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Creation and Evolution of ISO 12233, the International Standard for Measuring Digital Camera Resolution

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Abstract

Thirty years ago, ISO/TC42 WG18, a newly created ISO working group on digital photography, began developing a standard to measure the spatial resolution of digital cameras. After years of proposals, testing, and analysis, consensus was reached on a test chart with tilted edge features for measuring spatial frequency response (SFR) and hyperbolic wedges for measuring visual and limiting resolution. The group ensured that the test chart and analysis software would be available internationally. First published in 2000, ISO 12233 is now used to measure cameras in a wide range of applications. It was revised in 2014 to define three new charts, a sine-wave modulated target in polar format, a low contrast e-SFR target, and the CIPA chart with software which computes a "human equivalent visual resolution" value. ISO 12233 is now being revised to provide improved results in challenging applications. This paper describes early resolution measurement approaches, and work in the 1990s to standardize the SFR method. It also describes enhancement made in later editions, including the 4th edition which is nearing publication.

Early resolution measurement standards

The spatial resolution capability is an important attribute of a lens, an image sensor, a camera, or an imaging system. Camera resolution test charts were standardized more than 65 years ago. Figure 1 shows the EIA-1956 test chart, overlaid in the upper right with an enlargement of some of the vertically oriented triangular wedges used to measure the horizontal limiting resolution. A human observer determines the limiting resolution of a video camera focused on the chart, which has been properly framed by the camera. This is the value, normally given in "TV lines", of the thinnest line pattern which can be visually distinguished by the observer viewing an image of the chart on a high-quality display. In other cases, the number of "TV lines" at a minimum modulation level (e.g., 5%) is determined using an oscilloscope.

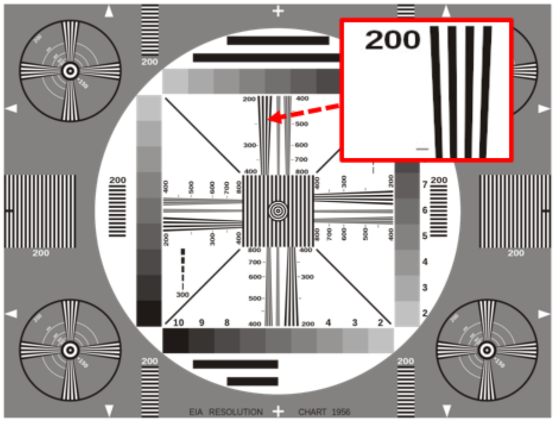

Figure 1: EIA-1956 Test Chart with enlarged portion at upper right

Film-based photography used a related metric, known as "resolving power", to quantify the resolution of camera lenses.[1] An example test chart, from the ANSI PH3.63 standard published in 1974, is shown in Figure 2. The chart, calibrated in units of line pairs per millimeter, is exposed through the lens onto a photographic emulsion, typically at a series of angular distances from the lens axis in order to provide radial and tangential measurements at multiple field angles. The resolving power value corresponds to the highest number (*i.e.,* the finest pattern) which can be corrected counted (*e.g.,* 3 black lines) in the recorded film image by the observer.

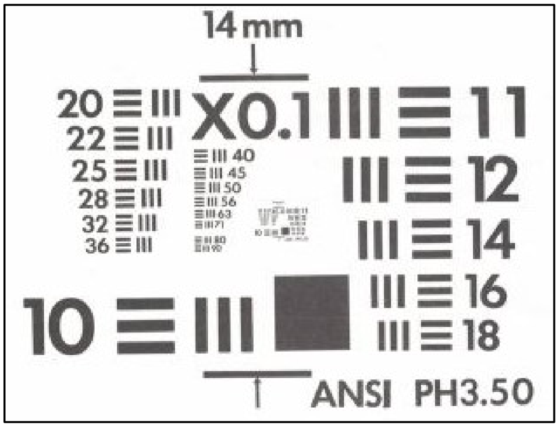

Figure 2: Resolution Test Target for Photographic Lenses

MTF measurements

Limiting resolution metrics provide a single value in each measurement direction (e.g., vertical and horizontal, or radial and tangential), enabling different cameras or lenses to be easily compared. However, the results can be misleading, since limiting resolution metrics do not correlate well with perceived sharpness, compared to metrics based on the modulation transfer function (MTF).[2]

By the 1970s, methods for measuring the MTF of photographic film had been standardized.[3] A transmissive test pattern comprising a series of sinusoids was projected onto the film using a high-quality lens. An example test pattern included 13 spatial frequencies, ranging from 1.2 to 200 cycles per millimeter. After processing, the modulation of each spatial frequency pattern on the film was measured with a microdensitometer.

