D.1 below. See Reference [6] for more information describing the updated algorithm.

Software that performs the e-SFR measurement algorithm specified in ISO 12233 can be accessed from http://www.iso.org/12233. Source code for this software is provided in informative Annex M.

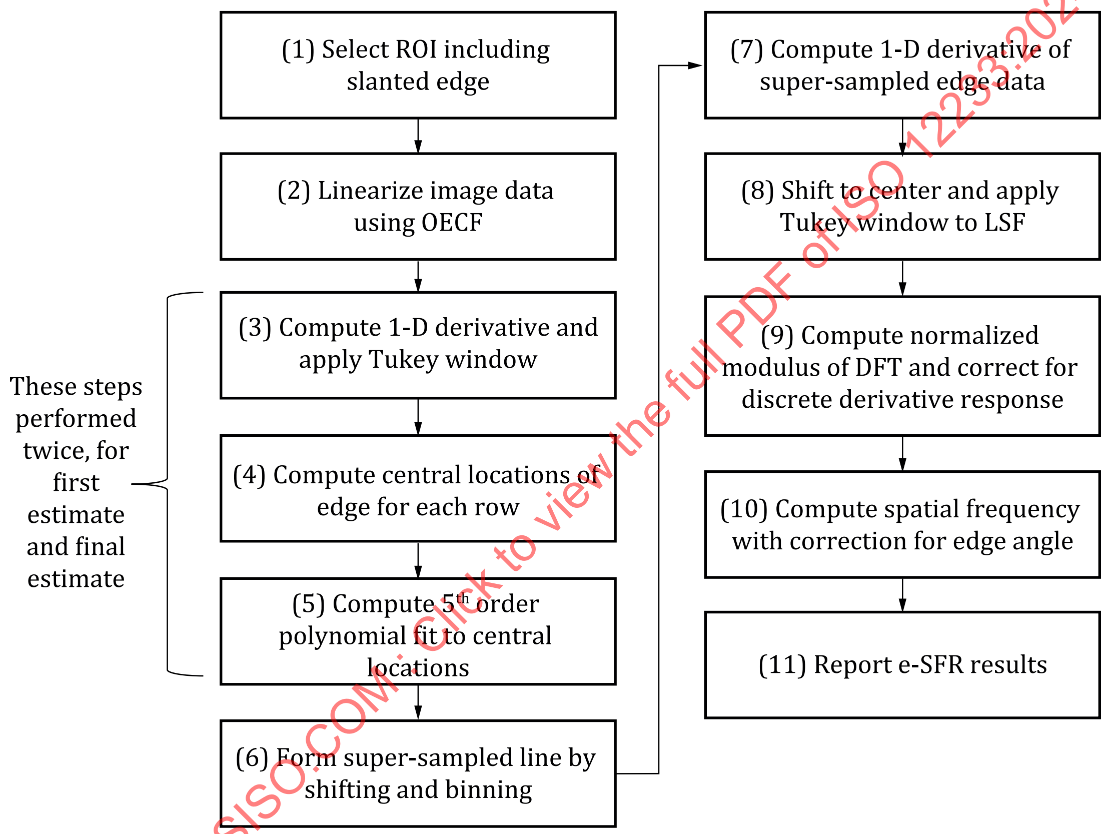


Figure D.1 — Flowchart of e-SFR measurement algorithm

Step (1) Select edge region of interest

The user selects the region of interest (ROI) containing the slightly slanted edge. If the image is a colour image, a luminance record shall be created before the SFR calculation is performed. The ROI shall be square or rectangular (i.e., having vertically and horizontally oriented sides, not slanted sides) and should have between 100 and 400 pixels on a side. Other sizes may be used, in which case the size of the ROI shall be reported.

The result is a two-dimensional matrix of data of values (n lines, m pixels). The software that performs the SFR measurement does not constrain the selection region to be an even number of pixels (P) and rows (R).

Step (2) Linearize image data using Inverse OECF

The image code values shall then be linearized by inverting the opto-electronic conversion function (OECF) of the camera. The OECF shall be measured using the OECF test patches on the test chart, as specified in ISO 14524. Each pixel value in the ROI is linearized using the inverse of the OECF.

In the software that performs the e-SFR measurement, the selected region is converted from digital code values to an edge spread image of normalized photopic intensities using the OECF and colour weighting coefficients *a*, *b*, and *c* shown in Formula (D.1). In general, *a*, *b*, and *c* should be determined as described in ISO 12232 (Reference [3]).

$$\varphi(p,r)=a\cdot 10^{OECF^{-1}(DN_{red})}+b\cdot 10^{OECF^{-1}(DN_{green})}+c\cdot 10^{OECF^{-1}(DN_{blue})} \tag{D.1}$$

where

DN	is the digital output level;
(p, r)	is the index of each pixel;
$OECF^{-1}$	is the inverse of the OECF defined in ISO 14524, and the function $10^{OECF^{-1}}$ converts the log intensities back to linear intensities.

NOTE In ISO 14524, the OECF is defined as the "relationship between the log of the input levels and the corresponding digital output levels...".

Step (3) Compute 1-D derivative and window

For each line of pixels perpendicular to the edge, the derivative of the linearized image data is computed using a [−½, +½] finite impulse response (FIR) filter. The result is an array which is the same size as the input ROI.

For each line of pixels in the resulting array, the data are multiplied with a Tukey window vector of the same length (m), as shown in Formula (D.2).

$$W(p,\alpha,m)=0{,}5\left(1-cos\left(\frac{2\pi p}{\alpha(m-1)}\right)\right), 0\le p\le\frac{\alpha(m-1)}{2} \tag{D.2}$$

$$W(m-p,\alpha,m)=W(p,\alpha,m), 0\le p\le\frac{\alpha(m-1)}{2}$$

$$W(p,\alpha,m)=1, \frac{\alpha(m-1)}{2}<p<\frac{(2-\alpha)\cdot(m-1)}{2}$$

The Tukey window function shape parameter α shall be equal to 1,0.

NOTE The decimal sign is a comma in ISO standards.

Step (3) is performed a first time to determine a first estimate. After steps (3) through (5) are completed for the first estimate, it is performed a second time for the final estimate. In the final estimate, the Tukey window function is centred for each line at the y value of the polynomial determined by Formula (D.4) in the first estimate.

To centre the Tukey window at the edge midpoint, *mid*, compute

$$mm=\max[m-mid,mid]$$

then compute

$$Win(p)=W(p,\alpha,2\,mm).$$

If *mid* > (*m*-1)/2

$$W(p)=Win(p), p=0,\ldots,m-1$$

else

$$W(p) = W\text{in}(m-p), p = 0, \ldots, m-1$$

end

Step (4) Compute central location of edge

The one-dimensional centroid of the derivative matrix from step (3) is calculated line by line, to determine the position of the edge on each line. The result is a vector of centroid locations (1, n).

The position of the centroid (*C*) of each *r* LSF is determined along the pixel (*p*) direction as shown in Formula (D.3).

$$C(r) = \frac{\sum_{p=1}^{p-1} p \cdot \phi(p,r)}{\sum_{p=1}^{p} \phi(p,r)} - ½ \quad \text{(D.3)}$$

where *C(r)* is a real-valued number.

This step is performed a first time to determine a first estimate. After steps (3) through (5) are completed for the first estimate, and step (3) is performed again for the final estimate, step (4) is performed a second time for the final estimate.

Step (5) Compute polynomial fit

A 5th order polynomial best-fit to the centroid locations as a function of line number should then be calculated using Formula (D.4).

$$y = a_0 + a_1 \cdot x + a_2 \cdot x^2 + a_3 \cdot x^3 + a_4 \cdot x^4 + a_5 \cdot x^5 \quad \text{(D.4)}$$

where

y is the set of centroid locations;

x is the set of line locations (1, n);

a_0 through a_5 provide the best-fit values.

Any other lower order polynomial may be used instead of a 5th order polynomial, in which case the polynomial order shall be reported along with the measurement results. For example, in case consistency with older versions of this standard is important to the user, a first-order (linear) fit may be used. However, using a low order polynomial can result in lower measurement accuracy, when high levels of geometric distortion are present. See Reference [10].

Step (5) is performed a first time to determine a first estimate. After steps (3) through (5) are completed for the first estimate, and steps (3) and (4) are performed for the final estimate, step (5) is performed a second time for the final estimate.

Step (6) Form super-sampled line by shifting and binning

A one-dimensional super-sampled edge spread function *ESF'(j)* is formed using the data of the truncated two-dimensional ROI image data and the 5th order polynomial edge fit, using Formula (D.5). Shifting the edge using the polynomial fit data effectively takes the tilt out of the edge.

