INTERNATIONAL STANDARD

ISO
12233

Second edition
2014-02-15

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

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

Reference number
ISO 12233:2014(E)

© ISO 2014

COPYRIGHT PROTECTED DOCUMENT

Contents

Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

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

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

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

For an explanation on the meaning of ISO specific terms and expressions related to conformity assessment, as well as information about ISO's adherence to the WTO principles in the Technical Barriers to Trade (TBT) see the following URL: Foreword - Supplementary information

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

This second edition cancels and replaces the first edition (ISO 12233:2000), which has been technically revised.

Introduction

0.1 Purpose

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

0.2 Technical background

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

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

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

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

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

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

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

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 International Standard. While resolution metrology of analog 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 is 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 International Standard, the target. For instance, in-camera edge detection algorithms might specifically operate on edge features and selectively enhance or blur them based on complex nonlinear decision rules. Depending on the intent, these algorithms might also be tuned differently for repetitive scene features such as those found in sine waves or bar pattern targets. Even for constrained camera settings recommended in this International Standard, these nonlinear operators can yield differing SFR results depending on the target feature set. Naturally, this causes confusion on which targets to use, either alone or in combination. Guidelines for selection are offered below.

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

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

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

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

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

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

1   Scope

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

2   Normative references

The following documents, in whole or in part, are normatively referenced in this document and are indispensable for its application. 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.

3.1
addressable photoelements
number of active photoelements in an image sensor

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 due to insufficient sampling

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

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

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

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

3.6
electronic still-picture camera
camera incorporating an image sensor that outputs an analog or digital signal representing a still picture

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

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

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

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

3.8
horizontal resolution
resolution value measured in the longer image dimension, corresponding to the horizontal direction for a "landscape" image orientation, typically using a vertical or near vertical oriented test-chart feature

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

3.10
image compression
process that alters the way digital image data is 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 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 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.

2

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

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

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

3.17
modulation
normalized amplitude of signal levels

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

3.18
modulation transfer function
MTF
modulus of the optical transfer function

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

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

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

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

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

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

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

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

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

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

3.24.1
edge-based spatial frequency response
e-SFR
measured amplitude response of an imaging system to a slanted-edge input, as defined in Clause 6

3.24.2
sine wave-based spatial frequency response
s-SFR
measured amplitude response of an imaging system to a range of sine wave inputs, as defined in Clause 7

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

3.26
test chart
arrangement of test patterns designed to test particular aspects of an imaging system

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

3.27.1
bi-tonal pattern
pattern that is spectrally neutral or effectively spectrally neutral, 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 by visual resolution method.

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

Note 1 to entry: A bi-tonal hyperbolic wedge test pattern is used to measure resolution by the visual resolution method in this International Standard.

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

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

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

4   Test conditions

4.1   Test chart illumination

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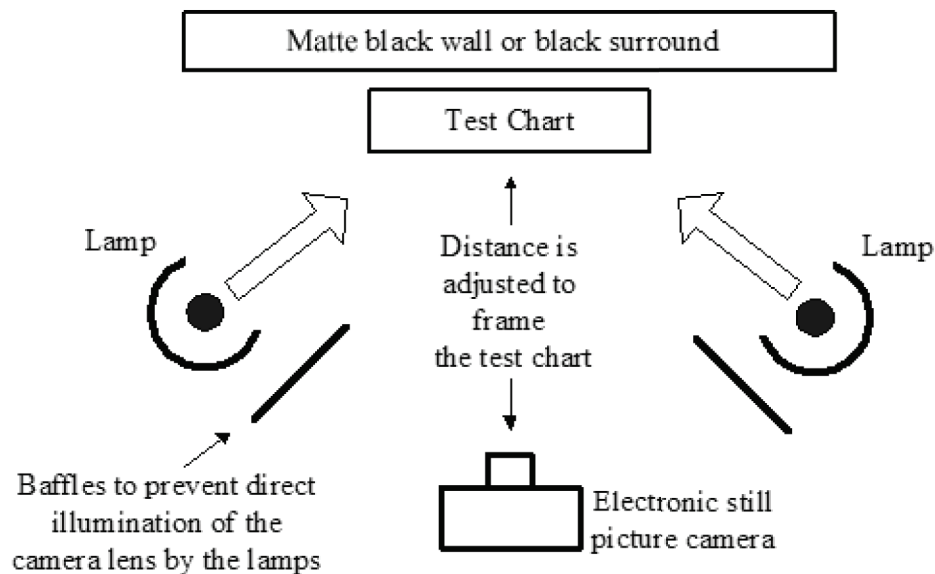

Figure 1 — Test chart illumination method

4.2   Camera framing and lens focal length setting

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

4.3   Camera focusing

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

4.4   Camera settings

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

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

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

4.5   White balance

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

4.6   Luminance and colour measurements

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

4.7   Gamma correction

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

5   Visual resolution measurement

5.1   General

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

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

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

5.2   Test chart

5.2.1   General

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

The chart shown in Figure 2 is designed to measure cameras having a resolution of less than 2 500 LW/PH. Nevertheless, it is possible to use the chart to measure the resolution of an electronic still camera having a resolution greater than 2 500 LW/PH. This is accomplished by adjusting the camera to target distance, or the focal length of the camera lens, so that the test chart active area fills only a portion of the vertical image height of the camera. This fraction is then measured in the digital image, by dividing the number of image lines in the camera image by the number of lines in the active chart area. The values of all test chart features, in LW/PH, printed on the chart or specified in this International Standard, 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.

5.2.2   Material

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

5.2.3   Size

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

5.2.4   Test patterns

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

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

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.

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.
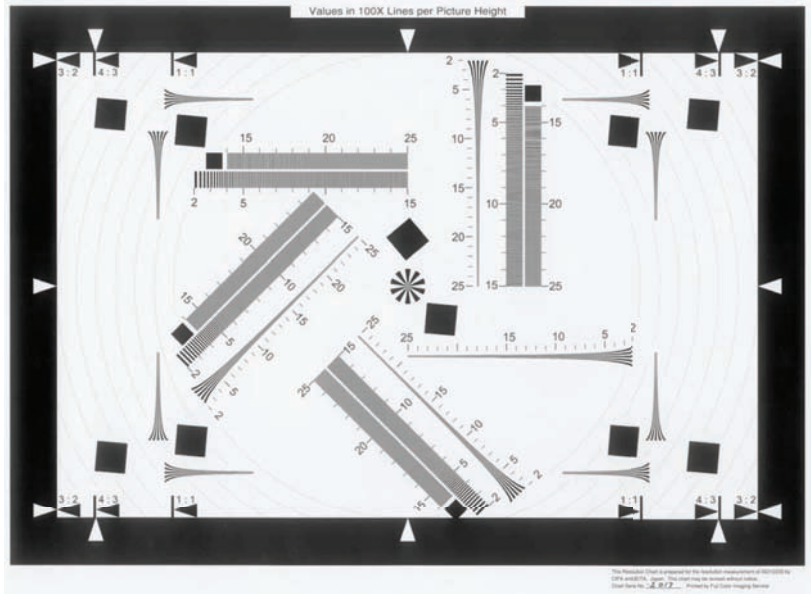
Figure 2 — CIPA resolution test chart

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 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 An example of a correct visual judgement

The boundary between the resolved and not resolved regions indicated by a dashed arrow is the corresponding point to resolution value to be measured as shown in Figure 3.

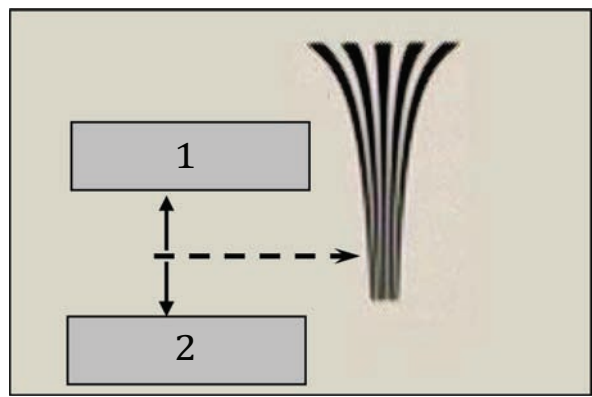**Figure 3 — Correct application of the wedge feature interpretation**

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

6.1 General

The edge-based spatial frequency response (e-SFR) of an electronic still-picture camera is measured by analysing the camera data near a slanted low contrast neutral edge. The preferred test chart for measuring e-SFR is shown in Figure 4 and specified in Annex C.
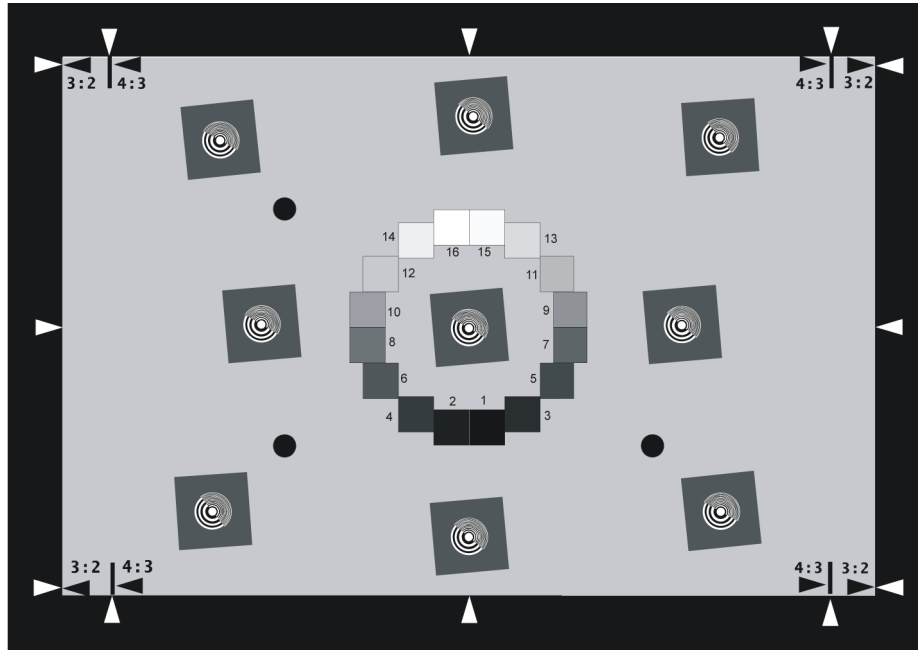

Figure 4 — Low contrast e-SFR test chart

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 SFR algorithm is defined in normative Annex D. A diagram depicting the key steps of the SFR algorithm is shown in Figure 5.

The algorithm can automatically compute the e-SFR, using image data from a user-defined rectangular region of the image which represents a near-vertically, or near-horizontally oriented dark to light or light to dark edge. The algorithm will be described assuming a near-vertical edge. To measure near-horizontally, 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.

6.2 Methodology

6.2.1 Selection of the edge region of interest (ROI)

The user selects the region containing the slightly slanted edge. If the image is coloured, a luminance record is created before the SFR calculation is performed. The result is a two-dimensional matrix of data of values (n lines, m pixels). See item A in Figure 5.