Reflectance test charts with sinusoidal patterns were developed by Robert Lamberts and others at Kodak, and commercialized by several test chart manufacturers including Sine Patterns in Rochester, N.Y. An example of a portion of a such a chart, created by LeRoy DeMarsh at Kodak in 1986, is shown in Figure 3. This chart was used internally at Kodak to determine and compare the MTFs of prototype megapixel digital cameras and film cameras.

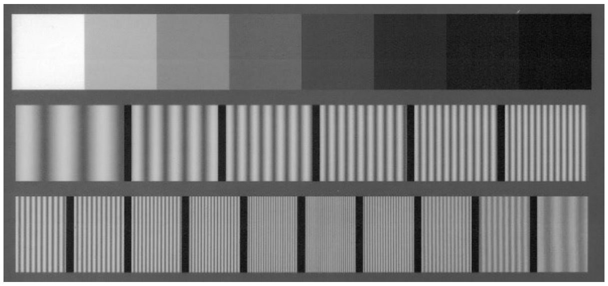

Figure 3: Portion of Kodak MTF measurement chart

Knife edge and slanted edge measurements

The measurement methods described above were not designed to test sampled imaging systems, such as digital cameras, which employ CCD or CMOS image sensors. In sampled systems, the measured pixel values depend on the alignment (phase) between the fine features of the test chart and the photoelements of the image sensor. In addition, the color filter patterns used in single-chip color digital cameras can cause color aliasing, which further influences the measured values.

Beginning in the 1980s, moving “knife edge” and moving “slit” measurements were developed to measure the MTF of solid-state sensors. These methods typically require capturing and analyzing many sequential images while carefully adjusting the relative positions of the sensor and the edge or slit target, such as by using a motorized micrometer.[4] While they provide useful results for sampled systems with linear signal processing, they are not practical in many applications, which require a simple test chart and automated measurement methods.

Two different research efforts appear to have independently recognized that processing a single image of a slightly slanted edge can provide results similar to the moving knife edge method. One is described in a well-known paper by Reichenbach, Park, and Narayanswamy, which was published in 1991[5] and cited in ISO 12233. The other was described in an unpublished Kodak Technical Report in 1989 by Jim Milch.[6] It was designed to perform in-the-field measurements of a multi-format film scanner utilizing linear CCD sensors.[7] Test films for each film size included numerous dark squares on a white background. The squares were tilted by about 5 degrees, so that each line of pixels recorded the edge in a slightly different place. The automated algorithm fit a linear curve to the fractional pixel transition points on each line. The slope of the line was used to offset the pixels of each line, so that all the data could be combined into a single supersampled line profile. Further processing, followed by a discrete Fourier transform, was used to determine the MTF.

In 1990, Ken Parulski created a reflection test chart which included slightly slanted squares, and adapted the software developed by Milch to measure Kodak prototype digital cameras. As Kodak’s representative to the IEEE G-2.1.3 standards committee, he proposed a new test chart design, to replace a chart which was similar to the EIA-1956 chart shown in Figure 1. The new chart included multiple slanted squares, as well as “hyperbolic wedge” patterns, where the width of the lines in the pattern varied linearly in the direction parallel to the measurement direction. The approved standard, IEEE 208-1995,[8] included the test chart shown in Figure 4, which has been overlayed with an enlarged portion of the vertically oriented hyperbolic wedges. The hyperbolic wedge patterns improve the accuracy of the “resolution response”, which is measured using an oscilloscope. The chart included only a single tilted black square, however, with no explanation of how it could be used, since most committee members felt that the measurement algorithm was too complex.