Using the first line as reference points, the data points from all the other lines shall be placed into one of four "bins" between these reference points, according to the distance from the edge for that particular line. This creates a single super-sampled "composite" edge spread function, having four times as many points along the line as the original image data.

This forms a composite resampled edge spread function over the discrete variable *j*, where *j* is four times more finely sampled than *p* but is not a continuous variable like *x*. The super sampling factor is 4, so 4*PX* bins are created, each with a width of ¼ pixels.

$$ESF'(j) = \frac{\sum_{r=1}^{R}\sum_{p=1}^{P}\phi(p,r)\bullet\beta(p,r,j)}{\sum_{r=1}^{R}\sum_{p=1}^{P}\beta(p,r,j)} \quad \text{(D.5)}$$

The function beta (β) is simply a counter and a switch to include or exclude a value in any bin, using Formula (D.6).

$$\beta(p,r,j) = \begin{cases} 1, -0{,}125 \le [p - S(r) - j] < 0{,}125 \\ 0, \text{otherwise} \end{cases} \quad \text{(D.6)}$$

where

(p, r)	is the index of each pixel;
$S(r)$	is the offset of each line (r) centroid location from the polynomial fit function of step 5 above;
j	is an integer.

NOTE The locations of the integers *j* are interpreted as being at *j*/4 times the input pixel locations.

Step (7) Compute line spread function

From this vector, a corresponding line spread function array *LSF'* shall be derived by computing the length-3 discrete derivative, using Formula (D.7). The derivative vector is computed using a [−½, 0, +½] finite impulse response (FIR) filter, meaning that the derivative value for pixel “X” is equal to −½ times the value of the pixel immediately to the left, plus ½ times the value of the pixel to the right. The result is a vector which is the same size as the super-sampled edge spread function.

$$LSF'(j) = \frac{ESF'(j+1) - ESF'(j-1)}{2}, \text{ for } j = 2, \ldots, N-1 \quad \text{(D.7)}$$

The first and last values of the computed LSF are then repeated, so the *LSF'* vector has a length *N* = 4P (4X)

Step (8) Shift and window LSF

The line spread function array shall be centred by circular rotation, so that the maximum value shall be at location trunk (*N*/2), where N is the length of the vector (4 m). The centred line spread function shall be multiplied by a Tukey window. This reduces the effects of noise by reducing the influence of pixels at the extremes of the window, which have response due to noise but little response due to the image edge located at the centre of the window.

The average super-sampled edge spread function which has been differentiated in step (7) is windowed in step (8) using Formula (D.8), which is similar to Formula (D.2). The Tukey window function shape parameter, α, shall be equal to 1,0.

$$LSF'_W(j) = W(j)\,LSF'(j) \quad \text{(D.8)}$$

where

$$W(j) = ½\left[1 - \cos\left(\frac{2\pi j}{\alpha(N-1)}\right)\right],\ 0 \le j \le \frac{\alpha(N-1)}{2}$$

$$W(N-j) = W(j),\ 0 \le j \le \frac{\alpha(N-1)}{2}$$

$$W(j)=1,\ \frac{\alpha(N-1)}{2} < j < \frac{(2-\alpha)\cdot(N-1)}{2}$$

Step (9) Compute normalized modulus of DFT and correct for discrete derivative response.

The e-SFR is determined using the normalized modulus of the DFT of the centred, windowed line spread function. The values of the modulus of the DFT are corrected for the bias introduced by the discrete derivative FIR filter. This correction is in the form of a frequency-by-frequency (element-by-element) multiplication by the reciprocal of a *sinc* function, as explained in Annex K.

The normalized discrete Fourier transform (DFT) of the windowed single line spread function (LSF) is calculated using Formula (D.9).

$$e\text{-}SFR(k)=D(k)\left|\frac{\sum_{n=1}^{N} LSF_W^{'}(n)e^{-\frac{i2\pi kn}{N}}}{\sum_{n=1}^{N} LSF_W^{'}(n)}\right|, \text{for } k=0,1,2,\ldots,\frac{N}{2}, \text{or } \frac{N+1}{2} \text{ if } N \text{ is odd} \qquad \text{(D.9)}$$

where

k is the index for spatial frequency;

$LSF_W^{'}$ is the windowed, centred, binned, super-sampled line spread function formed from the selected region of the chart image;

$D(k)$ is the correction for the frequency response of the discrete derivative used to derive the point spread function from the edge spread function, shown in Formula (D.10).

$$D(k)=\min\left[\frac{1}{\operatorname{sinc}\left(\frac{2\pi k}{N}\right)},10\right] \qquad \text{(D.10)}$$

The derivation of this expression for *D(k)* in Formula (D.10) is given in Annex K.

Step (10) Compute spatial frequency with correction for edge angle

The spatial frequency for each of the elements of the e-SFR vector are computed, based on the sampling interval of the LSF. This is done in two steps.

a. **Correct LSF sampling interval for edge angle**

The LSF is a super-sampled line profile based on the 4x binning operation of step (6). The nominal sampling interval associated with the LSF vector is four times the input image sampling. For example, if we express the image sampling interval as 1 pixel, the nominal LSF interval is ¼ pixel. However, this interval is now corrected so that the direction for this line-profile is normal to the edge-feature in the digital image. The origin and rationale for this correction is described in Reference [18].

If the image sampling interval is *d*, and the nominal LSF sampling interval is ¼ *d*, then the angle-corrected sampling interval is given by Formula (D.11).

$$d_{corr}=\tfrac{1}{4}\cdot d\cdot \cos\theta \qquad \text{(D.11)}$$

where

d_{corr} is the corrected sampling interval;

d is the image sampling interval;

θ is the angle of the edge feature from the vertical axis.

The derivation of Formula (D.11) is given in Annex K.

b. **Compute the spatial frequency values**

The spatial frequency values for each of the elements (values) of the e-SFR vector are computed as follows. If the number of elements (length) of the LSF is N, and the corresponding sampling interval is d_{corr}, as above, then the spatial frequency vector is given by Formula (D.12).

$$f(k)=\frac{k}{N \cdot d_{corr}}, \text{for } k=0,1,2,\ldots,\frac{N}{2} \quad \text{(D.12)}$$

If the sampling interval is in units of pixels, then the spatial frequency values, f, will be expressed using the normalized spatial frequency, in units of cycles/pixel.

Step (11) Report e-SFR results

The software that performs the measurement algorithm should report the e-SFR data using normalized spatial frequencies (cycles/pixel). The e-SFR data can also be reported by converting from cycles per pixel to other spatial frequency units, as discussed in informative Annex H.

To report the data in frequency units of LW/PH, multiply the frequency values by the number of rows of pixels per image height (for vertical SFR measurements) or by the number of columns of pixels within a horizontal distance equal to the image height (for horizontal SFR measurements).

To report the data in frequency units of cycles per millimetre on the image sensor, the frequency values are multiplied by ½ times the number of rows of photosites per millimetre on the sensor (for vertical SFR measurements) or ½ times the number of columns of pixels per millimetre on the sensor (for horizontal SFR measurements).

To report the data in frequency units of cycles per millimetre on the test chart, the frequency values are multiplied by the number of rows of photosites on the sensor divided by the height of the active area of the test chart (for vertical SFR measurements) or by the number of columns of pixels on the sensor divided by the width of the active area of the test chart (for horizontal SFR measurements).

Annex E
(normative)

Sine wave star test chart

The sine wave star test pattern shown in Figure 6 may be used as a single test chart, or multiple sine wave star test patterns may be included in a multiple target version test chart, as shown in Figure E.1. The chart should be grey. The camera should be white balanced prior to the measurement.

