Evolution of Slanted Edge Gradient SFR Measurement

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ABSTRACT

The well-established Modulation Transfer Function (MTF) is an imaging performance parameter that is well suited to describing certain sources of detail loss, such as optical focus and motion blur. As performance standards have developed for digital imaging systems, the MTF concept has been adapted and applied as the spatial frequency response (SFR). The international standard for measuring digital camera resolution, ISO 12233, was adopted over a decade ago. Since then the slanted edge-gradient analysis method on which it was based has been improved and applied beyond digital camera evaluation. Practitioners have modified minor elements of the standard method to suit specific system characteristics, unique measurement needs, or computational shortcomings in the original method. Some of these adaptations have been documented and benchmarked, but a number have not. In this paper we describe several of these modifications, and how they have improved the reliability of the resulting system evaluations. We also review several ways the method has been adapted and applied beyond camera resolution.

Keywords: image quality, MTF, SFR, raggedness, sharpness, digital camera, scanner, ISO 12233

1. INTRODUCTION

Several terms have been used to describe the capture of image detail in digital images. Informally, it is common to refer to an image or image capture system as being high-resolution or sharp, when fine detail is captured. Image resolution, or limiting resolution, has its roots in continuous optical imaging systems, and describes an imaging component or system's ability to distinguish finely spaced details. However, limiting resolution provides an incomplete measure of image sharpness when compared to measurements based on the modulation transfer function (MTF). The MTF is a measure of the capture (i.e., transfer from input-to-output) of image information (image contrast) as a function of spatial frequency. For optical and photographic imaging systems, several MTF measurement methods were developed and adopted. These were based on sinusoidal, line, edge and image noise test target features. One of these, edge-gradient analysis [1, 2], is our subject.

There are three basic operations for edge-gradient analysis (EGA), as shown in Fig. 1. We first acquire an edge profile from the (image) data. These image data are captured from a test object with a high quality edge feature. Next, the derivative of the edge profile in the direction across the edge is computed, to yield a measured line spread function (LSF). From this we compute the discrete Fourier transform, whose scaled modulus is the measured MTF. For traditional EGA, the edge feature would be vertical or horizontal, and the continuous optical or photographic image, sampled by a scanning sensor.

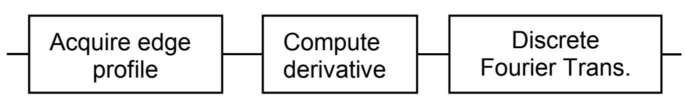


Figure 1: Steps in edge-gradient MTF analysis

This method was adapted in the first ISO standard for digital camera resolution as ISO 12233 [3]. The ISO method includes several improvements that had been described earlier by Reichenbach, et al. [4]. A key improvement was the use of a rotated, or slanted, edge feature, rather than one precisely aligned with the pixel sampling array. In addition, including the estimation of the edge location and slope as part of the analysis made the measurement more practical for automated system evaluation. The details of the slanted-edge method for camera Spatial Frequency Response (SFR) can be found in ref. [5]. In this paper we review several ways in which the method has been adapted and applied beyond the original camera resolution method.

Our approach borrows from statistics as we describe how the slanted-edge SFR method can be thought of as a way of estimating the underlying imaging performance parameter. Careful sampling of available observations is important. In our case this involves intelligent region-of-interest (ROI) selection around the edge feature to be used. A second notion is bias error that is introduced by characteristics, such as optical distortion, which are in conflict with underlying assumptions of the method. We describe how the influence of such spatial effects can be minimized by improved edge-detection. We then discuss how elements of the SFR method have been adapted to other imaging characteristics, such as optical flare and edge-raggedness.