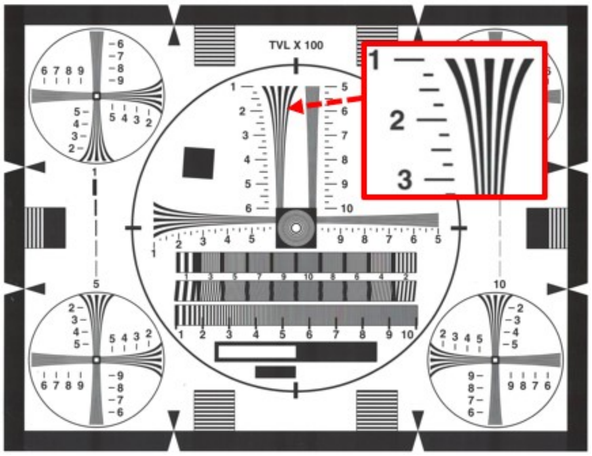

Figure 4: IEEE 208-1995 Test Chart with enlarged portion

ISO standards for digital photography

The ISO technical committee responsible for photography standards, known as ISO/TC42, was created when ISO was formed in 1947. ISO/TC42 has developed 210 published standards, with 19 standards under development,[9] including the 4th edition of ISO 12233. ISO standards are developed by experts from participating countries (P-members) using processes codified in the ISO directives,[10] which include five mandatory stages from new project proposal to publication.

The American National Standards Institute (ANSI) has served as the secretariat for ISO/TC42 beginning in 1947, under the sponsorship of NAPM (National Association of Photographic Manufacturers), which was renamed PIMA in 1997 and I3A in 2002. The sponsorship was moved to IS&T in 2011, which continues to sponsor ANSI’s work as secretariat as well as the IS&T technical committees which provide the U.S. input and experts to ISO/TC42. These include IS&T IT10, which is responsible for digital photography standards, including ISO 12233.

At the 14th plenary meeting of ISO/TC42 in 1991, the P-members approved a resolution to create working group 18 (ISO/TC42 WG18) to develop standards for what was then called “electronic still picture imaging”. Initially led by convenor Fara Faramarzpour of Polaroid, WG18 experts developed proposals to begin work on four digital photography related standards: terminology (ISO 12231), sensitivity / ISO speed measurements (ISO 12232), resolution measurements (ISO 12233) and removable storage (ISO 12234).

Development of ISO 12233:2000

The development of a new ISO standard is initiated by a proposal from a project leader and approved by the P-member countries. It normally proceeds through several document drafting stages, starting with a new project proposal (NP), followed by one or more working drafts (WDs). Once the working group reaches consensus, typically after improvements have been made over the course of numerous WDs, it approves the document as a committee draft (CD). A CD ballot is then issued, with each P-member country having one vote. The project leader (PL) reviews any negative ballots and comments, and a decision is made on whether to proceed with a draft international standard (DIS) or to modify the CD and issue another CD ballot. A DIS ballot is then issued to the P-members. If the DIS is approved with no technical changes, the standard proceeds to publication. In other cases, a final draft international standard (FDIS) ballot is issued to confirm the changes made following the DIS ballot.

Standards are valuable only if they are widely used by the industry, which means they must evolve to meet the changing needs of the industry. The biggest challenge in developing digital photography metrology standards is obtaining international consensus on the required and optional types of tests, analysis methods, test charts, and reporting requirements from the experts representing major imaging companies and other stakeholders. This takes time and requires compromises. In some situations, it is appropriate to include multiple measurement methods, and allow the industry to decide which is best. In the case of ISO 12233:2000, this meant defining visual resolution and limiting resolution measurements, in addition to the spatial frequency response (SFR).

Ken Parulski has served as project leader for ISO 12233 since the NP was submitted in June 1992, and is co-project leader with Dietmar Wueller for the current revision. The NP described how the OTF (Optical Transfer Function) is measured by analyzing a slanted black square, and included a draft version of the IEEE 208 chart shown in Figure 4 as an example test chart. The NP stated that the project was anticipated to be completed in two years. This was wildly optimistic since the standard was not published until eight years later. During this process, the term OTF was replaced by SFR. A single OTF and MTF are only applicable to a continuous linear system. Digital cameras, however, involve spatial and color sampling, and employ non-linear image processing.

Experts from Japan, Europe, and the U.S, representing numerous companies and organizations, participated in refining and testing the measurement methods and reviewing draft documents during the development of ISO 12233:2000. A total of nine WDs were prepared and reviewed, as the test chart and measurement software were refined. The first CD was created in April 1997 and the DIS was approved August 1998.

The test chart was modified several times during the development of ISO 12233:2000. The final chart is shown in Figure 5. In order to inexpensively produce high resolution charts, it was agreed that the chart would use bitonal patterns, and not include greyscales. The central slanted squares were replaced by long slanted bars, to provide an adequately large region of interest (ROI) for low pixel count digital cameras. It was agreed that the maximum spatial frequency of the center hyperbolic wedges, used to determine the "visual resolution", would be 2,000 LW/PH (line widths per picture height, similar to "TV lines"). The limiting resolution was determined using vertical and horizontal "square wave sweep" patterns, which ranged from 100 to 1,000 LW/PH.