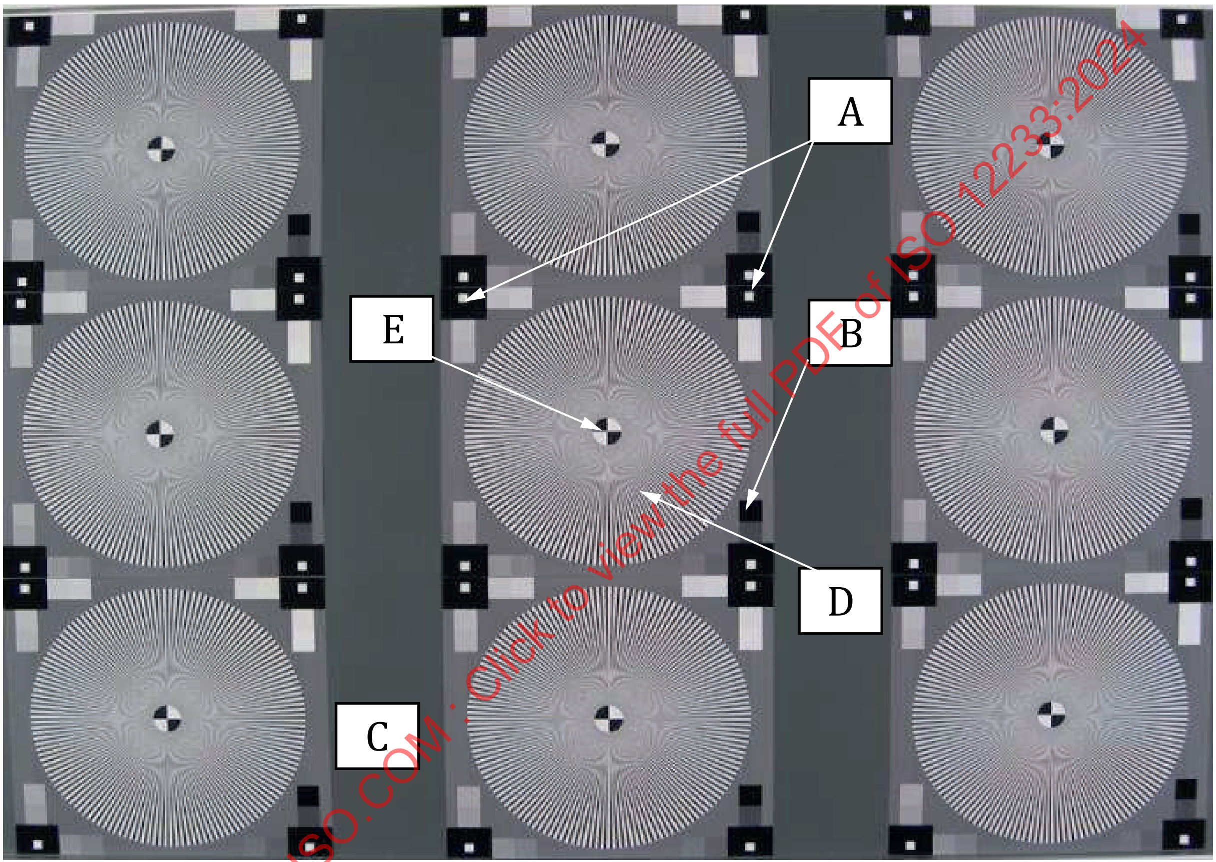


Figure E.1 — Sine wave test chart (multiple target version)

The chart includes the features listed in Table E.1.

Table E.1 — Features of sine wave test chart

Code	Application	Characteristics
A	Markers for the region of interest	Black squares with a smaller white square inside
B	16 grey patches for linearization	Squares aligned along the ROI markers equally spaced in reflection from white to max. black
C	Background	The background should have a reflection of 18 %.
D	Sine wave star	The star should be a sine wave (in reflection) modulated starburst pattern with a frequency of typically 144 cycles. For lower resolution cameras, a 72-cycle star may be used.
E	Centre marker for the exact positioning of the star	A circle with two white and two black segments opposite to each other. The size of the circle should be chosen to cover the area that should not be used due to the lack of resolution of the output system used to produce the star.

The charts are limited in their application because of the production method used to generate the chart. Therefore, the manufacturer should report the maximum number of pixels the chart shall cover in an image.

The given sizes are scaled to a chart width of 29 cm and a height of 27 cm. The diameter of the starburst pattern is 25 cm. If the design is carried out in a vector-based software, it is possible to scale the chart to any size required, keeping production and application limits in mind. The contrast of the structures should be greater than a 50:1 and less than a 250:1 reflectance ratio.

A listing of the design features of the sine wave star test chart can be found in Table E.2.

Table E.2 — Design of sine wave star test chart

Code	Subcode	Position upper left corner x;y	Size	Digital value in linear image
A1	Black	0;0	40 mm; 30 mm	0
A1	White	16 mm; 6 mm	8 mm; 8 mm	255
A2	Black	250 mm; 0 mm	40 mm; 30 mm	0
A2	White	266 mm; 0 mm	8 mm; 8 mm	255
A3	Black	0 mm; 240 mm	40 mm; 30 mm	0
A3	White	16 mm; 256 mm	8 mm; 8 mm	255
A4	Black	250 mm; 240 mm	40 mm; 30 mm	0
A4	White	266 mm; 256 mm	8 mm; 8 mm	255
B	1	260 mm; 50 mm	20 mm; 20 mm	255
B	2	260 mm; 30 mm	20 mm; 20 mm	238
B	3	230 mm; 0 mm	20 mm; 20 mm	221
B	4	210 mm; 0 mm	20 mm;20 mm	204
B	5	60 mm; 0 mm	20 mm; 20 mm	187
B	6	40 mm; 0 mm	20 mm; 20 mm	170
B	7	10 mm; 30 mm	20 mm; 20 mm	153
B	8	10 mm; 50 mm	20 mm; 20 mm	136
B	9	10 mm; 200 mm	20 mm; 20 mm	119
B	10	10 mm; 220 mm	20 mm; 20 mm	102
B	11	40 mm; 250 mm	20 mm; 20 mm	85
B	12	60 mm; 250 mm	20 mm; 20 mm	68
B	13	210 mm; 250 mm	20 mm; 20 mm	51
NOTE 1 Position 0;0 is located in the upper left corner.				
NOTE 2 Chart size: width is 290 mm (*x*), height is 270 mm (*y*).				

Table E.2 *(continued)*

Code	Subcode	Position upper left corner x;y	Size	Digital value in linear image
B	14	230 mm; 250 mm	20 mm; 20 mm	34
B	15	260 mm; 220 mm	20 mm; 20 mm	17
B	16	260 mm; 200 mm	20 mm; 20 mm	0
C		0 mm; 0 mm	290 mm; 270 mm	46
D		145 mm; 135 mm	Diameter 250 mm	144 cycles sine wave starburst
E		145 mm; 135 mm	Depending on production method	0 and 255
NOTE 1 Position 0;0 is located in the upper left corner.				
NOTE 2 Chart size: width is 290 mm (x), height is 270 mm (y).				

Annex F
(normative)

Sine wave spatial frequency response (s-SFR) analysis algorithm

An executable version of software has been developed to perform measurements using the test chart defined in Annex E. The software, which was created using Matlab®[3], can be accessed from www.iso.org/12233. The software can report the results from a single image or can average the results from numerous images. The star is divided into a user-selected number of segments (typically eight segments) for analysis. The user selects the area of the captured image that contains the chart, with the lightest patch in the upper right corner. The result shows the modulation versus frequency (in LP/PH) for each of the segments.

The Siemens star elements are identified using the marks in the corners and the centre of each star. Next, the measured amplitude values of the camera are linearized by using the 16 grey patches of the central star (see Figure F.1) to determine the OECF (opto-electronic conversion function) and then inverting this OECF function.

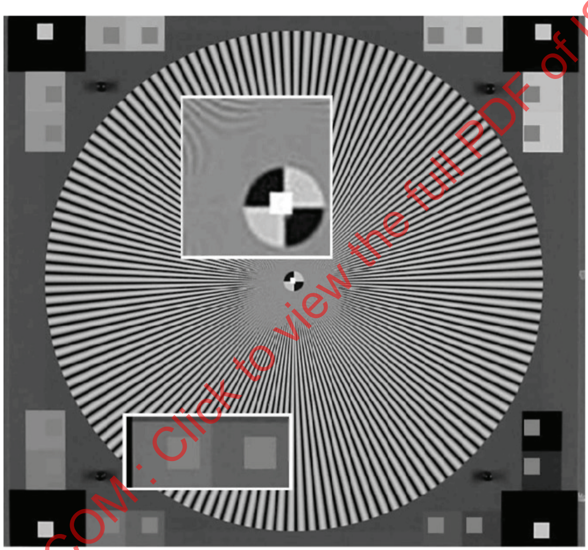


Figure F.1 — Chosen positions of the OECF patches and the centre of the star number 0

From the diameter of the stars and the image height, the scale is determined to translate the star frequency into line pairs per picture height (LP/PH). See Table H.1 for conversion between different resolution metrics.

$$R = \frac{N_y}{g} = \frac{N_p \cdot N_y}{2\pi r_{\text{Pixel}}} \tag{F.1}$$

with

$$g = \frac{2\pi \cdot r_{\text{Pixel}}}{N_p} = \text{cycle length in pixels} \tag{F.2}$$

3) Matlab is an example of a suitable product available commercially. This information is given for the convenience of users of this document and does not constitute an endorsement by ISO of this product.

where

R is the resolution, in LP/PH;

N_p is the number of cycles for the Siemens star;

N_y is the image height in pixel;

r_{Pixel} is the radius of the circle (from the centre of the star).