6.2.2 Transformation into effective exposure

The image code values shall then be linearized by inverting the opto-electronic conversion function (OECF) of the camera. The OECF shall be measured as specified in ISO 14524. Each pixel value in the ROI is now transformed into an equivalent target reflectance value. See item B in Figure 5.

9

6.2.3   Estimation of the location of the edge

This is done in two steps. See items C1 and C2 in <u>Figure 5</u>.

6.2.3.1   Initial estimation of edge location (offset) and slope

6.2.3.2   Final estimation of edge location (offset) and slope

— Compute one-dimensional derivative

For each line of pixels perpendicular to the edge, the data are multiplied with a Hamming window vector of the same length (m). For each line of pixels in the resulting array, the derivative of the linearized image data are computed using a $[-1/2, +1/2]$ finite impulse response (FIR) filter. The result is an array which is the same size as the input ROI.

Figure 5 — Flowchart of e-SFR measurement algorithm

Figure 6 — Parts of element C in [Figure 5](#)

— Compute location of the edge for each line of data

The one-dimensional centroid of this derivative matrix 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).

— Estimate slope and location of the edge

A linear best-line fit to the centroid locations as a function of line number is then calculated. That is, from Formula (1)

$$y = mx + b \tag{1}$$

where y is the set of centroid location and x is the set of line location (1, n), compute the best-fit values for the slope, m, and offset, b. Error messages shall be reported if any centroid is within two pixels of either side of the input image edges, or if the edge does not contain at least 20 % modulation.

6.2.3.3 Final estimation of edge location

For each line of pixels perpendicular to the edge, the location of the centroid of the line is computed from Formula (2),

$$y_1 = m_1 x + b_1 \tag{2}$$

where y_1 represents the vector of centroid location computed as illustrated in [Figure 6](#). This results in a vector of y' values.

The transformed image data are multiplied with a Hamming window vector of the same length (n). In this case, the Hamming window function is centred at y' for each line. For each line of pixels multiplied with thus-centred Hamming window array, the derivative of the image data are computed using a [−1/2, +1/2] finite impulse response (FIR) filter. The result is an array which is the same size as the input ROI.
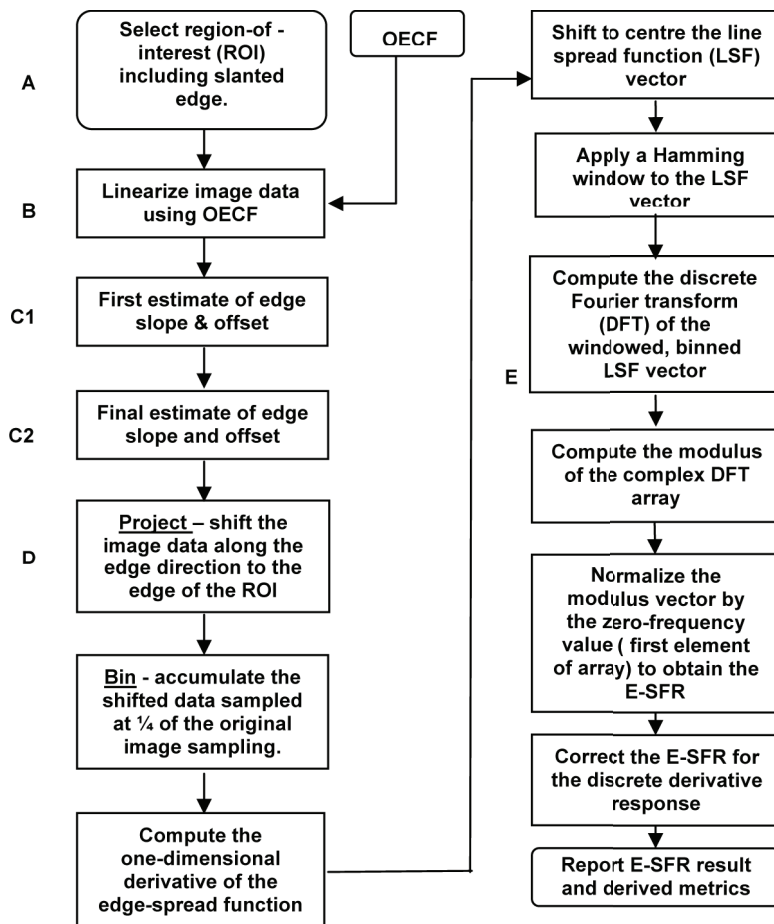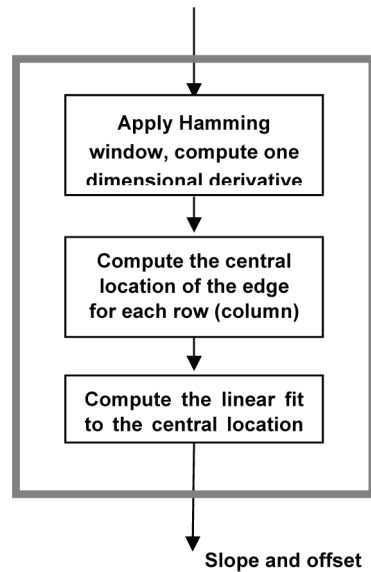
6.2.3.4 Computation of final location of the edge for each line of data

The one-dimensional centroid of this derivative matrix 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).

6.2.3.5 Estimation of final slope and location of the edge

A linear best-line fit to the centroid locations as a function of line number is then calculated. That is, from Formula (3)

$$y = mx + b \tag{3}$$

where y is the set of centroid location and x is the set of line location (1, n), compute the best-fit values for the slope, m, and offset, b.

6.2.4 Formation of a super-sampled line spread function array

A one-dimensional super-sampled edge spread function shall be formed using the data of the truncated two-dimensional ROI image data. 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.

From this vector, a corresponding line spread function array shall be derived by computing the length-3 discrete derivative. The derivative vector is computed using a [–1/2, 0, +1/2] finite impulse response (FIR) filter, meaning that the derivative value for pixel "X" is equal to –1/2 times the value of the pixel immediately to the left, plus 1/2 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.

6.2.5 Computation of the e-SFR

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 (4n). The centred line spread function shall be multiplied by a centred Hamming 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 discrete Fourier transform (DFT) of the windowed line spread function shall be calculated. The e-SFR is the normalized modulus of the DFT of the centred, windowed line spread function. The final e-SFR is 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. See References [13], [17], and [20] for supplementary information on the e-SFR method.

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

The sine-based spatial frequency response (s-SFR) of an electronic still-picture camera is measured by analysing the camera image taken of a sine wave-modulated starburst pattern. The preferred test chart for measuring the maximum resolution is shown in Figure 7 and will be specified in 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 opto-electronic conversion function shall be measured as specified in ISO 14524. 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.

---

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.

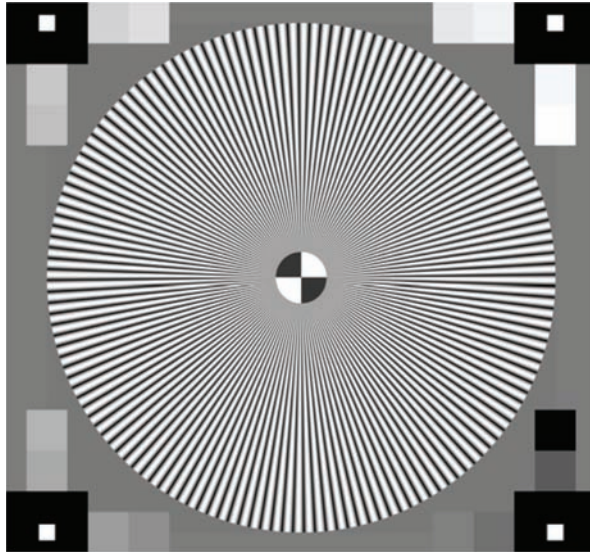A detailed description of the algorithm used is specified in Annex F.

Figure 7 — 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 or not dark-field and 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 can be the same for any interchangeable lens), the calculated camera measurements without a lens can also be reported in the case of SFR.

NOTE   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 by visual resolution measurement shall be reported as spatial frequency values, in LW/PH.

The resolution value derived from the SFR as the spatial frequency value for a given 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 can 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 can also be reported as the frequency value associated with a given modulation level. It shall be reported using a graph plot or a chart diagram.

Summary resolution metrics derived from the SFR may also be used. Depending on the use case, the spatial frequency associated with selected SFR response levels (ordinate value) may also be used. The SFR criterion levels and SFR methodology used shall be cited in this case. The reader is referred to Reference [20] for a comparison 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 and vertical directions. The values shall be the average of four replicate SFR measurements of a low contrast 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 cycles/mm on the sensor, or with equations 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 8 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.
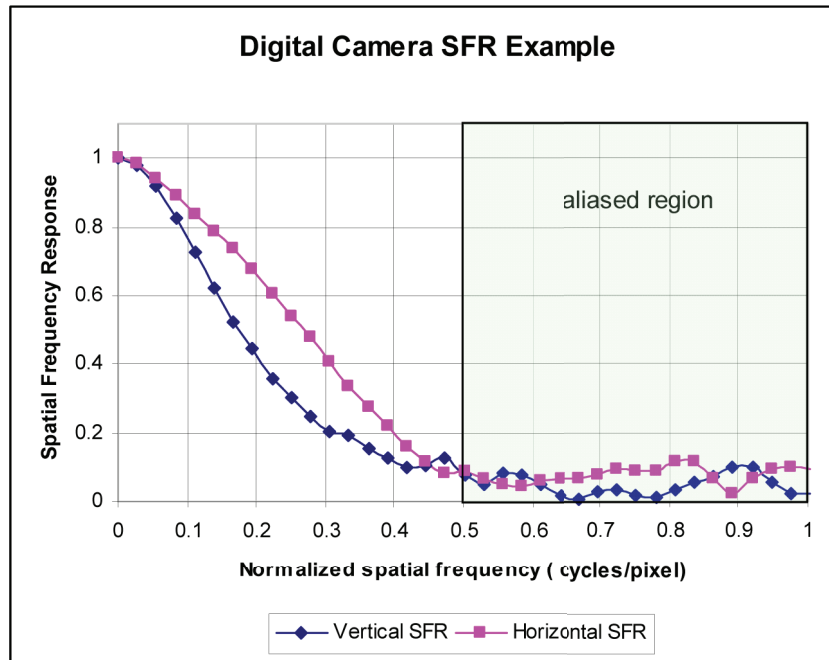
Figure 8 — Spatial frequency response plot

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 9 shows an example of a suitable method for reporting the frequency values corresponding to certain modulation levels (for example 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.
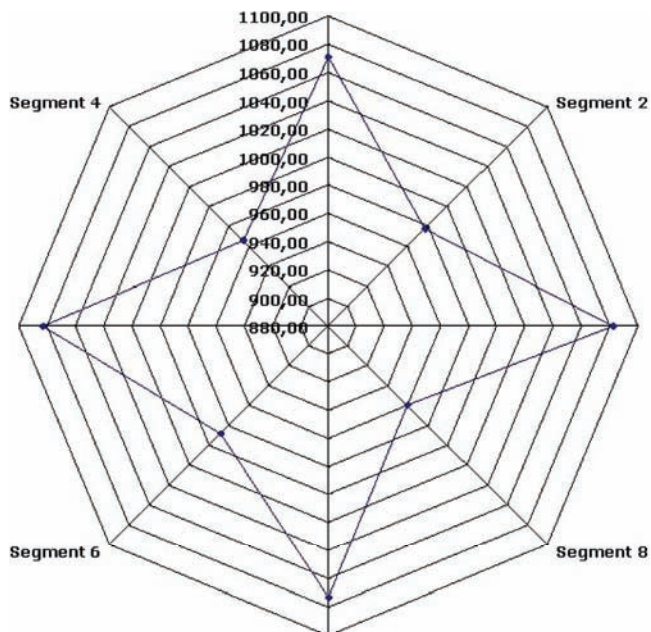
NOTE   Measurement conditions: lens focal length = 55 mm, lens aperture = f/4, camera compression = off, white balance setting = daylight, dark-field and flat-field correction were not used, 2 000 lx daylight illumination.