The initial and final test chart designs were manufactured by Fuji Color Service, Japan, with guidance from Tatsuji Kitamoto and Makoto Tsugita of Fuji Photo Film, and distributed to numerous WG18 experts for testing. The SFR algorithm can determine the spatial frequency response using a single captured image of this test chart, which can be used measure a wide range of digital cameras.

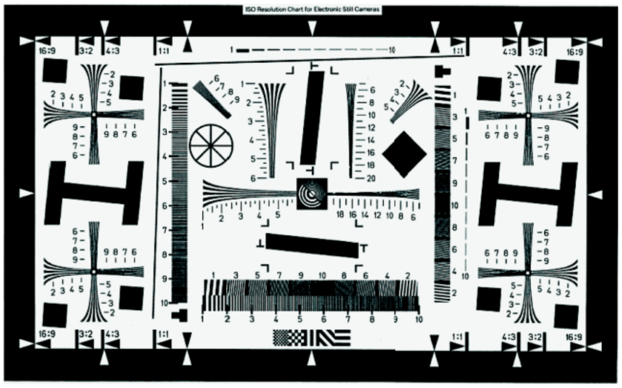

Figure 5: Test chart defined in ISO 12233:2000

The SFR measurement C-code originally written at Kodak was converted into a Photoshop plug-in by Eric Higgins and Andrew Juenger of Polaroid, so that WG18 experts could easily test the SFR algorithm.[11] The code was modified to implement 4x binning and other improvements, and the final source code was included as informative Annex A in ISO 12233:2000.

Figures 6(a)-(f) depict key steps in the SFR software. In Figure 6(a), a region of interest (ROI) window containing pixels from a slanted edge portion of the test target are selected. The edge slant causes the position of the edge, relative to the center of the pixel sampling locations on the image sensor (shown as different small triangles, circles, and squares for different line), to be displaced slightly from row to row. Figure 6(b) shows the resulting edge profiles from the pixels of the 8 rows in this example. The location of the edge on each row is then estimated using curve fitting. In the first three editions of ISO 12233, a linear fit was used to estimate the edge position. The positions of the pixels from each row are adjusted to compensate for the estimated position of the edge, producing oversampled edge values shown in Figure 6(c).

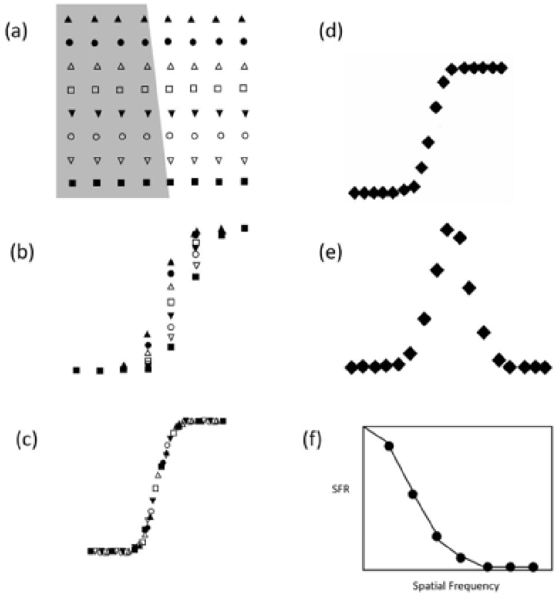

Figure 6: Key steps in slanted-edge SFR software

The oversampled edge values are “binned”, by averaging the values within ¼ pixel width bins, to provide a 4x supersampled edge profile shown in Figure 6(d). A finite difference filter is applied to the supersampled values to produce a corresponding line spread function, shown in Figure 6(e). The discrete Fourier transform (DFT) of the line spread function is computed, and the SFR is the absolute value of DFT, shown in Figure 6(f).

Initial results of the SFR measurement method were reported at IS&T’s 47th Annual Conferences in 1994[12] and 1997,[13] and other imaging conferences[14]. The SFR measurement defined in ISO 12233:2000 was later applied to reflection scanners[15] and film scanners.[16] This slanted-edge SFR method was written in the Matlab software language by Peter Burns, and distributed since 2000. [17]

Updating ISO 12233

ISO standards are reviewed every five years, using a well-defined systematic review process, to ensure that they remain up-to-date and globally relevant. Beginning in 2005, several major additions and modifications to ISO 12233 were considered. A significant amount of testing and consensus building was required before the second edition was published in 2014. One important decision was to replace the single “combination” test chart defined in the first edition with three charts. This meant the charts could be optimized for each of the three test methods defined in the second edition, including a new spatial frequency response measurement using sine waves, called the s-SFR.