NOTE To get LW/PH, the above result needs to be multiplied by 2. See Table H.1.

To correct for a possible distortion, the star is divided into 24 segments, and for each segment, the boundary of the star is detected. The appropriate radii for the evaluation (Figure F.2) of the stars are calculated. These calculated radii are corrected with a factor depending on the irregular circular shape which was found for the single star. This way, a distortion can be corrected without modification of the image itself.

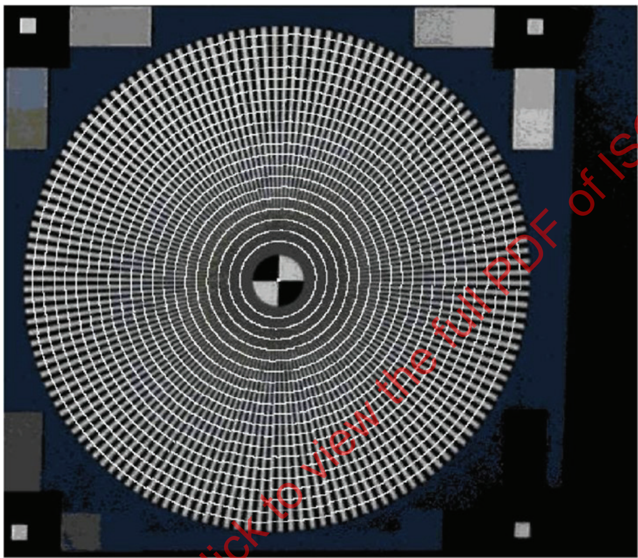


Figure F.2 — For 24 segments, the border of the star is detected and results in a distortion corrected analysis

The star is divided into 24 segments. Each segment covers 15° of the full circle with the centre of segment #1 at 0° (where 0° is defined as the positive x-axis in a Cartesian system and angles are counted counterclockwise). So, segment #1 is defined as the range of 352,5° to 7,5°, segment #2 as the range of 7,5° to 22,5° and so on.

Two vectors are created in the analysis process: digital value and angle. The vectors are built based on the read out process of the image pixels.

The first pixel is the one closest to the calculated position defined by the intended radius and angle (start-angle as smallest angle in the segment). The digital value of the pixel and the angle of the pixel are the first entries in the vectors.

Depending on the quadrant that the current pixel is located in, the next pixel in the counter-clockwise direction on the digital circle is either a single pixel shift on the x-axis or a single pixel shift on the y-axis. The chosen new pixel is the pixel that has the lower difference between the measured radius and the given radius, as shown in Figure F.3. From this new pixel, the digital value and the angle are stored in the vectors. This process stops as soon as the angle reaches the largest angle for the particular segment.

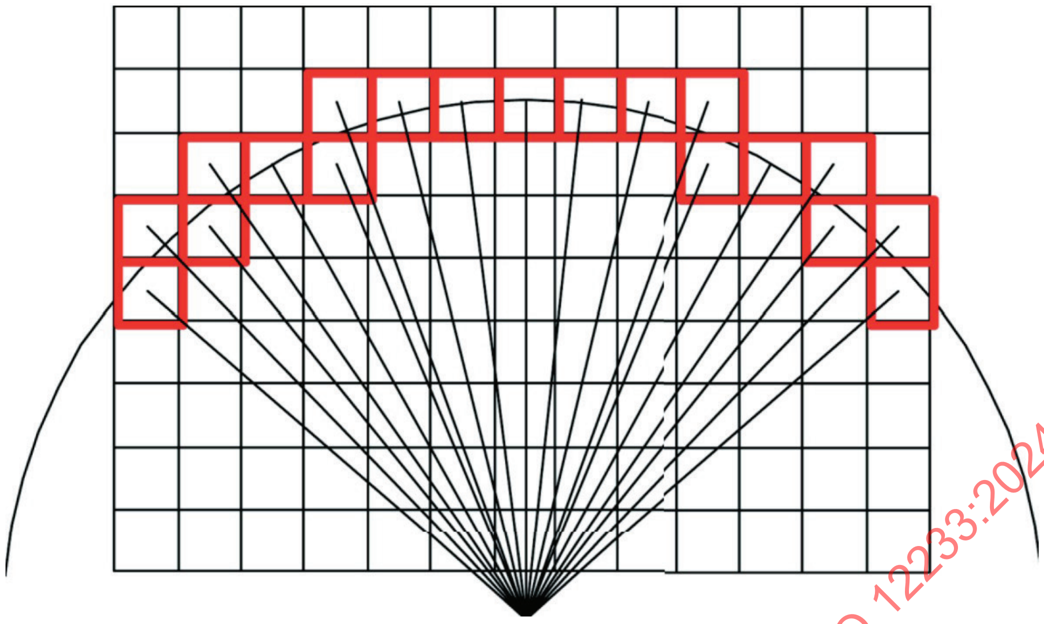


Figure F.3 — Location of pixels along a specific radius.

The pixels that are used are all 4-connected to each other. Depending on the quadrant, two possibilities for the new position are evaluated and the distance between the intended radius and the measured radius is minimized.

For the s-SFR measurement, a minimum of four images of the test chart described in Annex E shall be evaluated and averaged. Using the software which can be accessed from www.iso.org/12233, the star may be divided into a user-selected number of segments (typically eight). For each segment, a minimum of 32 equally spaced radii should be analysed.

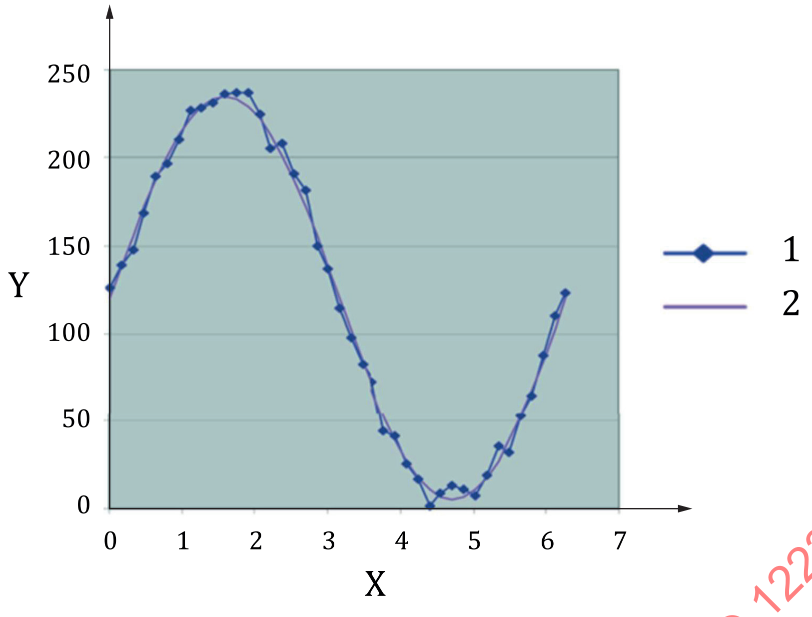
The following is a detailed description of the steps taken by the analysis.

— Step 1: The star is located in the image using four surrounding markers to define the region of interest. The centre of the star is located to define the origin of the radii used to analyse the image.

— Step 2: The measured amplitude values are linearized by using the 16 grey patches of the central star to determine the OECF, as described in ISO 14524.

— Step 3: A user-selectable segmentation of the star is made.

— Step 4: A minimum of 32 radii are analysed by locating the pixels along the radius and selecting the digital code values for the linearized image as a function of the angle (see Figure F.4).



Key

X angle (radians)

Y digital values

1 pixel values

2 fitted sine curve

Figure F.4 — Digital code values as a function of the angle

For a Siemens star, the intensity is given as:

$$I(\phi)=a+b\cdot\cos\left[\frac{2\pi}{g}(\phi-\phi_0)\right] \tag{F.3}$$

The angle for each pixel is calculated using

$$\phi=\arctan\left(\frac{x}{y}\right) \tag{F.4}$$

with x = 0 and y = 0 as the centre of the star. Since the phase of the signal, ϕ_0, is not known, Formula (F.5) must be used instead of Formula (F.3).

$$I(\phi)=a+b_1\cdot\sin\left(\frac{2\pi}{g}\phi\right)+b2\cdot\cos\left(\frac{2\pi}{g}\phi\right) \tag{F.5}$$

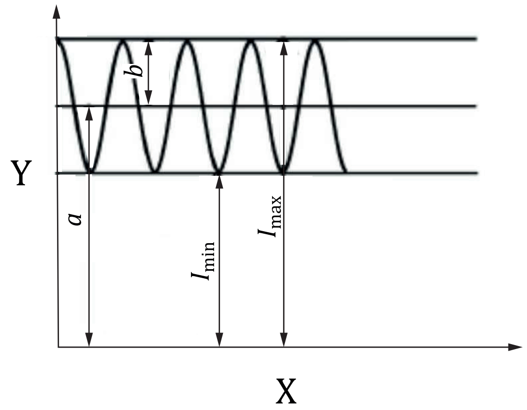
with

$$b=\sqrt{b_1^2+b_2^2} \tag{F.6}$$

— Step 5: A sine curve with the expected frequency is fitted into the measured values by minimizing the square error.