Figure 9 — Resolution value derived from the s-SFR (e.g. 10 % modulation) measured for different angular orientations

Annex A
(informative)

CIPA resolution test chart

A.1   Test chart features

The CIPA test chart includes the features listed in Table A.1, which are located as shown in Figure A.1.

Table A.1 — Description of CIPA test 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
J	200 LW/PH to 2 500 LW/PH hyperbolic zone plates used to measure visual resolution
L	Slightly slanted (approx. 5° or 50°) small black squares used to measure SFR
P	200 LW to 2 500 LW/PH square wave sweep
Q	For checking whether the peripheral portions are in focus
S	Concentric circles for reference when other patterns are added
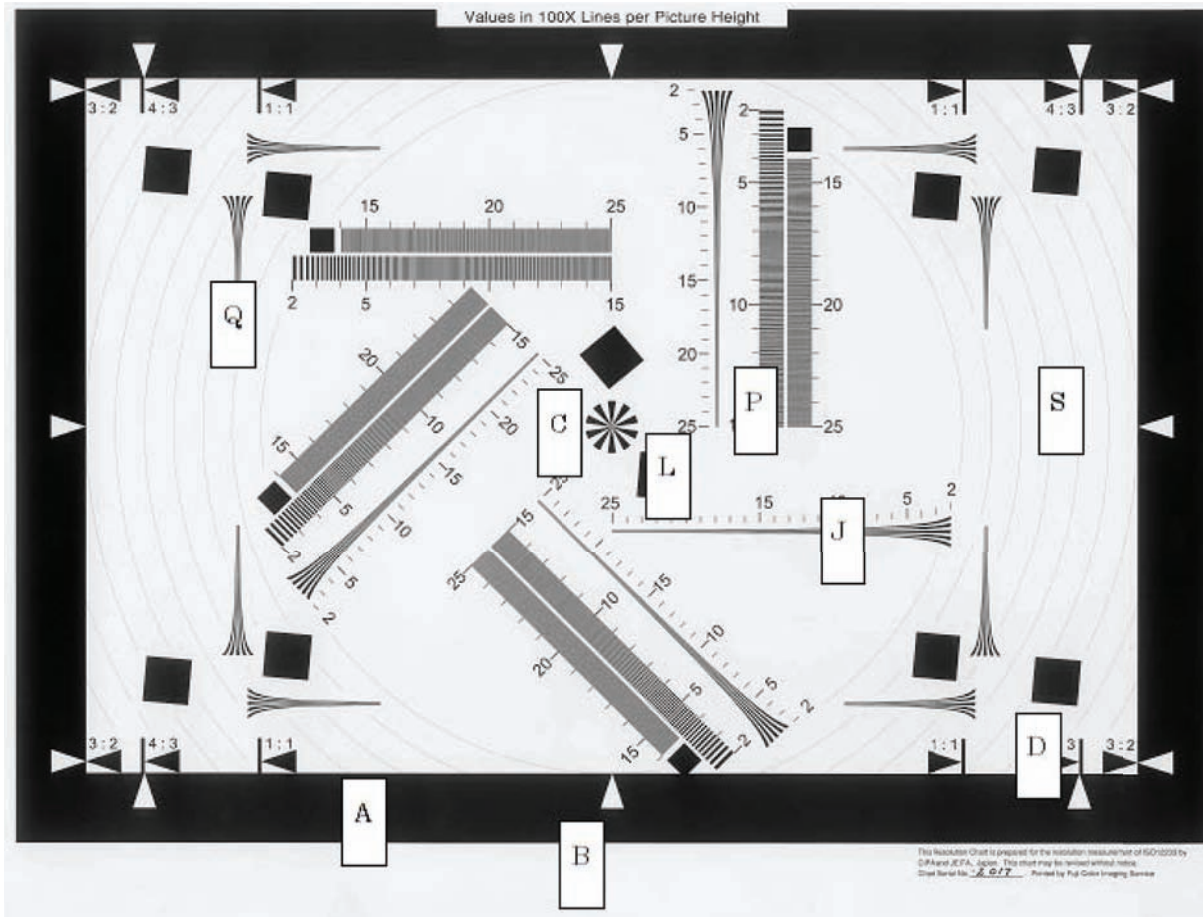
Figure A.1 — Characteristics of the visual resolution test chart

A.2 Test chart tolerance

This chart satisfies the following requirements.

a) The ratio of the reflectance of the white background, R_{max}, and the reflectance of the large black areas, R_{min}, shall satisfy the following: $80 > R_{max}/R_{min} > 40$.

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 test chart

Figure A.2 — Dimensional drawing "A" for visual resolution target
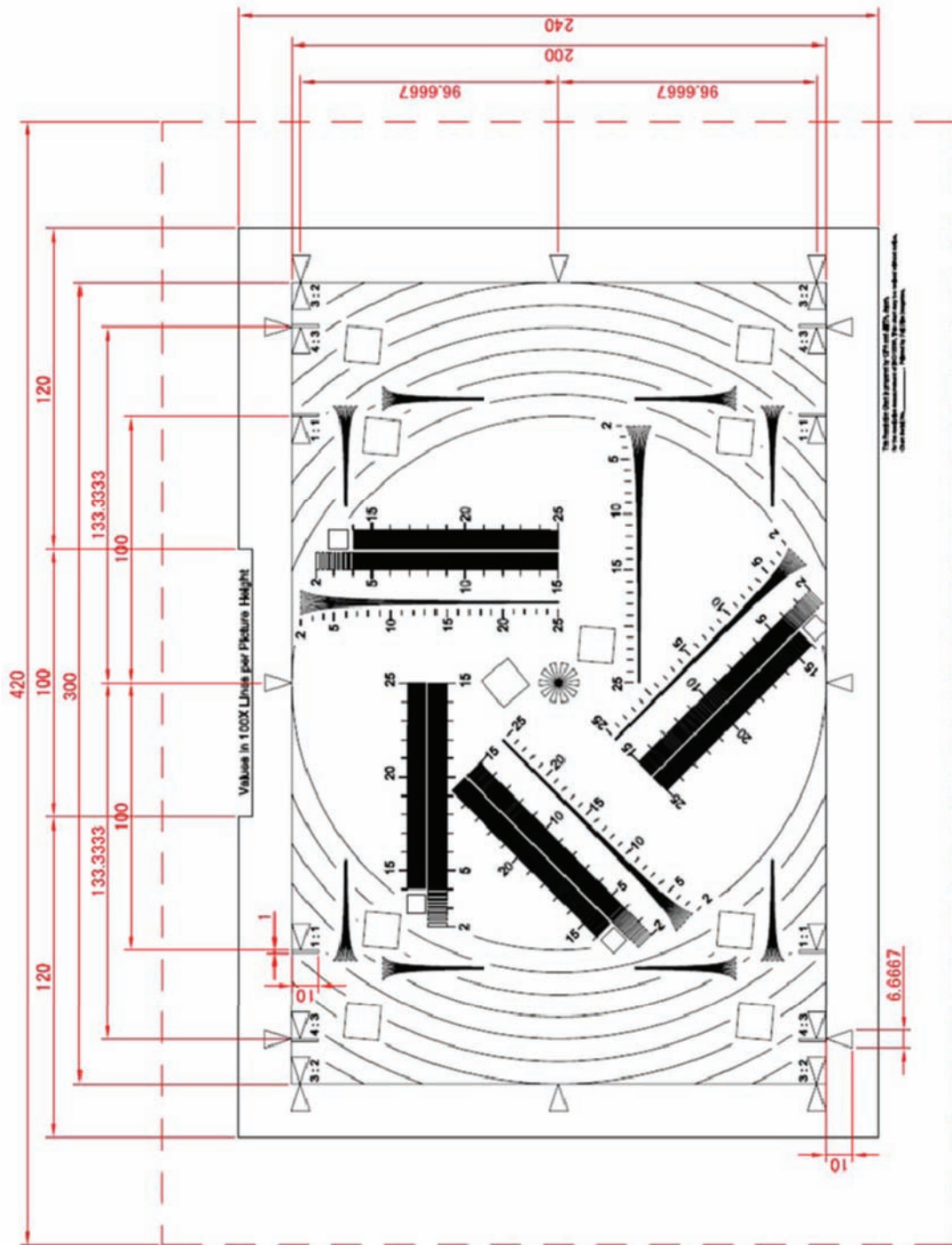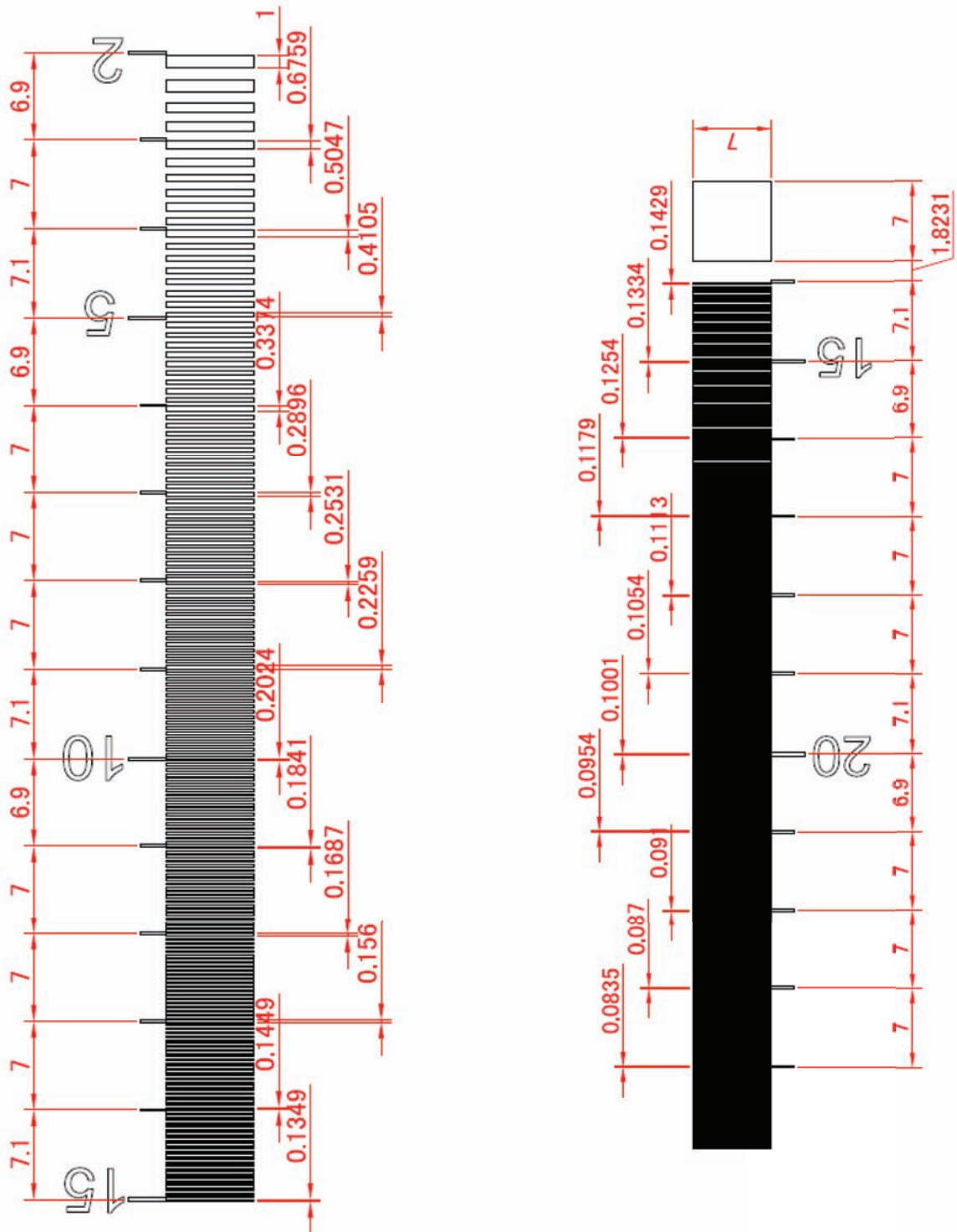
Figure A.3 — Dimensional drawing "B" for visual resolution target