Since the technology for producing test charts had evolved, two of these charts used continuous tones. Figure 7 shows the new slanted edge SFR test chart used to measure what was now called the e-SFR (edge SFR) to distinguish it from the new s-SFR (sine-wave SFR) measurement. The chart, initially proposed by Don Williams, includes nine tilted dark squares on a grey background, and a circular pattern of 16 greyscale patches surrounding the center square, used to determine the OECF.[18]

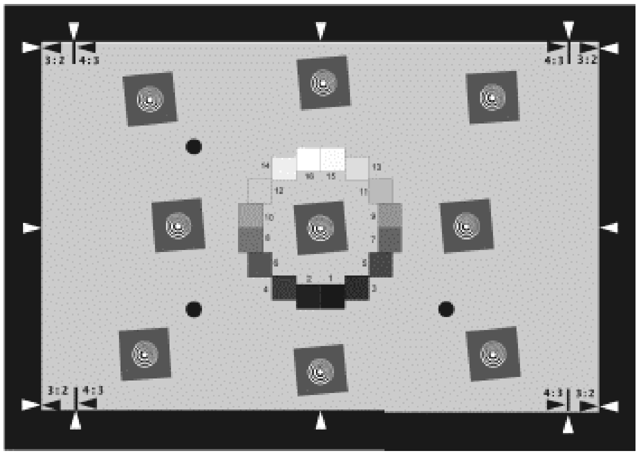

Figure 7: e- SFR test chart from ISO 12233:2014

The high contrast test chart defined in the first edition sometimes yielded “clipped” pixel values in the image file, due to camera image processing such as edge sharpening. This caused spurious SFR results. The lower contrast edges in the new e-SFR test chart eliminated this issue. The squares were designed to be large enough to measure even VGA level cameras, to replace the long, slanted bars in the chart defined in ISO 12233:2000.

s-SFR measurement method

The s-SFR measurement method standardized in ISO 12233:2014 captures and analyzes an image of a sine-wave modulated starburst pattern, shown in Figure 8, which was developed by Dietmar Wueller in cooperation with the Cologne University of Applied Sciences. The pattern includes 4 corner markers and 16 greyscale patches which are used to determine the OECF.[18] The test chart includes a 3 x 3 grid of these patterns.

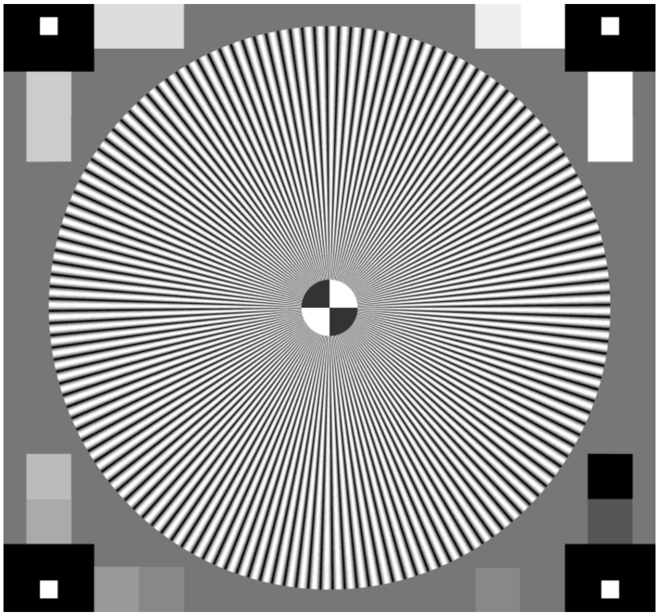

Figure 8: s- SFR test pattern from ISO 12233:2014

An automated software algorithm[19] locates each star using the four surrounding markers and linearizes the image data using the 16 grey patches. The star is radially segmented, and the radii in each segment are analyzed. A sinusoidal curve with the expected frequency is fitted to the measured values by minimizing the square error, and the modulation level of this function is determined by calculating the contrast. The modulation for each frequency in the vertical, horizontal, and various sagittal directions can then be reported.