— Step 6: The contrast of the sine curve is determined by calculating the contrast using Formula (F.7). The values a, b, I_{max}, and I_{min} are determined as depicted in Figure F.5.

$$M=\frac{I_{max}-I_{min}}{I_{max}+I_{min}}=\frac{a+b-(a-b)}{a+b+(a-b)}=\frac{b}{a} \tag{F.7}$$



Key

X angle

Y intensity

Figure F.5 — Calculation of the contrast of the sine curve

— Step 7: The s-SFR is built as a function of the measured contrast (step 6) and the calculated spatial frequency (see Formula F.1).

— Step 8: The s-SFR obtained in step 7 needs to be normalized, because the relationship of the reflection of the patches in the target and the digital value in the image is not fixed and depends on many parameters of the camera being tested. By definition, the s-SFR for a spatial frequency = 0 should be equal to 1.

The lowest spatial frequency the s-SFR can directly measure depends on the largest radius used for the analysis. As this frequency cannot be 0, the normalization process cannot be performed with the s-SFR measurement itself.

The s-SFR obtained from step 7 shall be normalized by dividing all calculated contrasts by the contrast calculated from the brightest and the darkest patch surrounding the Siemens star. (F.5 with Imax equal to the digital value of the brightest patch in the linearized image and I_{min} equal to the digital value of the darkest patch in the linearized image.)

Annex G
(informative)

Colour-filtered resolution measurements

G.1 General

Although it is well known that luminance resolution is most important, the ability to accurately render coloured details, colour textures, and coloured fabrics cannot be overlooked. This includes the ability to accurately render single-pixel colour details, as well as avoiding colour aliasing. All consumer digital cameras on the market today record in colour and the scenes people are photographing are usually in colour. In this annex, a technique for measuring how well a camera can reproduce the details of a test scene that includes saturated colours is recommended.

The method uses the standard grey test charts and their existing analysis methods (as described in this document) but are photographed through colour separation filters. This method is easily implemented and controlled and is an easy way to isolate a camera's ability to render modulation of patterns formed by coloured objects. By simple specification of the appropriate colour separation filters, the method avoids the problems and variation involved in fabricating a coloured resolution target. The red colour filter, for example, produces a scene which includes saturated red patterns on a dark background.

G.2 Choice of colour filters

One set of colour filters which can be used is the “Status T” filters specified in ISO 5-3. Kodak Wratten[4)] filter sets can also be used for this application, such as numbers 29 (red), 61 (green), and 47B (blue) or the less aggressive colour separation set numbers 25 (red), 58 (green), and 47 (blue). Although these filters provide a better analysis of a camera's ability to resolve coloured details, other filters could be used either to avoid an overly sensitive interaction with a particular camera's internal filters or as an additional comparison aimed at increasing the range of colours considered. The colour filters used in the measurements should be reported with the results. Because these filters are chosen to separate the red, green, and blue components employed in most camera implementations, the Nyquist frequencies of the colour components can be estimated depending on the results and the particular sensor configuration.

G.3 Camera settings

In these measurements, it is important to make sure that the camera's settings are consistent. It is recommended that the camera be adjusted as described in Clause 4 and the illumination used as described in 4.1. In particular, the camera should be focused on the target before the colour filters are placed in front of the camera lens either by the auto-focusing system or by selecting the focus position as described in 4.3. Using this method, the chromatic properties of the camera lens are integrated into the measurement, in addition to the sensor design and the processing algorithms. This technique best represents the typical photographic scene where a range of coloured scene content exists. White balance should also be either manually set to the illumination conditions (without the coloured filter) or set to the test chart before the filter is added to the optical path (if a pre-shutter release position is used in the camera for this function). In order to obtain sufficient signal-to-noise ratio of the test image, the exposure level and/or camera ISO speed may be adjusted for each filter, so long as the camera's aperture does not change, and the shutter speed and ISO speed settings are noted.

Another option, applicable for some applications, is to focus the camera lens on the test chart separately for each filter being used in the study. This method segregates the effects of the sensor and processing

4) Kodak Wratten is an example of a suitable product available commercially. This information is given for the convenience of users of this document and does not constitute an endorsement by ISO of this product.

algorithms from the optical properties of the camera lens (by providing image signals that are optimally focused for each exposure).

Annex H
(informative)

Units and summary metrics

H.1 Conversions between commonly used units

To convert from the left column units to the top row units in Table H.1, use the operation at their row/column intersection.

EXAMPLE 5 LP/mm × 2 = 10 L/mm.

Table H.1 — Spatial frequency unit conversion chart

	LW/PH	LP/mm	L/mm	Cycles/mm	Cycles/pixel	LP/PH
LW/PH	× 1	/[2 × picture height]	/picture height	/[2 × picture height]	/[2 × # vert. pixels]	/2,0
LP/mm	× [2 × picture height]	× 1	× 2	× 1	× pixel pitch	× [picture height]
L/mm	× picture height	× ½	× 1	× ½	× [pixel pitch/2]	× [picture height/2]
Cycles/mm	× [2 × picture height]	× 1	× 2	× 1	× pixel pitch	× [picture height]
Cycles/pixel	× [2 × # vert. pixels]	/pixel pitch	× [2/pixel pitch]	/pixel pitch	× 1	× [# vert. pixels]
LP/PH	× 2	/picture height	2/picture height	/picture height	/# vert. pixels	× 1

where

LW/PH is line widths per picture height

LP/mm is line pairs per millimetre

L/mm is lines per millimetre

LP/PH is line pairs per picture height

NOTE 1 The pixel pitch in the 45° diagonal direction is not the same as in the vertical and horizontal directions. Therefore, the diagonal pixel pitch is used when applying this table to measurements in the diagonal directions.

NOTE 2 The pixel pitch is the pitch of pixels in the image file. The picture height and pixel pitch used, in millimetres, are for the same magnification at which the lines per millimetre was determined, or vice versa.

NOTE 3 The decimal sign is a comma in ISO standards.

H.2 Relation between SFR, sharpness, and acutance

It is important to note the relation between spatial resolution and image sharpness. Spatial resolution, as defined in this document, is an objective analytical measure of a digital capture device's ability to maintain the contrast or modulation of increasingly finer spaced details in a scene. This is what the SFR characterizes. Image sharpness is the subjective impression of visually detecting finely spaced detail or edge transitions. The higher the contrast of visually important details (i.e. the greater the SFR over a wide range of spatial frequencies), the greater the likelihood of visually judging a rendered image of those details as sharp. While image noise and tone reproduction are also influential in the perception of image sharpness, the SFR of the imaging system (e.g., camera plus display) has proven to be the strongest correlate to image sharpness and is the basis for all acutance-type image sharpness predictors. Excellent reviews of early sharpness metrics can be found in References [11] and [15]. The calculation of acutance from SFR values is described in Annex L.

H.2.1 Sampling efficiency rating (E_s)

For digital cameras, there are two main items that determine the resolution.

a) Sampling frequency of the image sensor: usually referred to in terms of the number of addressable photoelements.

EXAMPLE 5 megapixels on a sensor.

b) Optical effects of the camera lens: factors such as focus, lens *f*-number, anti-aliasing filter, optical glass quality, and assembly.

Many users consider the number of addressable photoelements (pixels) on an image sensor (effectively its horizontal or vertical sampling frequency) as the only variable that determines the resolution of a camera. However, the limitations of the camera lens need to be considered as well. One cannot compensate for a sensor with a small number of pixels by using a high-quality lens, nor can one compensate for a low quality lens by using a sensor with a large number of pixels.

Ideally, one would like the camera lens to take full advantage of the image sensor, but that is not always the case. As a result, a single number, or efficiency, indicating the extent of such a shortcoming of the camera lens, relative to the sensor sampling frequency, can be helpful. See Reference [7] for more information.

The calculation of Formula (H.1) yields the number of optically resolved photoelements using the sampling efficiency value, E_s.

$$Po = \frac{Es}{100 \cdot Pc} \tag{H.1}$$

where

P_o is the number of optically resolved photoelements;

E_s is the sampling efficiency;

P_c is the number of addressable (claimed) photoelements.