Figure A.4 — Detail drawing for linear frequency sweep
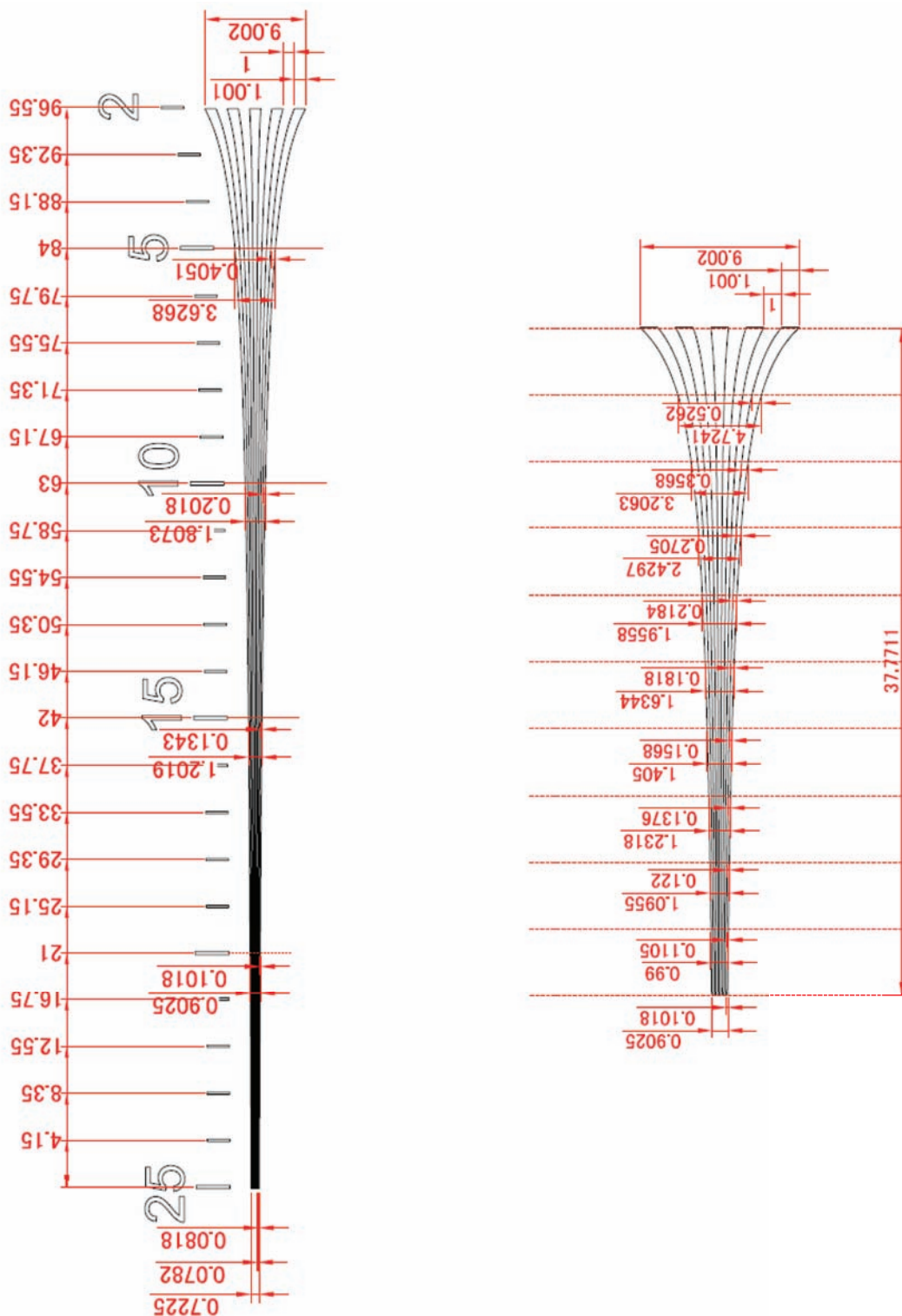
Figure A.5 — Detail drawing for five-line hyperbolic wedge pattern

Annex B
(informative)

Visual resolution measurement software

B.1   Background and purpose

The HYResACE[2] measurement software correlates 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.

The HYResACE 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 of this International Standard to remove the influence of artefacts.

B.2   Downloading the software

The "HYResACE" measure software that performs this measurement and the document "CIPA standard DC-003", which contains a more detailed description of the software algorithm, can be downloaded (at no cost) from the following URL:

http://www.cipa.jp/english/hyoujunka/kikaku/cipa_e_kikaku_list.html

This web page is labelled "List of new or revised standards" under CIPA's homepage, and the link to HYResACE download page is added at the bottom in the column of DC-003.

The document includes some annexes for HYRes (the original HYResACE software that uses the same algorithm) and a flowchart that completely describes the corresponding source code. There is also an annex report 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.

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

2) 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.

---

2)   HYResACE 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.
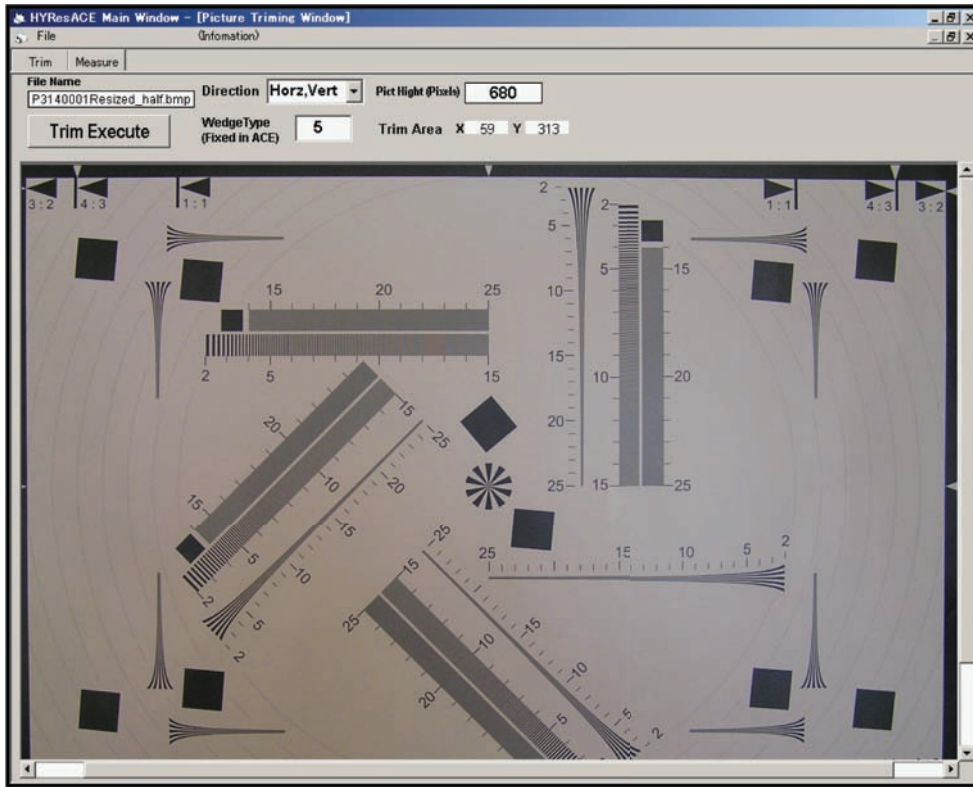
Figure B.1 — Trimming window of HYResACE
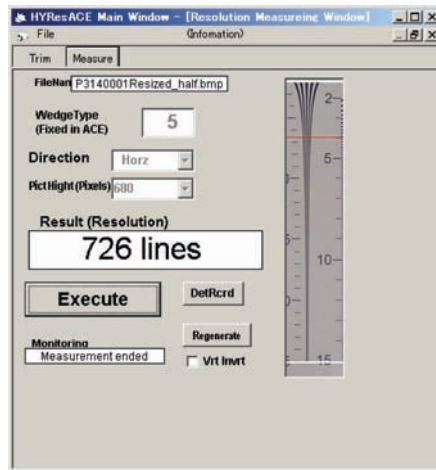
Figure B.2 — Measuring window of HYResACE

3) 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.

4) 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 — An example of automatic rotation (the case of 45° multiple rotation)

B.4   The outline of the software processing

B.4.1   Main process

HYResACE 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.