The s-SFR method was added to the standard to provide measurements at angles other than vertical and horizontal, and to provide additional information for cameras that employ adaptive spatial image processing. Examples of such steps include image compression, adaptive sharpening, and noise-reduction, which are used in many current products. For systems whose imaging pipelines use global image processing, such as sharpening using a fixed convolution, SFR results based on edge- and sine-wave features yield very similar results. This is assuming that conditions such as signal clipping, and severe aliasing are not present. Edge-gradient and sine-wave methods can yield equivalent estimates of the system SFR in these cases.

When advanced image processing is used, however, spatial processing that varies with local image content can result in some features, such as edges, being treated differently than others (e.g., sine waves). Consider a common sharpening method that identifies edge-like image content and increases its local contrast, and its apparent sharpness. This may have the desired effect of improving the visual impression of the image, and e-SFR results may show higher values. However, these results apply only to certain content in the image. Having a second method that is based on a different type of feature provides a way to detect the presence, and gauge the influence of, such adaptive image processing.

Figure 9 shows SFR results from both e-SFR and s-SFR analysis based on the same test image, where global, fixed-convolution spatial filtering was used. The results are very similar, except at high frequencies near 0.5 cy/pixel.

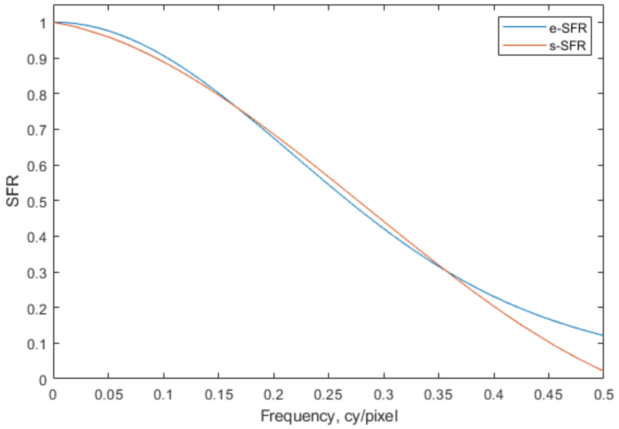

Figure 9: Comparison of e-SFR and s-SFR results

We then applied adaptive sharpening using PhotoShop software and the *Sharpen Edges* filter to the test image. After this sharpening, the e-SFR and s-SFR differ significantly, as shown in Figure 10. The e-SFR is higher, as expected, while the s-SFR is almost unchanged. We can use this difference as an indication that adaptive sharpening has been applied.

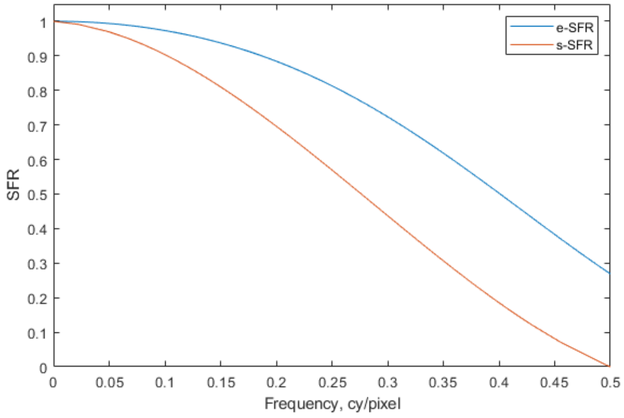

Figure 10: SFR results following an adaptive edge sharpening operation

In other cases, the e-SFR is less influenced by adaptive processing than the s-SFR. Figure 11 shows results following a median filter operation used in noise reduction, applied to the original, unfiltered image.

Comparing the differences between the s-SFR and the e-SFR can indicate the extent to which nonlinear processing is used. This comparison can also be used when adjusting spatial image processing parameters in order to target particular scene content.

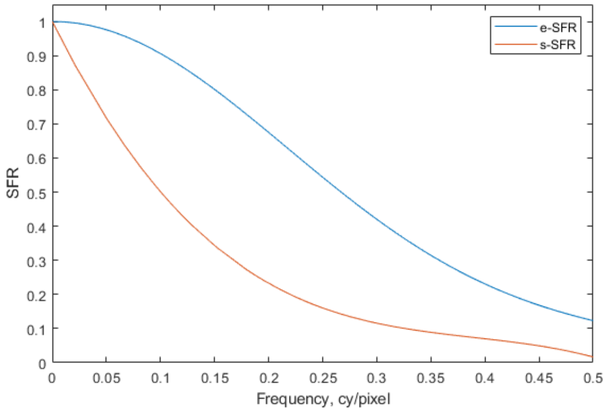

Figure 11: SFR results following a median-filter operation

Visual resolution measurement

The visual resolution method standardized in ISO 12233:2014 uses the CIPA test chart shown in Figure 12, developed by the Camera and Imaging Products Association's standardization committee. The bi-tonal chart includes vertical, horizontal, and diagonal hyperbolic from 200 to 2,500 LW/PH for measuring the visual resolution. The value is the lowest spatial frequency at which the five black and four white lines are blurred together to produce a reduced number of lines or change polarity, which indicates aliasing. Visual resolution measurement software,[20] developed by Hideaki Yoshida, can be used to automate the measurement, and avoid visual observation errors due to aliasing.