The sampling efficiency rating ranges from 0 % to 100 % and uses a two-dimensional SFR area-normalized approach in its formulation. See Figure H.1, which depicts a circular quadrant area. The perimeter of the quadrant is the locus of maximum sampling efficiency (100 %) for any angular direction. Ideally, if the sampling efficiency in all angular directions was characterized as 100, then a number of points would lie on that locus. A step-by-step procedure for calculating sampling efficiency is provided below when using horizontal, vertical, and near-45° diagonal resolution values.

1) Determine the visual resolution in LW/PH for the horizontal (R_H), vertical (R_V), and ±45° (R_{+45}, R_{-45}) directions. Alternately, the equivalent SFR10 frequencies in units of cycles/pixel (e.g., the normalized spatial frequencies where the SFR response levels of either of the SFR methods falls to 10%) may also be used.

2) Calculate individual directional efficiencies for E_H, E_V, E_{+45}, and E_{-45} by normalizing the visual resolutions of step 1) by the captured image's picture height. When using cycles/pixel frequency units, normalize by ½ cycles/pixel. Any normalized value greater than 1,0 shall be assigned the value of 1,0.

3) Combine E_{+45} and E_{-45} efficiencies into an equally weighted average diagonal value, E_D.

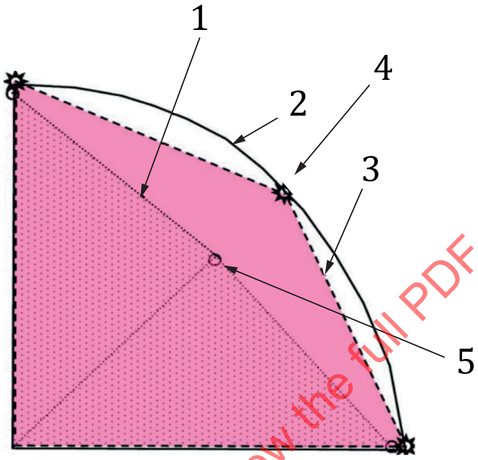
4) Calculate the sampling efficiency rating (E_R) as the product of 100, E_D, and the average of E_H and E_V using Formula H.2.

$$E_R = 100 \times [E_D \times (E_H + E_V)/2] \tag{H.2}$$

EXAMPLE 2 048 pixel high × 3 072 pixel wide, 6 MPixel camera file.

Visual horizontal resolution:	R_H = 1 970 LW/PH	Horizontal sampling efficiency: E_H = 1 970/2 048 = 0,96
Visual vertical resolution:	R_V = 1 980 LW/PH	LW/PH diagonal sampling efficiency
Visual +45° resolution:	R_{+45} = 1 500 LW/PH	E_D (1 500/2 048) + (1 500/2 048)/2 = 0,73
Visual −45° resolution:	R_{-45} = 1 500 LW/PH	E_D (1 500/2 048) + (1 500/2 048)/2 = 0,73

Sampling Efficiency Rating $_{(H, V, D)}$ = 100 × [0,73 × (0,96 + 0,97)/2] = 0,704



Key

1 area bounded by measured efficiency points (dotted line) = 0,707 × E_D × (E_H + E_V)/2

2 locus of maximum efficiency for all angles = 100 %

3 area bounded by maximum efficiency points (dashed line) = 0,707

4 maximum efficiency point (aim) = 100 %

5 measured efficiency points (E_D, E_H, E_V)

Camera efficiency rating = 100 × E_D × (E_H + E_V)/2

Figure H.1 — Frequency domain area technique for integrating individual sampling efficiencies

If only E_H and E_V are known, the formula for sampling efficiency is

$$E_R = 100 \times (E_H \times E_V) \tag{H.3}$$

Using the same example values as above,

Visual horizontal resolution:	R_H = 1 970 LW/PH	Horizontal sampling efficiency: E_H = 1 970/2 048 = 0,96
Visual vertical resolution:	R_V = 1 980 LW/PH	Diagonal sampling efficiency

Sampling Efficiency Rating $_{(H, V)}$ = 100 × (0,96 × 0,97) = 0,931

Annex I
(informative)

Original test chart defined in ISO 12233:2000

I.1 General

This edition of ISO 12233 defines multiple test charts which are used to measure the visual resolution, e-SFR, and s-SFR. The first edition of ISO 12233 defined a single, composite test chart which was widely used to perform multiple types of measurements, and can still be used to perform some of the measurements defined in this current edition of ISO 12233. For this reason, this annex describes the test chart originally defined in ISO 12233:2000.

I.2 The original test chart defined in ISO 12233:2000

A reproduction of the original test chart defined in ISO 12233:2000 is shown in Figure I.1. Figure I.2 is a diagram showing the locations of particular features of the test chart, which may be either a reflective or transmissive chart. The purpose of each test pattern element is listed in Table I.1.

The required test pattern modulation and positional tolerances are the same as listed in 5.2.4 and 5.2.5.

All test chart features are specified in units of line widths per picture height (LW/PH), where the height is the active image distance in the shorter test chart dimension. The finest features are 2 000 LW/PH, which is equivalent to 1 000 line pairs per picture height.