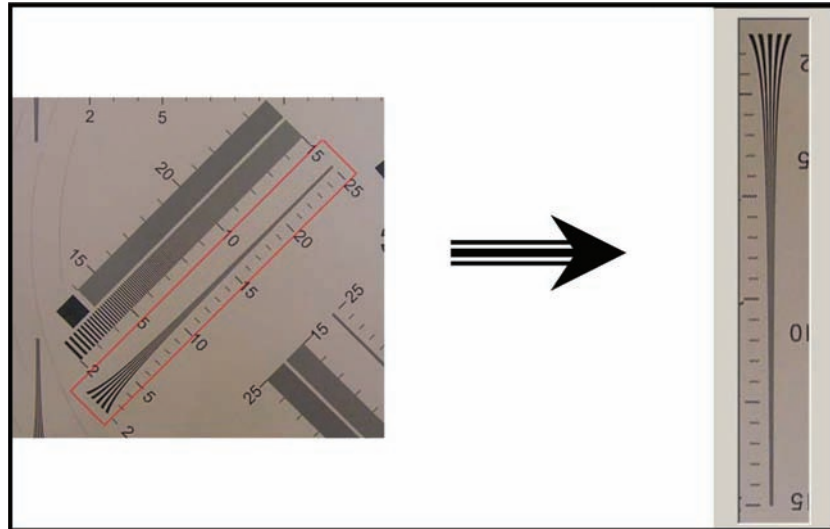The reported visual resolution is easily calculated by taking the ratio of the calculated position of the resolution limit line to the overall wedge length. The correct absolute value is calculated by correcting the ratio to the actual magnification by using the wedge length and the image height (vertical 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

HYResACE 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 and 45° slanted resolution measurements are performed by rotating the captured wedge images before performing the measurement.

The 90 degrees 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 degree (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. HYResACE automatically compensates for this factor as required.

5	10	15	20	25
4	9	14	19	24
3	8	13	18	23
2	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)

Low contrast edge SFR test chart with OECF patches

A lower contrast SFR test chart is used based on experiences from the original ISO 12233 target shown in Figure I.1. The high contrast edge features of the original ISO 12233 target often yielded clipped count values in the final image file, especially for processed image files. This led to corrupted and variable SFR results. The lack of OECF patches in the original target also made it inconvenient to account for the OECF response without a separate capture. The proposed test chart is shown in Figure C.1. It is a grey scale test chart which includes a low modulation slanted edge. The test chart also includes grey scale patches which are used to determine the OECF. While the example chart in Figure C.1 uses 16 OECF test patches, a 20 patch version as described in ISO 14524 may also be substituted.
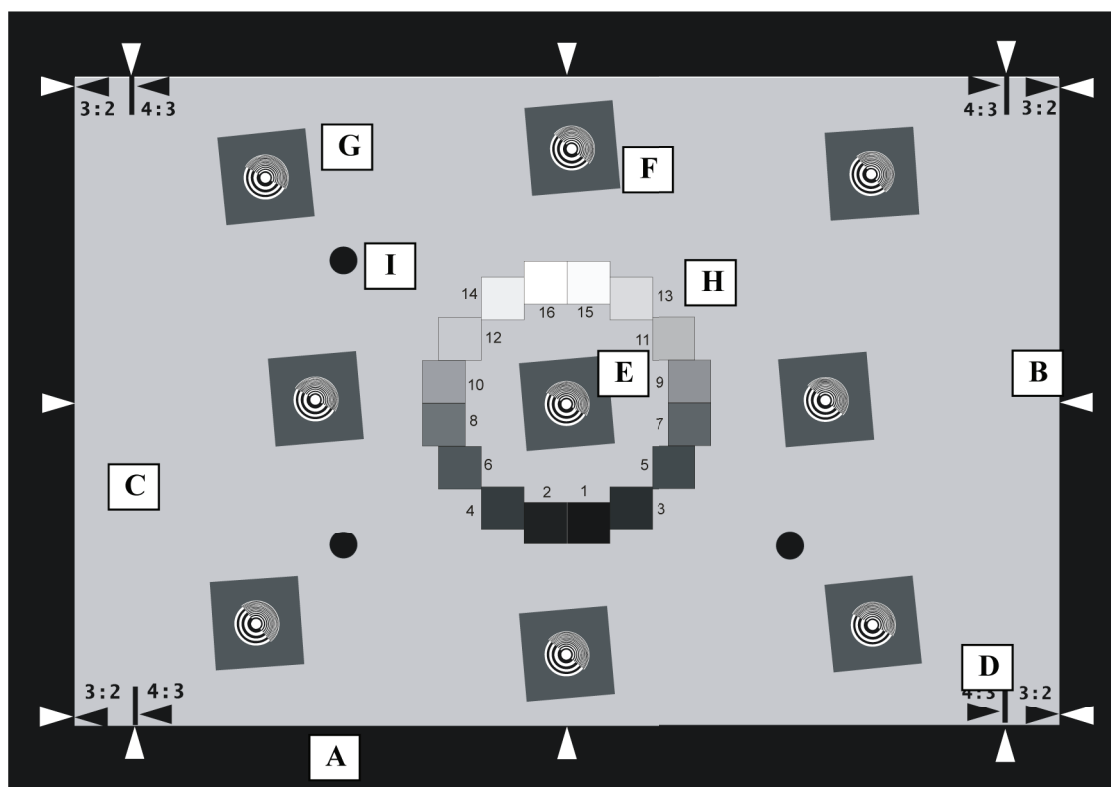

Figure C.1 — Low contrast edge SFR test chart with OECF patches

Table C.1 — Details and requirements of the low contrast edge SFR test chart in Figure C.1

Code	Characteristics and application
A	Black border with inner edge which defines active target area
B	White framing arrows used to frame target horizontally or vertically
C	Active target area. The integrated reflectance (or transmittance) of the area within the 4:3 aspect ratio bounds (R_L) shall be between 0,15 and 0,25.
D	Framing lines and arrows that define 4:3 and 3:2 aspect ratios
E	Centre slanted edge square (5°) with focusing aid to provide on-axis SFR metrology. This feature shall be of sufficient size to satisfy the 32 frequency sample requirement of 8.3.2 for a 640 × 480 pixel dimension of the active area. It shall be centred within the active area. The modulation contrast shall be between 0,55 and 0,65.
F	Slanted edge squares used to measure SFR at 50 % field position for 4:3 aspect ratio. This feature shall be of sufficient size to satisfy the 32 frequency sample requirement of 8.3.2 for a 640 × 480 pixel dimension of the active area. There shall be four of these features, two centred horizontally and two centred vertically on either side of the feature E. A 5 % positional tolerance relative to the 50 % field position is allowed. The modulation contrast shall be between 0,55 and 0,65.
G	Slanted edge squares used to measure SFR at 70 % field position for 4:3 aspect ratio. This feature shall be of sufficient size to satisfy the 32 frequency sample requirement of 8.3.2 for a 640 × 480 pixel dimension of the active area. There shall be four of these features positioned on the active area diagonals as shown in Figure C.1. A 5 % positional tolerance relative to the 70 % field position is allowed. The modulation contrast shall be between 0,55 and 0,65.
H	OECF patches whose reflectances, 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 edge features. 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 aspect ratio, but can be placed for convenience as dictated by use cases.

Annex D
(normative)

Edge spatial frequency response (e-SFR) algorithm

Software that performs this measurement can be accessed from www.iso.org/12233.

The edge-based SFR (e-SFR) measurement algorithm used in this International Standard for analysis of the low contrast tilted edge uses the normalized discrete Fourier transform (DFT) of a single line spread function (LSF):

$$\text{e-SFR}(k) = D(j) \left| \frac{\sum_{j=1}^{N} LSD'_W(j) e^{-2\pi kj/N}}{\sum_{j=1}^{N} LSD'_W(j)} \right|, \text{ for } k = 0,1,2,...,N/2, \text{ or } (N+1)/2 \text{ if } N \text{ is odd} \qquad \text{(D.1)}$$

where

k is the index for spatial frequency;

$LSD'_W(j)$ is the windowed, average, centred, super-sampled line spread function formed from the selected region of the chart image. Much of the data processing in the algorithm and employed in the SFR measurement algorithm is involved in preparing LSD'_W for the DFT;

$D(j)$ is the correction for the frequency response of the discrete derivative used to derive the point spread function from the edge spread function, $D(j) = \min\left[\dfrac{1}{\sin(\pi k/N)}, 10\right]$.

The SFR measurement algorithm constrains the selection region to be an even number of pixels (P) and rows (R). The selected region is converted from digital code values to an edge spread image of normalized photopic intensities via the OECF and colour weighting coefficients a, b, and c [see Formula (D.2)].

$$\varphi(p,r) = a \, OECF\left[DN_{red}\right] + b \, OECF\left[DN_{green}\right] + c \, OECF\left[DN_{blue}\right] \qquad \text{(D.2)}$$

where

DN   is the digital output level;

(p, r) is the index of each pixel.

Each row (r) of the edge spread image is an estimate of the camera edge spread function (ESF). Each of these ESFs is differentiated to form its discrete line spread function (LSF). The position of the centroid (C) of each r LSF is determined along the continuous variable x [see Formula (D.3)].

$$C(r) = \frac{\sum_{P=1}^{P-1} p\left[\phi(p+1,r) - \phi(p,r)\right]}{\sum_{P=1}^{P-1} \left[\phi(p+1,r) - \phi(p,r)\right]} - 0,5 \tag{D.3}$$

The slope, m, of the best-fit line relating the x positions of the centroids to the r index of each row is computed as follows:

$$m = \frac{\Delta r}{\Delta C(r)} \tag{D.4}$$

This slope, m, is used to compute a shift, $S(r)$, to be applied to each row to bring each ESF to coincidence around a common origin at $x = 0$. It effectively takes the tilt out of the edge.

$$S(r) = \bar{C} \frac{(R/2) - r}{m} \tag{D.5}$$

The next step is the super sampling and averaging. This step forms a composite requantized edge spread function (ESF) 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 $N = 4X$ bins are created, each with a width of 1/4 pixels.

$$ESF'(j) = \frac{\sum_{r=1}^{R'} \sum_{p=1}^{P} \varphi(p,r) - \alpha(p,r,j)}{\sum_{r=1}^{R'} \sum_{p=1}^{P} \alpha(p,r,j)} \tag{D.6}$$

The function alpha (α) is simply a counter and a switch to include or exclude a value in any bin.

$$\alpha(p,r,j) = \begin{cases} 1, & -0,125 \leq \left[p - S(r) - j\right] < 0,125 \\ 0, & \text{otherwise} \end{cases} \tag{D.7}$$

where

    j is an integer.

The average super-sampled edge spread function is then differentiated and windowed.

$$LSF_W'(j) = W(j) \frac{ESF(j+1) - ESF'(j-1)}{2} \tag{D.8}$$

$$W(j) = 0,54 + 0,46\cos\left(2\pi(j - 2X)/4X\right) \tag{D.9}$$

Substitution of Formula (D.8) into Formula (D.1) produces SFR(f), where $f = k/X$, so that the data are reported in cycles/pixel.

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 1/2 times the number of rows of photosites per millimetre on the sensor (for vertical SFR measurements) or 1/2 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).

A diagram depicting the key steps of the e-SFR algorithm is shown in Figure D.1.