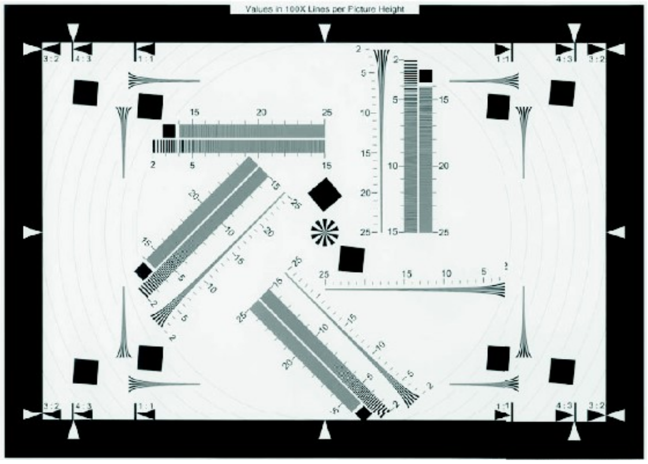

Figure 12: CIPA test chart from ISO 12233:2014

3rd Edition of ISO 12233

The current edition of ISO 12233 was published in 2017. This third edition was a minor revision of ISO 12233:2014. It addressed issues with two equations used in the description of the e-SFR algorithm, which were identified by Frank Steinbacher of Siemens AG.

Resources for implementing the current version of ISO 12233 are available from the standards section of the IS&T website[21]. This includes links to analysis software, test chart suppliers and relevant IS&T papers.

4th Edition of ISO 12233

During the third edition, several possible enhancements and clarifications were identified and discussed. The consensus was that after the 3rd edition was published, these features would be considered for inclusion in the 4th edition. The DIS ballot for this new edition is currently underway. It includes a new e-SFR test chart, shown in Figure 13, which replaces each of the "slanted square" features shown in Figure 7 with a four-cycle "slanted star" feature. This facilitates e-SFR measurements normal to the diagonal direction, in addition to the horizontal and vertical directions.

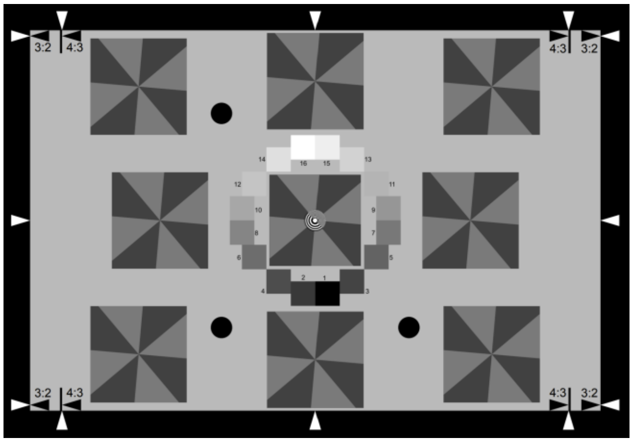

Figure 13: e-SFR test chart for 4th edition of ISO 12233

In this 4th edition, the e-SFR algorithm has been improved by using a 5th-order polynomial equation to fit the edge, and by correcting for the edge-angle sampling. In addition, the Hammimg smoothing window has been replaced by a Tukey window.