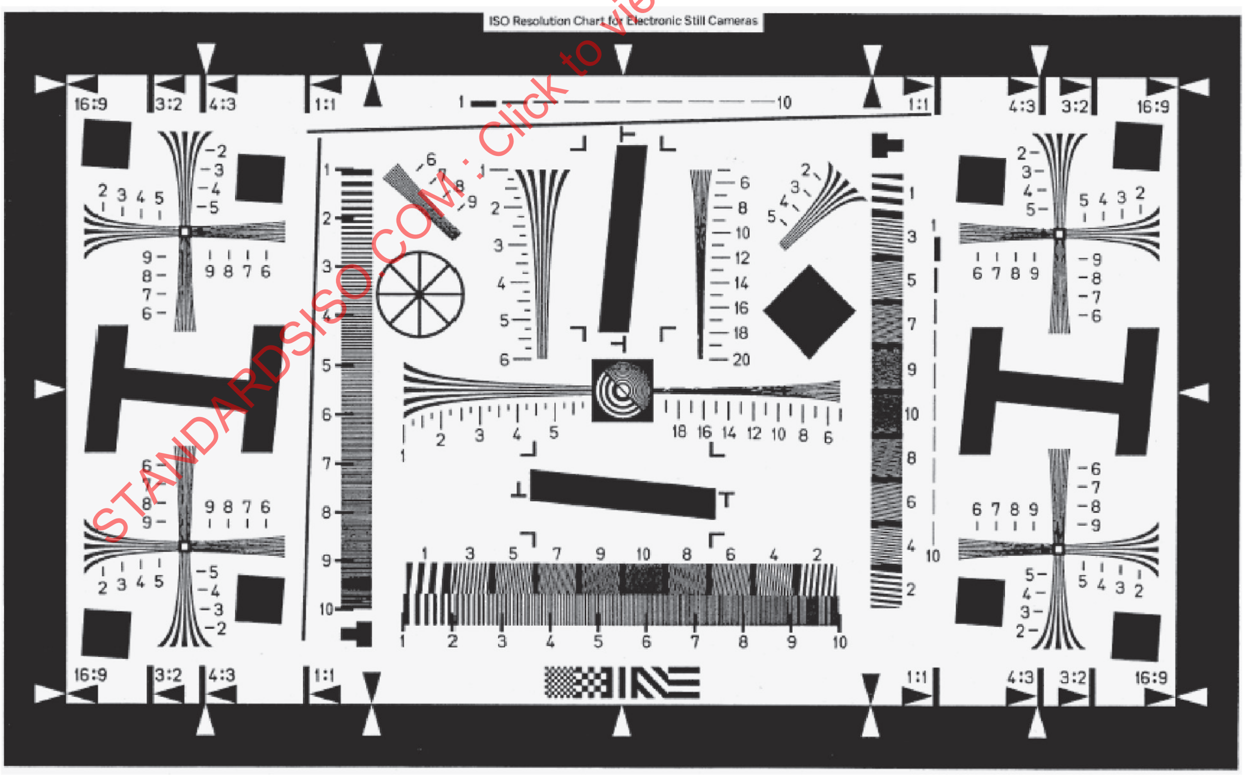


Figure I.1 — Resolution test chart

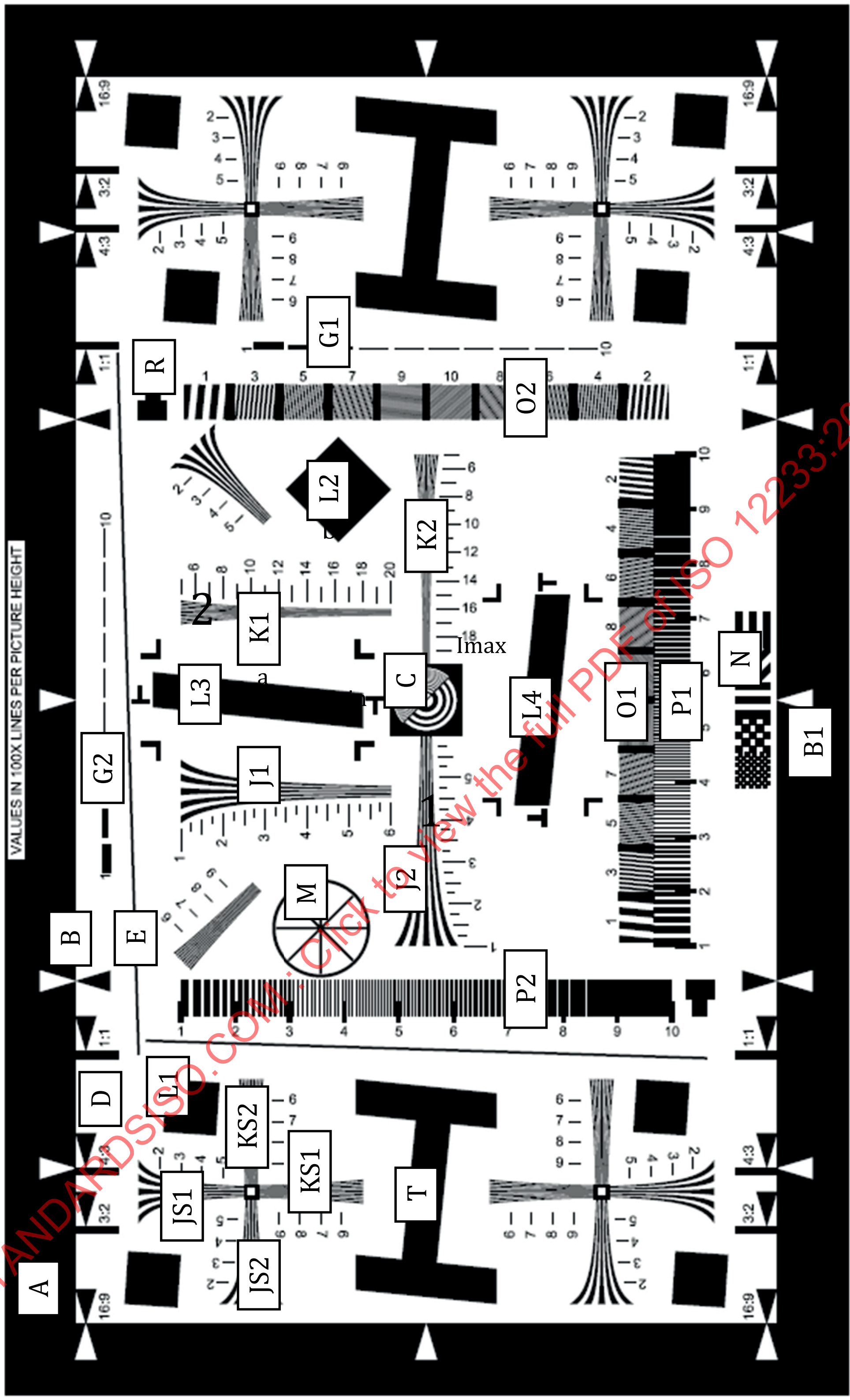


Figure I.2 — Test chart features

Table I.1 — Test chart elements

Element	Purpose
A	Black border with inner edge which defines active test chart area
B	Black and white framing arrows used to frame test chart vertically (used for horizontal framing only for 16:9 image aspect ratio formats)
B1	White framing arrows used to assist in framing test chart
C[a]	Centre dual-frequency zone plate inside black square used to set focus
D[a]	Framing lines and arrows that define 1:1, 4:3, and 3:2 image aspect ratios
E[a]	Slightly slanted lines used to check scan linearity and “stair stepping”
G1[a]	100 LW/PH to 1 000 LW/PH black bars to measure horizontal pulse response
G2[a]	100 LW/PH to 1 000 LW/PH black bars to measure vertical pulse response
J1	100 LW/PH to 600 LW/PH hyperbolic zone plate used to measure centre horizontal visual resolution
J2	100 LW/PH to 600 LW/PH hyperbolic zone plate used to measure centre vertical visual resolution
JS1[a]	100 LW/PH to 600 LW/PH hyperbolic zone plate used to measure corner horizontal visual resolution
JS2[a]	100 LW/PH to 600 LW/PH hyperbolic zone plate used to measure corner vertical visual resolution
K1	500 LW/PH to 2 000 LW/PH hyperbolic zone plate used to measure centre horizontal visual resolution
K2	500 LW/PH to 2 000 LW/PH hyperbolic zone plate used to measure centre vertical visual resolution
KS1[a]	500 LW/PH to 1 000 LW/PH hyperbolic zone plate used to measure corner horizontal visual resolution
KS2[a]	500 LW/PH to 1 000 LW/PH hyperbolic zone plate used to measure corner vertical visual resolution
L1[a]	Slightly slanted (approx. 5°) small black squares used to measure vertical and horizontal e-SFR at extreme corners of image
L2[a]	45° diagonal black square used to measure diagonal e-SFR
L3	Slightly slanted (approx. 5°) black bar used to measure centre horizontal e-SFR
L4	Slightly slanted (approx. 5°) black bar used to measure centre vertical e-SFR
M[a]	Circle containing vertical, horizontal and diagonal lines used to observe scanning nonlinearities
N[a]	Checkerboard patterns used to observe image compression artefacts
O1	Tilted (approximately. 5°) square wave bursts used to measure horizontal aliasing ratio
O2	Tilted (approximately5°) square wave bursts used to measure vertical aliasing ratio
P1[a]	100 to 1 000 line square wave sweep
P2[a]	100 to 1 000 line square wave sweep
R[a]	Indicators that may be used for automatic target alignment
T[a]	Slanted (approximately 5°) H-shaped bars used to measure e-SFR at far sides of image

[a] Indicates optional element.

I.3 Limiting resolution measurements in ISO 12233:2000

The limiting resolution in ISO 12233:2000 was defined as the value, in LW/PH, of that portion of a specified resolution test pattern that corresponds to an average modulation value equal to some specified SFR value (specifically 10 % SFR value). The test chart includes vertical, horizontal, and two diagonal square wave sweeps, labelled as P in Figure I.2, which are used to perform this measurement. For all four patterns, the reference response is defined as the difference between the signal values from the black squares at the end of the square wave sweeps and the white region around the square wave sweeps.

Some patterns included in the ISO 12233:2000 chart shown in Figure I.1 are provided for limiting resolution measurements as shown in Table I.1.

I.4 Spatial frequency response measurement in ISO 12233:2000 (high contrast edge SFR)

The edge spatial frequency response (SFR) measurement in ISO 12233:2000 was defined as the value measured by analysing the camera data near a slanted black to white edge. For the target shown in Figure I.2, the black L and T patterns are to be used to measure the horizontal, vertical, and diagonal e-SFR.

This method is an edge-based spatial frequency response (e-SFR) measurement using high contrast edge patterns, and has been replaced by the method using low contrast edge patterns described in Clause 6 and Annexes C and D.

NOTE Attention is drawn to the possibility of overstating the measured e-SFR values due to data clipping when using a test chart having a large reflectance ratio such as the original test chart defined in ISO 12233:2000. See the Introduction for additional information.