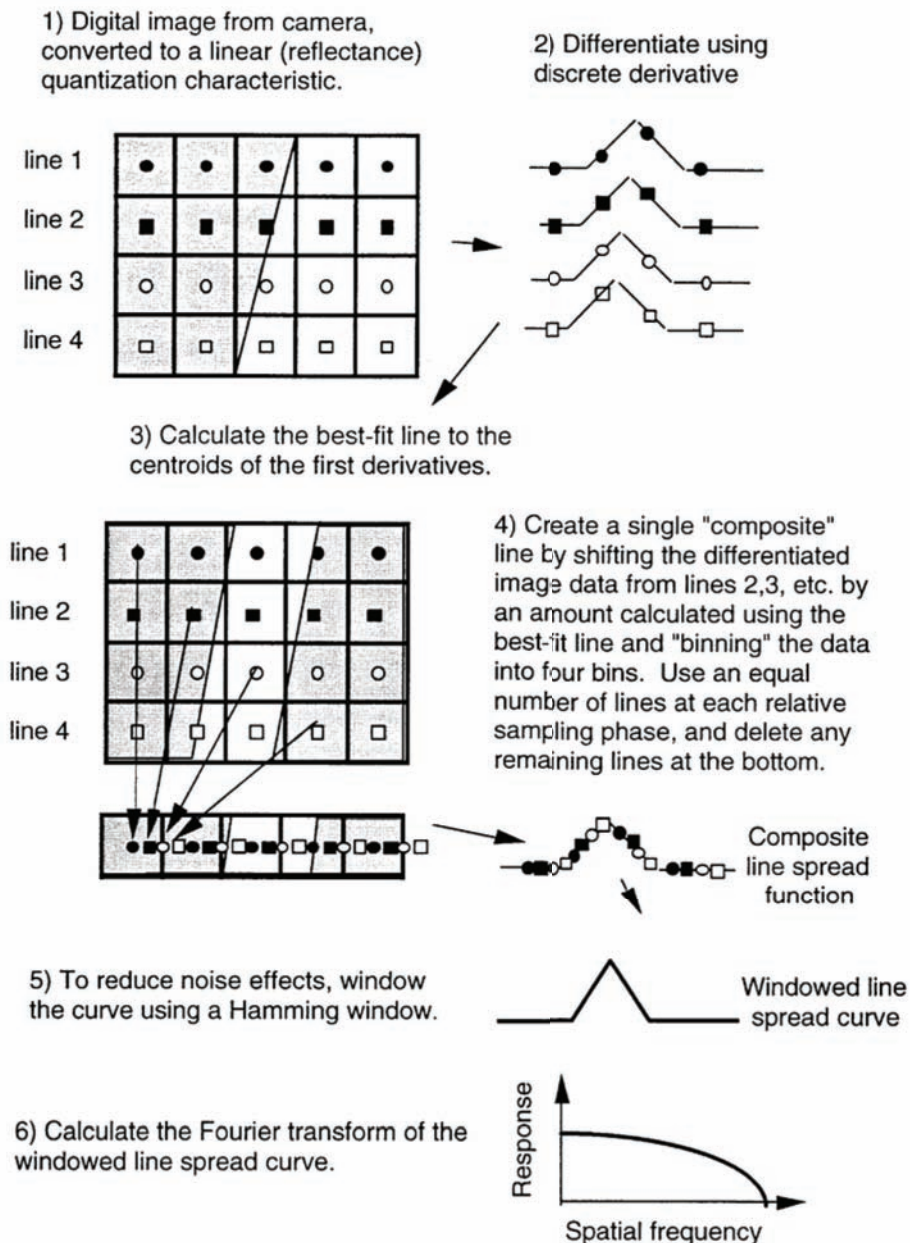**Figure D.1 — Diagram depicting the key steps of the e_SFR algorithm**

Annex E
(normative)

Sine wave star test chart

The sine wave star test chart can be used as a single chart or multiple charts can be arranged in one image. The chart should be grey. The camera should be white balanced prior to the measurement.
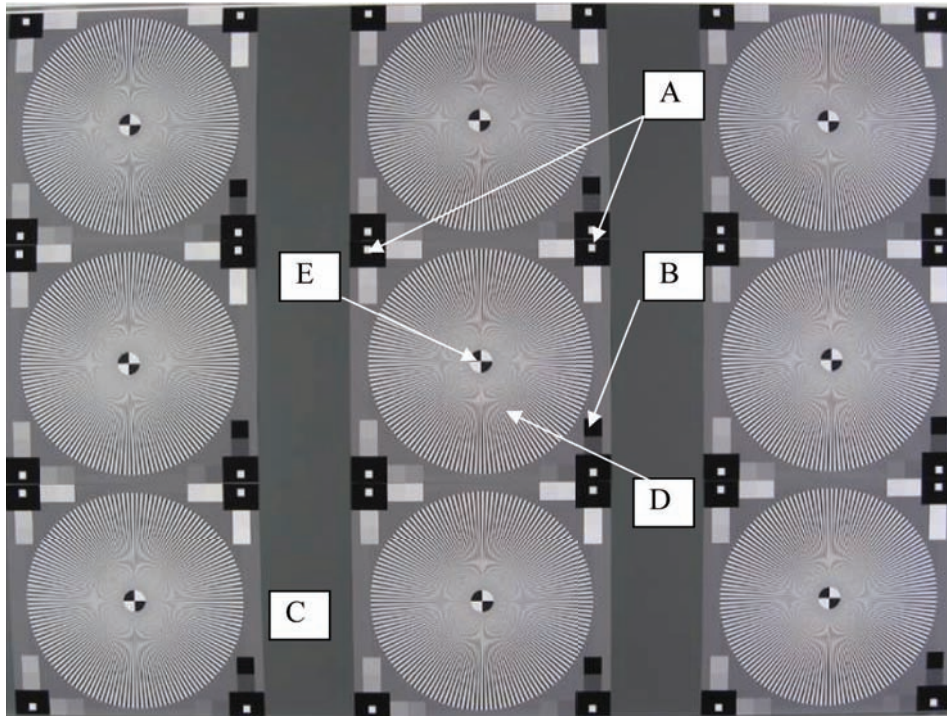

Figure E.1 — Sine wave test chart (multiple target version)

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 can be used.
E	Center 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 above 50:1 and below 250:1 reflectance ratio.

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
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
Code	**Subcode**	**Position centre** (x;y)	**Size**	**Digital value in linear image**
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 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 this test chart. 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 8 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. Then the OECF of the camera is determined using the 16 grey patches of the central star. The image is linearized using the inverse of the OECF.
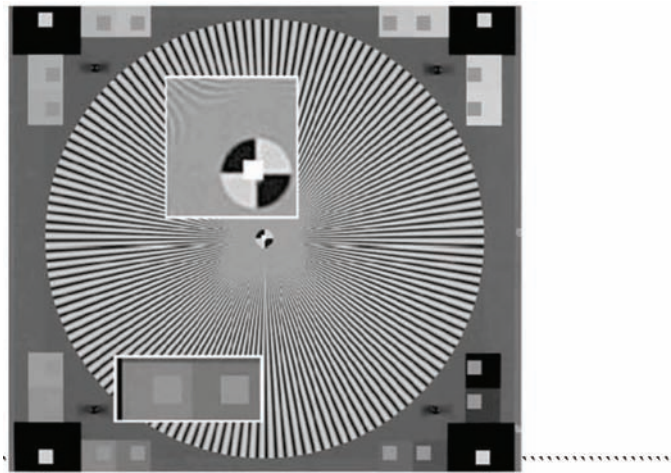

Figure F.1 — Chosen positions of the OECF patches and the centre of the star number 0

---

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.

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.

$$res = \frac{N_y}{g} = \frac{N_p \cdot N_y}{2\pi r_{Pixel}} \qquad (F.1)$$

with

$$g = \frac{2\pi r_{Pixel}}{N_p} = cycle\ length\ in\ Pixels \qquad (F.2)$$

where

   res 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 I.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.

Then the star is divided into 24 segments. In one segment on one single radius, the nearest pixels to that radius are searched, and the digital value and the angle under which the pixel was found are stored. There is no interpolation for pixel values on the radius. Instead of using interpolation methods, the nearest pixel beside the correct radius position is used, if there is no pixel in the exact place (Figure F.3). This leads to lower errors in the result than pixel value interpolation. The mean value of the data of three segments is calculated. So finally, data of eight segments are obtained. This provides information on vertical, horizontal, and diagonal contrast behaviour of the cameras.
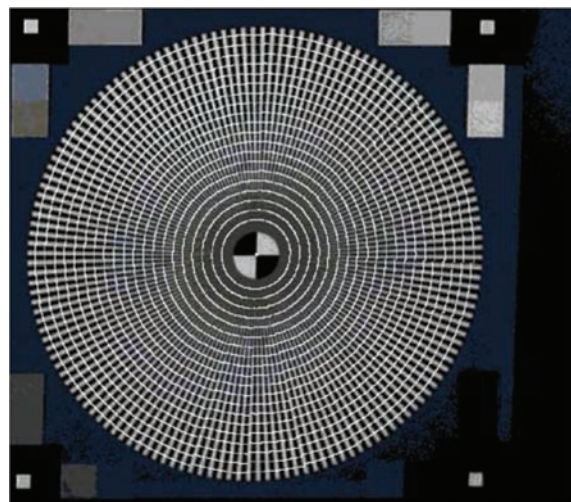

Figure F.2 — For 24 segments, the border of the star is detected and results in a distortion corrected analysis

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 can be divided into a user-selected number of segments (typically 8). 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 using the four surrounding markers for the region of interest.

— Step 2: The image is linearized using the 16 grey patches around the star.