As a result, the measurement results may be different from the results obtained using the 3rd edition. An optional non-uniformity correction method was added, along with derivations of the edge-angle and finite difference filter corrections. Matlab analysis source code is listed in a new Annex M. The details of these improvements are reported in a companion paper presented at this conference.[22]

Another significant addition in the 4th edition of ISO 12233 is an informative annex which describes how to compute an acutance value from either the e-SFR or the s-SFR data. This provides a "single number" resolution metric which can be correlated with perceived sharpness.[2]

Acutance calculation

The acutance value can be computed for a particular display sampling resolution and viewing distance. This is done by first transforming the e-SFR or s-SFR spatial frequency values to the corresponding values of visual angle. If p is the display pixel distance, and D is the viewing distance, then

$$f_{cy/degree} = \frac{\pi D}{180p} f_{cy/pixel} \tag{1}$$

The acutance is computed by summing the SFR, weighted by the visual Contrast Sensitivity Function (CSF).[22, 23]

$$CSF(f) = \frac{(a \cdot f^{c}) \cdot e^{-bf}}{K}, \tag{2}$$

where $a = 75$, $b = 0.2$, $c = 0.8$, $K = 102.16$, and f is the spatial frequency in cy/degree. For an SFR with N values up to the maximum frequency of 0.5 cy/pixel, the acutance is computed as

$$Q = \frac{\sum_{i=1}^{N} SFR_i \, \mathrm{CSF}_i}{\sum_{i=1}^{N} \mathrm{CSF}_i}, i = 1, 2, \ldots, \mathrm{N} \tag{3}$$

Consider a tablet-device with display sampling of 10 pixels/mm (254 pixels/inch). A typical viewing distance in this case is 35 cm. We first compute the SFR for a test image, a computed edge with moderate image noise added. The result is shown in Fig. 14. Using Eq. (1), we can now add an equivalent axis, above, in cy/degree, which is used for the CSF. Applying Eq. (3) results in an acutance, $Q = 0.77$.

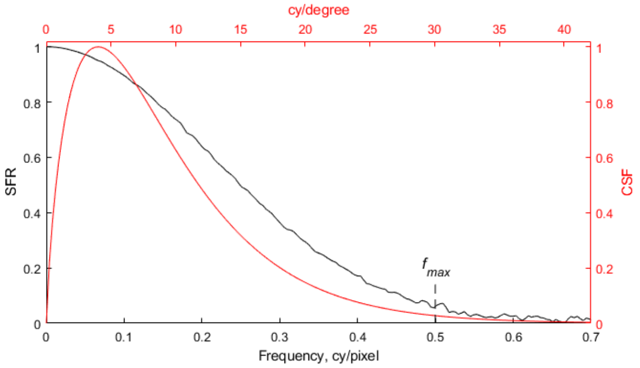

Figure 14: Example SFR with corresponding CSF weighting for a 10 pixel/mm (254 PPI) display viewed at 35 cm (acutance, 0.77)

Conclusion

The development of ISO 12233:2000 required eight years of work within ISO/TC42 WG18, including several iterations of proposals, test chart and software development, testing, and consensus building. The result was a standardized method of for measuring digital cameras that is widely used internationally. It is now broadly used to measure cameras in applications such as smartphones, autonomous vehicles, machine vision, and medical imaging, and is cited in other standards and best-practice guidelines. It continues to evolve, to meet the needs of this diverse user community. We anticipate that the 4th edition of ISO 12233, which includes a new e-SFR test chart and other improvements, will be published in the second half of 2022. ISO/TC42 WG18 welcomes input from users of the standards it has developed, including suggestions for possible additions, clarifications, and corrections.

Acknowledgement

We are pleased to acknowledge the many contributions of our colleagues in the ISO/TC42 WG18 standards working group. We also thank Edward Terhune at ANSI, who administers ISO/TC42.

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Authors Biographies

Ken Parulski joined Kodak Research Labs after receiving electrical engineering degrees from MIT in 1980 and retired as Chief Scientist and Research Fellow in 2012. He is now a consultant to numerous mobile imaging companies and chairs the US IT10 group responsible for ANSI and ISO digital photography standards. He has been project leader for ISO 12233 since 1992.

Dietmar Wueller studied photographic technology at the Cologne University of applied sciences. He is the founder of Image Engineering, an independent test lab that tests cameras for several publications and manufacturers. He is the German chair of the DIN standardization committee for photographic equipment and active in ISO, IEC, VCX, IEEE and other standardization activities.

Peter Burns is a consultant for imaging system evaluation, modeling, and design. Previously he worked for Carestream Health, Xerox, and Eastman Kodak. A frequent speaker at technical conferences, he has taught imaging courses for clients and universities for many years.

Hideaki Yoshida received his BS degree in physics from Kyoto University in 1983 and began working at Olympus. He was an early inventor and developer of digital cameras. His division, now named OM Digital Solutions, became an independent company in January 2021. He currently serves as vice-chair of CIPA's standardization committee and is a technical expert in ISO/TC42 and a director of SPIJ.