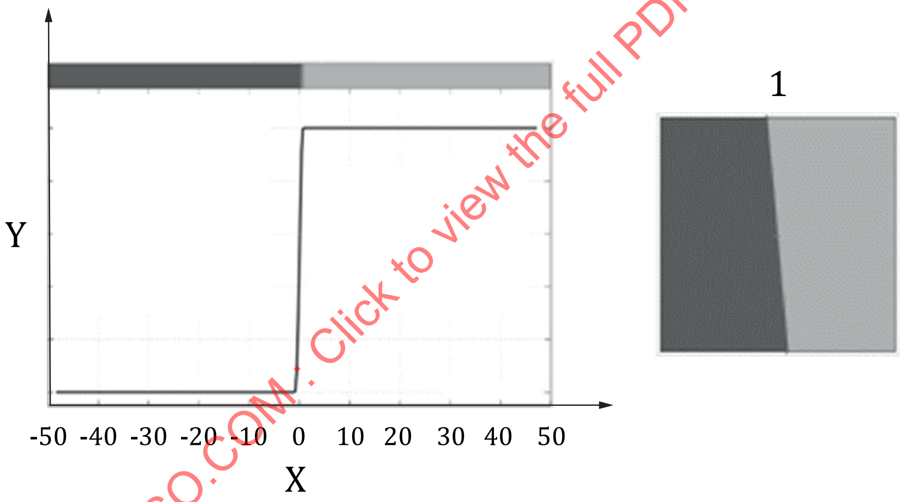
Annex J
(informative)

Non-uniform illumination compensation for some applications

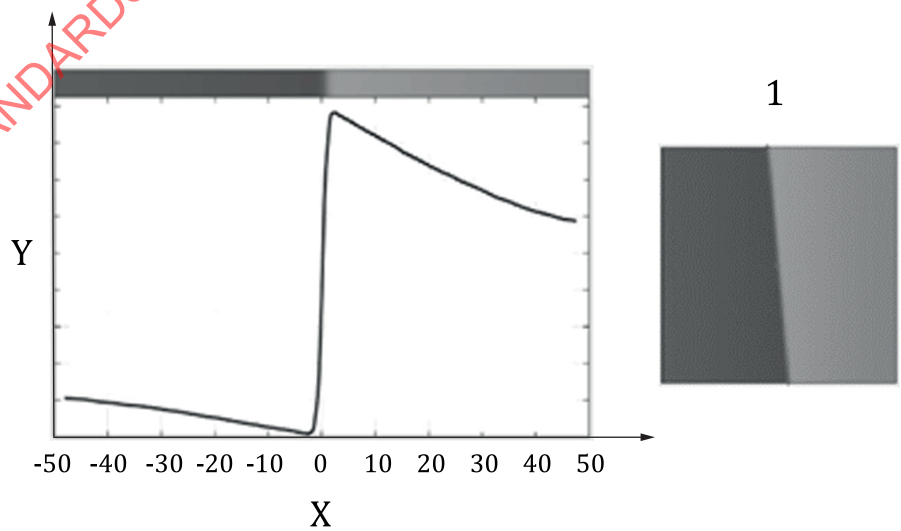
J.1 General

This informative annex describes an optional method of compensating for illumination non-uniformity when performing the e-SFR measurements. It allows the optional reporting of the e-SFR results "with non-uniformity compensation", along with the results with no compensation.

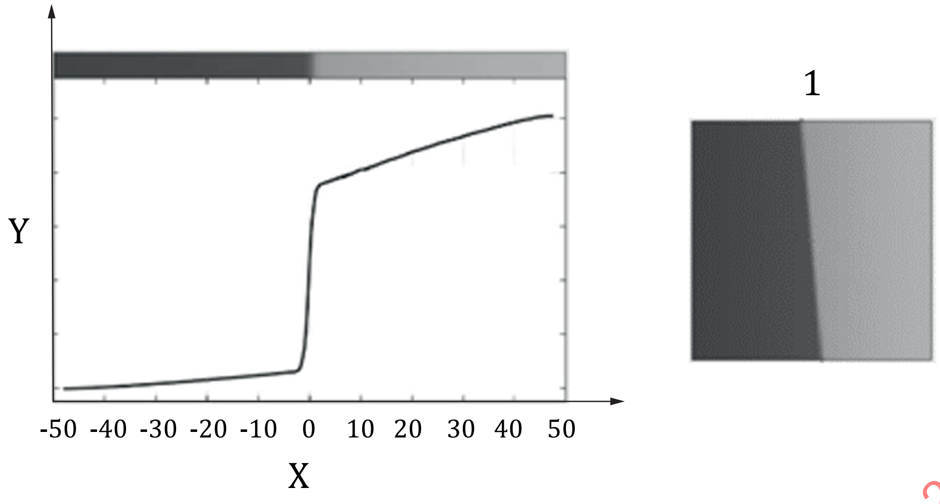
Although test chart illumination is specified to be within +/-10 % over the chart area, in some applications it may be difficult to obtain such uniformity because the illumination may be difficult to control (e.g. in medical devices, such as endoscopes) or because of lens and sensor vignetting. When the illumination is non-uniform within the region of interest (ROI) of the slanted-edge, e-SFR measurements can be significantly affected. Using uniform illumination is recommended for e-SFR measurements. However, when this is not possible, the non-uniform illumination compensation described in this annex can compensate for much of the effects of nonuniformity.



a) No illumination falloff



b) Left to right illumination falloff



c) Right to left illumination falloff

Key

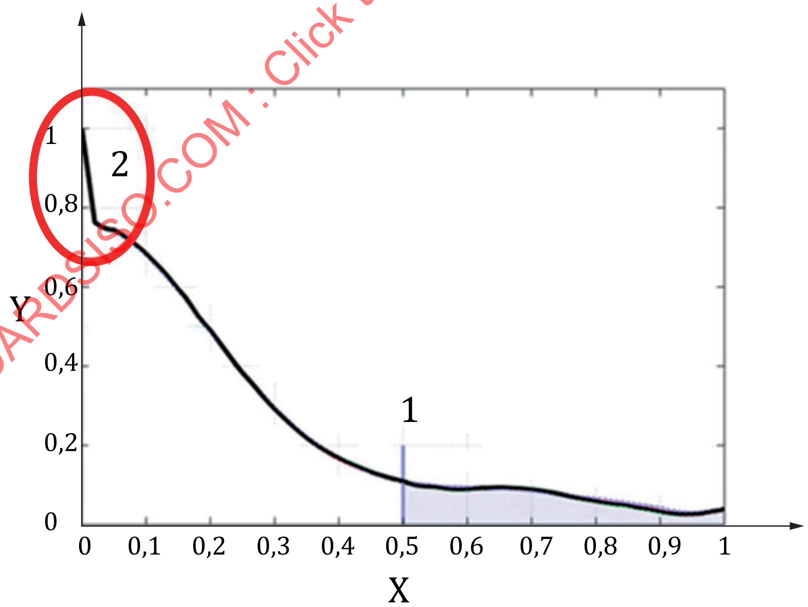
X pixels (horizontal)

Y ESF (edge spread function)

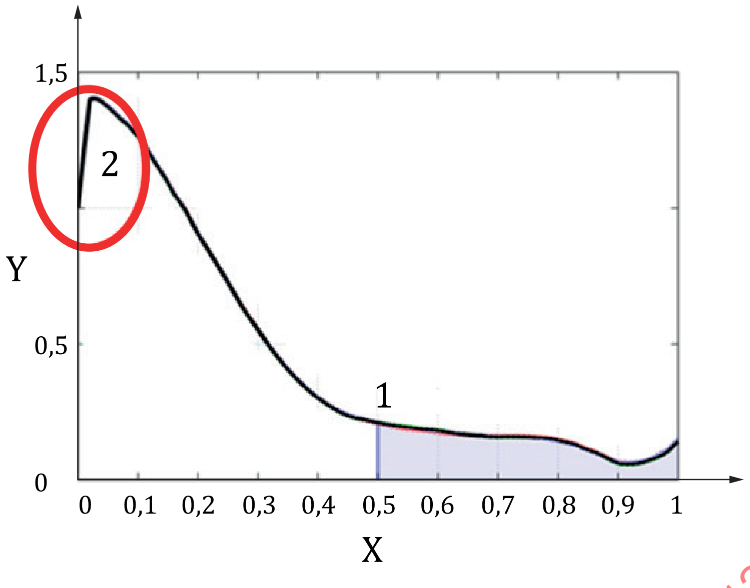
1 ROI (region of interest) 100 x 100 pixels

Figure J.1 — Simulated edge spread function (ESF)

The data in Figure J.1 is from simulated slanted-edge images, with and without simulated illumination falloff. The edge profile plots show the average edge response for the selected Region of Interest (ROI), shown to the right of the edge profile plots. The three examples demonstrate how non-uniformity effects the edge response for three different types of illumination: a) no falloff, b) falloff directed left-to-right, and c) falloff directed right-to-left.



a) Left-to-right falloff



b) Right-to-left falloff

Key

X normalized spatial frequency (cycles/pixel)

Y e-SFR values

1 nyquist frequency

2 low frequency irregularities

Figure J.2 — Resulting e-SFR plots for two slanted-edge regions from Figure J.1 having illumination falloff

The e-SFR values for the two examples with illumination falloff in Figure J.1 are shown in Figure J.2, where a) shows the e-SFR for the left-to-right illumination falloff, and b) shows the e-SFR for the right-to-left illumination falloff. Low frequency irregularities in the e-SFR response (circled in red) are caused by the non-uniform illumination. These irregularities can have a significant effect on important summary metrics such as SFR50 (the spatial frequency where the e-SFR value drops to 50 %), because e-SFR is normalized to 1 (or 100 %) at low spatial frequencies.