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

— Step 4: A minimum of 32 radii are analysed by localizing the pixels along the radius and selecting the digital code values for the linearized image as a function of the angle.
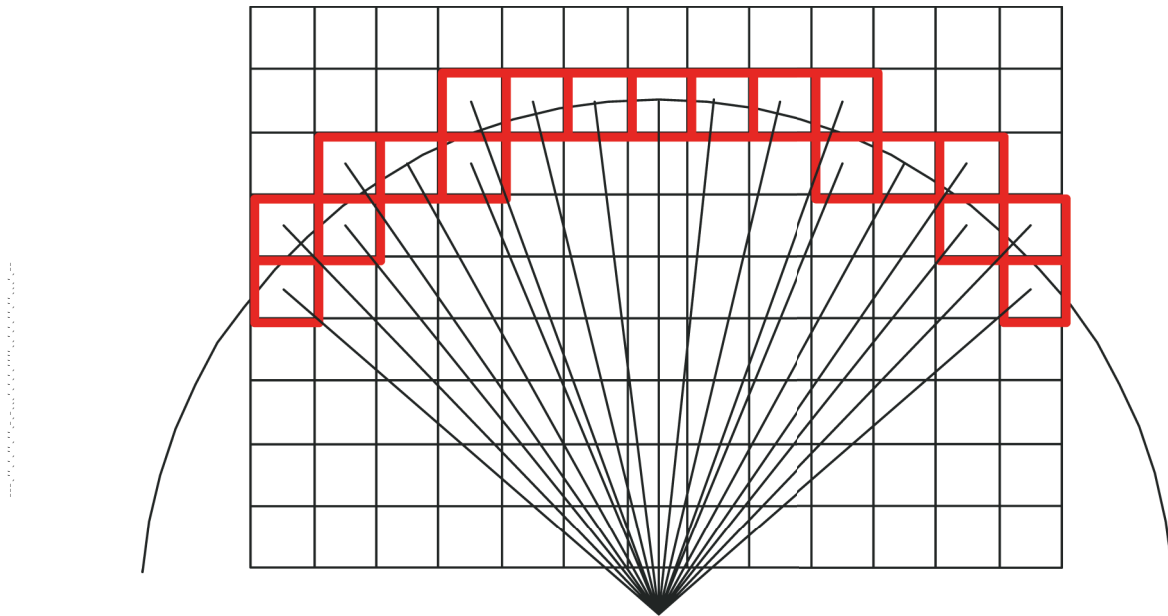
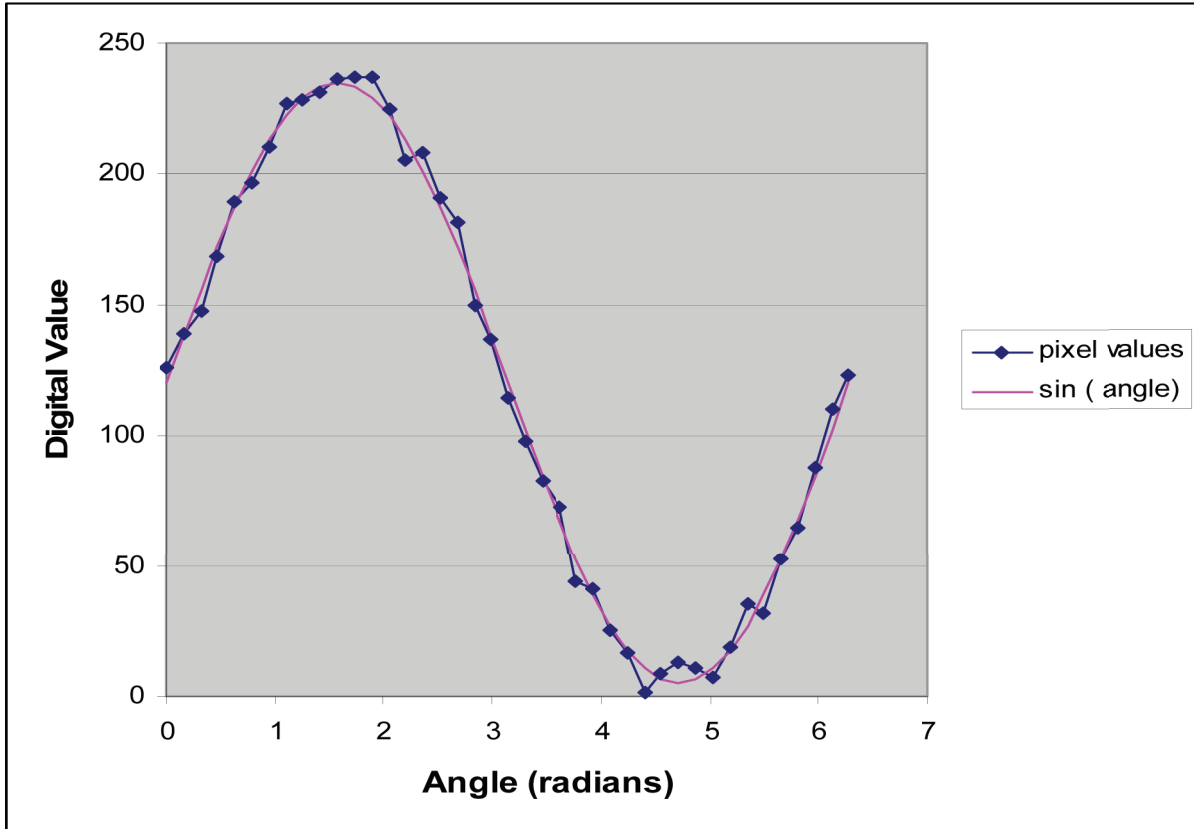**Figure F.3 — Location of pixels along a specific radius**

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

For a harmonic 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 can be 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) has to 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 from .

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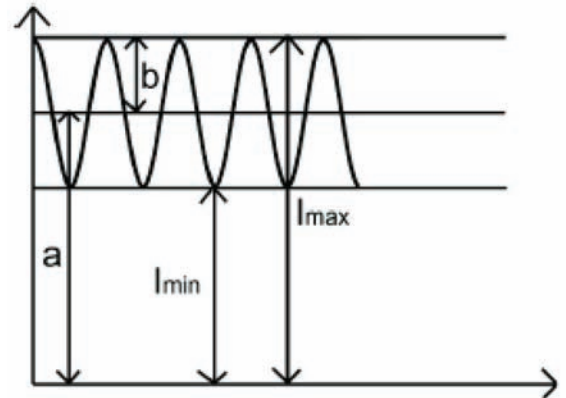

Figure F.5 — Calculation of the contrast of the sine curve

— Step 7: The modulation as a function of the frequency is the result of the analysis and shall be reported as stated in 8.3.2 or 8.3.3.

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 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 proposed method is to use the standard black and white targets and their existing analysis methods (as described in this International Standard), but have these 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, a method is suggested that 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 black background.

G.2 Choice of colour filters

One set of colour filters proposed is the "Status T" filters specified in ISO 5-3:2009. Kodak Wratten[4] filter sets could 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. We recommend 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 is 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 energy and/or camera ISO speed can 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.

---

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.

Another option, applicable for some applications, would be to focus the camera lens on the target separately for each filter being used in the study. This method segregates the effects of the sensor and processing algorithms from the optical properties of the camera lens (by providing image signals that are optimally focused for each exposure).

41

Annex H
(informative)

Units and summary metrics

H.1 Conversions between commonly used units

LW/PH   Line width per picture height

LP/mm   Line pairs per millimetre

L/mm   Lines per millimetre

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

EXAMPLE   5 LP/mm × 2,0 = 10,0 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	× 2,0	× 1	× pixel pitch	× [picture height]
L/mm	× picture height	× 0,5	× 1	× 0,5	× [pixel pitch/2]	× [picture height/2]
Cycles/mm	× [2 × picture height]	× 1	× 2,0	× 1	× pixel pitch	× [picture height]
Cycles/pixel	× [2 × # vert. pixels]	/pixel pitch	× [2/pixel pitch]	/pixel pitch	× 1	× [# vert. pixels]
LP/PH	× 2,0	/picture height	2/picture height	/picture height	/# vert. pixels	× 1

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, in millimetres, used should be for the same magnification at which the lines per millimetre was determined, or vice versa.

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 International Standard, is an objective analytical measure of a digital capture device's ability to maintain the optical 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 details), 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 print) has proven to be the strongest correlate to image sharpness and is the basis for all acutance-type image sharpness predictors. A number of sharpness or acutance metrics based on SFR metrology have been proposed and

demonstrated over the years. An excellent review of early metrics can be found in a paper by Higgins[19] and a publication by Barten.[25]

H.3 Sampling efficiency rating (E_S)

For digital imaging, there are primarily two items that determine true optical resolution.

1) Sampling frequency: usually referred to in terms of the number of addressable photoelements.

EXAMPLE   5 megapixels on a sensor.

2) Optical effects: factors such as focus, lens *f*-number, optical glass quality, and assembly.

Most users consider sampling frequency as the only variable in determining resolution. Optical effects need to be considered also. If the sampling frequency (i.e number of megapixels) is low, one cannot compensate by using high quality optics. Similarly, a high number of megapixels cannot compensate for low quality optics. It is the latter case for which the sampling efficiency rating is intended. Ideally, one would like the sampling, or number of photoelements, to take full advantage of a camera's optical quality. If not, a single number, or efficiency, indicating the extent of such a shortcoming, would be helpful in assessing the effective number of claimed photoelements.[21]

The calculation of Formula (H.1) would yield the number of optically resolved photo elements using the sampling efficiency value, E_s.

$$P_o = E_s /100 \times P_c \tag{H.1}$$

where

     P_o is the number of optically resolved photoelements;

     E_s is the sampling efficiency;

     P_c is the number of claimed photoelements.

The sampling efficiency rating ranges from 0 % to 100 % and uses a two-dimensional SFR area-normalized approach in its formulation. The reader is referred to Figure H.1 for clarity. It 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 45° 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, equivalent frequency units of cycle/pixel derived from the 0,10 SFR response levels of either of the SFR methods can also be used.

2) Calculate individual directional efficiencies for E_H, E_V, E_{+45}, and E_{-45} by normalizing the visual resolutions of item #1 by the captured image's picture height. When using cycles/pixel frequency units, normalize by 0,5 cycle/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.

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

EXAMPLE   2 048 pixel high x 3 072 pixel wide, 6,0 MPixel camera file

43

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
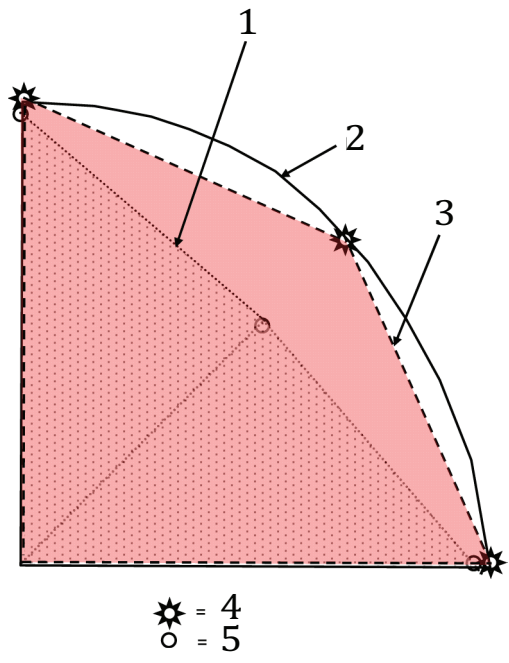

Figure H.1 — Frequency domain area technique for integrating individual sampling efficiencies

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

$$E_R = 100 \times (E_H \times E_V)$$

(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 second edition of ISO 12233 cancels and replaces the first edition, ISO 12233:2000. However, users are allowed to use the test chart defined in ISO 12233:2000 to perform some of the measurements defined in this second 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 requirement to both of test pattern modulation and the positional tolerance are the same as described in 5.2.4 and 5.2.5 in this International Standard because there are no fundamental changes in the revision.

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.
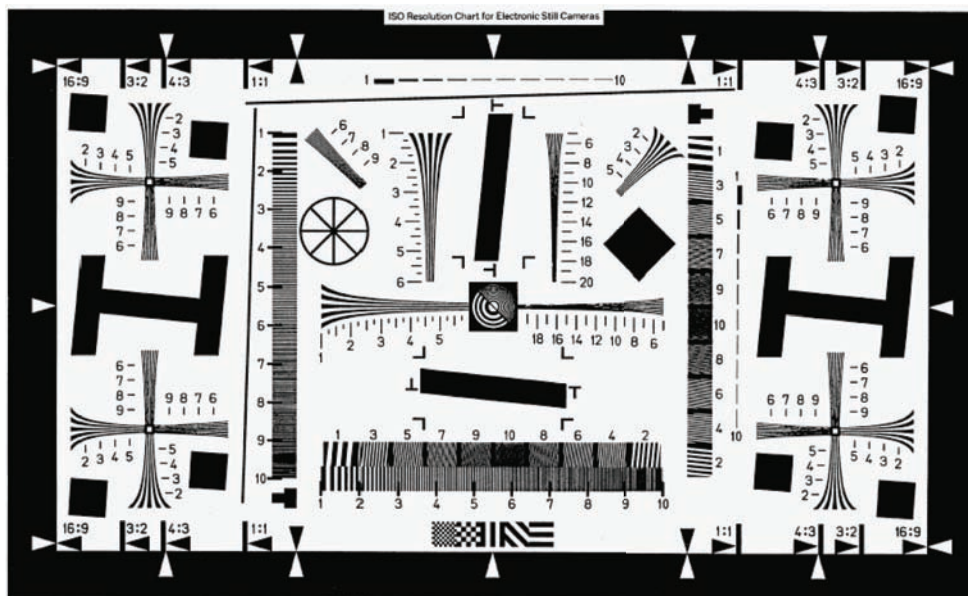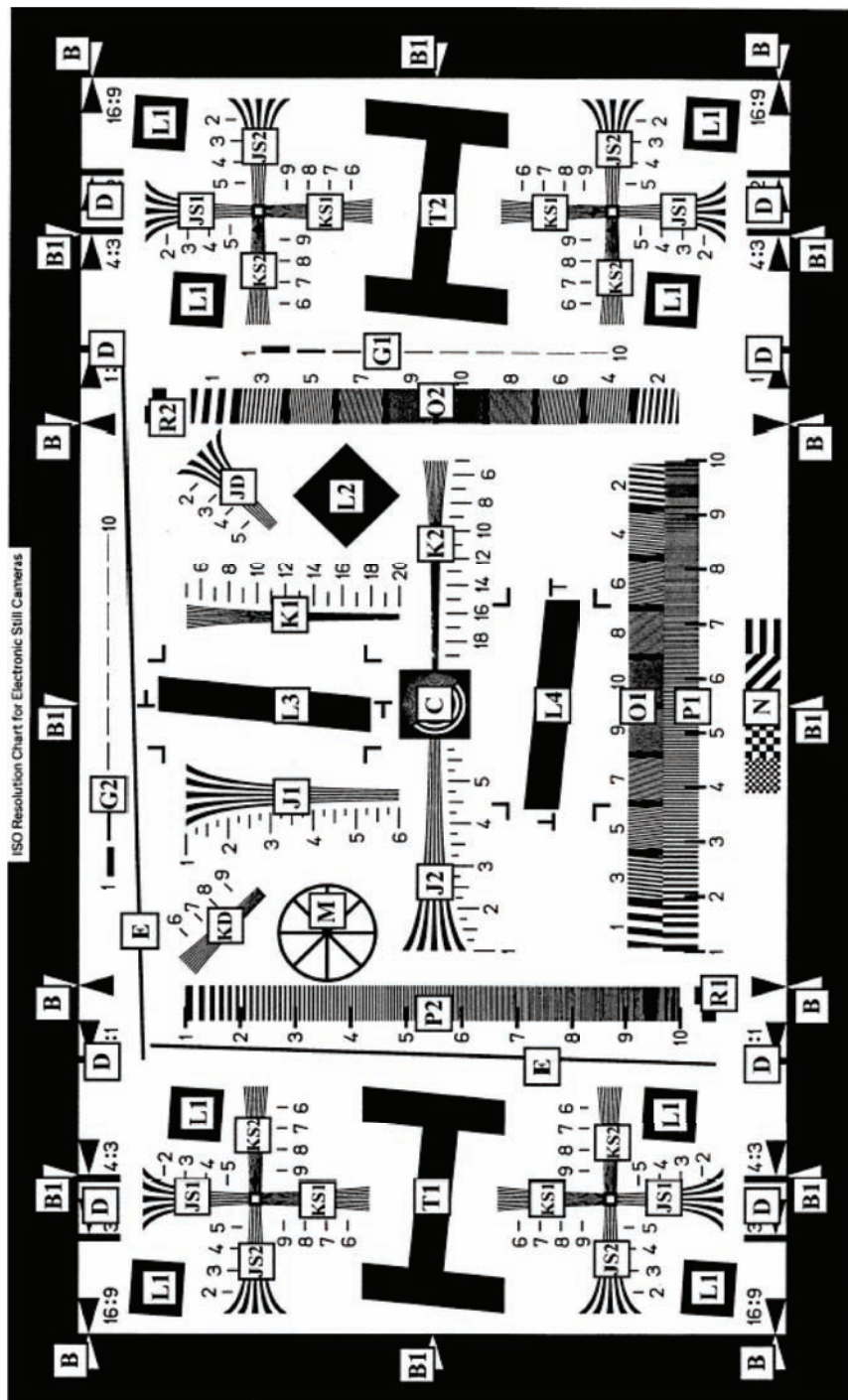

Figure I.1 — Resolution test chart

Figure I.2 — Test chart features

Table I.1 — Test chart elements

Element	Purpose
A	Black border with inner edge which defines active target area
B	Black and white framing arrows used to frame target vertically (used for horizontal framing only for 16:9 aspect ratio image formats)
B1	White framing arrows used to assist in framing target
Ca	Centre dual-frequency zone plate inside black square used to set focus
Da	Framing lines and arrows that define 1:1, 4:3, and 3:2 aspect ratios
Ea	Slightly slanted lines used to check scan linearity and "stair stepping"
G1a	100 LW/PH to 1 000 LW/PH black bars to measure horizontal pulse response
G2a	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
JS1a	100 LW/PH to 600 LW/PH hyperbolic zone plate used to measure corner horizontal visual resolution
JS2a	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
KS1a	500 LW/PH to 1 000 LW/PH hyperbolic zone plate used to measure corner horizontal visual resolution
KS2a	500 LW/PH to 1 000 LW/PH hyperbolic zone plate used to measure corner vertical visual resolution
L1a	Slightly slanted (approx. 5°) small black squares used to measure vertical and horizontal SFR at extreme corners of image
L2a	45° diagonal black square used to measure diagonal SFR
L3	Slightly slanted (approx. 5°) black bar used to measure centre horizontal SFR
L4	Slightly slanted (approx. 5°) black bar used to measure centre vertical SFR
Ma	Circle containing vertical, horizontal and diagonal lines used to observe scanning nonlinearities
Na	Checkerboard patterns used to observe image compression artefacts
O1	Tilted (approx. 5°) square wave bursts used to measure horizontal aliasing ratio
O2	Tilted (approx. 5°) square wave bursts used to measure vertical aliasing ratio
P1a	100 to 1 000 line square wave sweep
P2a	100 to 1 000 line square wave sweep
Ra	Indicators that can be used for automatic target alignment
T1, T2a	Slanted (approx. 5°) H-shaped bars used to measure 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 placed on the original ISO 12233 chart shown in Figure I.1 are provided for limiting resolution measurement as shown in Table I.1 in this annex.

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

The 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 two diagonal SFR.

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

Bibliography

[1]   ISO 6328:1982, *Photography — Photographic materials — Determination of ISO resolving power*

[2]   ISO 9334:1995, *Optics and optical instruments — Optical transfer function — Definitions and mathematical relationships*

[3]   ISO 9335:1995, *Optics and optical instruments — Optical transfer function — Principles and procedures of measurement*

[4]   ISO 9336-1:1994, *Optics and optical instruments — Optical transfer function — Application — Part 1: Interchangeable lenses for 35 mm still cameras*

[5]   ISO 12231:1997, *Photography — Electronic still-picture cameras — Terminology*

[6]   IEC 61146-1:1994, *Video cameras (PAL/SECAM/NTSC) — Methods of measurement — Part 1: Non-broadcast single-sensor cameras*

[7]   IEC 61146-2:1997, *Video cameras (PAL/SECAM/NTSC) — Methods of measurement — Part 2: Two- and three-sensor professional cameras*

[8]   ANSI PH2.39-1977 (R1990), *Method of measuring the photographic modulation transfer function of continuous-tone, black-and-white photographic films*

[9]   ITU-R BT.709:1993, *Basic parameter values for the HDTV standard for the studio and for international programme exchange*

[10]   Baker L. Optical transfer function: measurement, *SPIE Milestone Series*, Vol. *Ms.* 1992, ••• p. 60

[11]   Fischer T.A., & Holm J. *Electronic still-picture camera spatial frequency response measurement,* IS & T's 47th Annual Conference / ICPS 1994, vol. II, pp. 626-630

[12]   Okano Y. *MTF Analysis and its Measurements for Digital Still Camera,* IS & T's 50th Annual Conference, pp. 383-387

[13]   Reichenbach S.E. et al. Characterizing digital image acquisition devices. *Opt. Eng.* 1991 Feb., **30** (2) pp. 170–176

[14]   Schulz M. *Measurement technique for the characterization of electronic still-picture cameras, EUROPT0.* Advanced Focal Plane Arrays and Electronic Cameras, 1996

[15]   Williams D. *Benchmarking of the ISO/TC 42/WG 18 slanted-edge spatial frequency response Photoshop plug-in,* IS & T's 51st Annual Conference 1998

[16]   CIPA DC-003(2003) Resolution Measurement Methods for Digital Cameras

[17]   Williams D. *Debunking of Specsmanship: Progress on ISO/TC42 Standards for Digital Imaging Performance.* PIC, 2004

[18]   ISO 15529, *Optics and photonics — Optical transfer function — Principles of measurement of modulation transfer function (MTF) of sampled imaging systems*

[19]   Higgins G.C. Image Quality Criteria. *J. Appl. Photogr. Eng.* 1977, **3** (2) pp. 53–60

[20]   Williams D. et al. *A Pilot Study of Digital Camera Resolution Metrology Protocols Proposed under ISO 12233.* Electronic Imaging, Second Edition, 2008

[21]   *Sampling Efficiency in Digital Camera Performance Standards*, P. Burns & D. Williams, Proc. SPIE-IS&T Electronic Imaging Symposium, 2008

[22] *Digital Camera Resolution Measurement Using Sinusoidal Siemens Stars*, C. Loebich, D. Wueller, B. Klingen, A. Jaeger, IS+T,SPIE Electronic Imaging Conference 2007

[23] *Method for Resolution Measurement*, Anke Neumann, Diploma thesis at the University of Applied Sciences in Cologne, 2003

[24] *Noise Reduction vs Spatial Resolution*, Uwe Artmann, Diploma thesis at the University of Applied Sciences in Cologne, 2007

[25] Contrast Sensitivity of the Human Eye and Its Effects on Image Quality, Peter G.J. Barten, SPIE Press, Dec. 1999, ISBN: 9780819434968

[26] ISO 7589, *Photography — Illuminants for sensitometry — Specifications for daylight, incandescent tungsten and printer*

ICS 37.040.10

Price based on 50 pages