2. IMPROVEMENTS TO THE METHOD

2.1 Understanding and reducing variability

As with any estimation effort, acquisition and selection of input data are the first steps in designing a robust measurement. The input data for this method are the pixel values within the selected region of interest (ROI). This is usually the rectangular area in the direction of the edge. In many cases the SFR measurement can be improved by limiting the width of the ROI across the edge. For measurements of practical systems, image noise fluctuations on either side of the edge contribute both a positive bias and fluctuations to the resulting SFR. This was described in Ref. [5]. The measured SFR is shown for a simulated digital camera, and several data lengths (width of the ROI). This simulation is for a camera with a Gaussian lens MTF and the addition of spatially correlated image noise. The line shows the noise-free reference function. Note that the frequency-to-frequency SFR fluctuations are reduced as the data length decreases. This is similar to data 'windowing' that is used at a later stage in the analysis. There is usually a balance to be struck between edge-truncation, which will introduce an (smoothing) SFR bias, and excess data leading to measurement variability. The selection of the ROI width is often automated by statistical testing to detect the start of the edge (i.e., a non-zero slope) in the presence of image noise fluctuations. In general, the influence of image noise of SFR measurements will vary with exposure/ISO camera setting. However it can easily be understood by empirical estimation based on replicated measurements. See, for example, Ref. 6 where variation due to location of the ROI (for a fixed size) was observed to have a standard error of 1-2%.

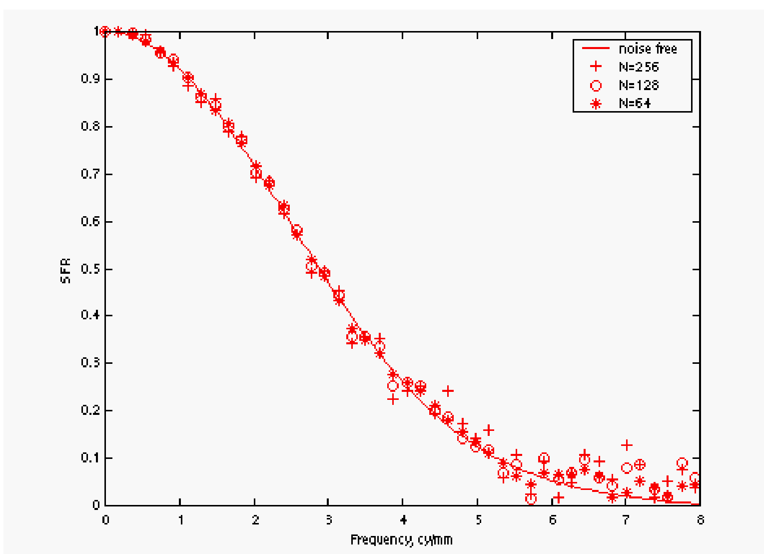


Figure 2: SFR measurements from simulated edge with image noise for varying data lengths [5]

The above selection is aimed at improving the input data; however for systems with moderate to high noise levels, intelligent data selection can still result in high measurement variability. In this case, it is possible to improve results by modifying the line-spread function prior to the DFT. Rather than simply truncating the input ROI, or equivalently the line-spread function (LSF); one can apply noise-filtering to the tails of the LSF or edges of the ROI data. It is important to apply this in the space (pixel) domain. This is done so as to reduce positive bias introduced into the SFR by the image noise. Since the SFR is derived from the modulus of the DFT, the addition of image noise in the LSF can result in a positive, 'noise-floor' bias into the measurement.

When successful, the results can be a smooth and largely unbiased SFR estimate. An example of this is illustrated in Fig. 3. Note how the SFR for the noise filtered edge closely follows the reference (aim) SFR from which these examples are synthesized, while the unfiltered edge follows a positive bias, especially at the high frequencies. One does need to be careful when using this technique to avoid spatial filtering too close to the important edge margins. This step should be used in moderation and only when noisy edge-ROIs are unavoidable. This example resulted from using a Gaussian blur filter operating on the edges of the ROI. We do not recommend filtering the entire LSF vector because this is likely to modify the shape of the entire resulting SFR.

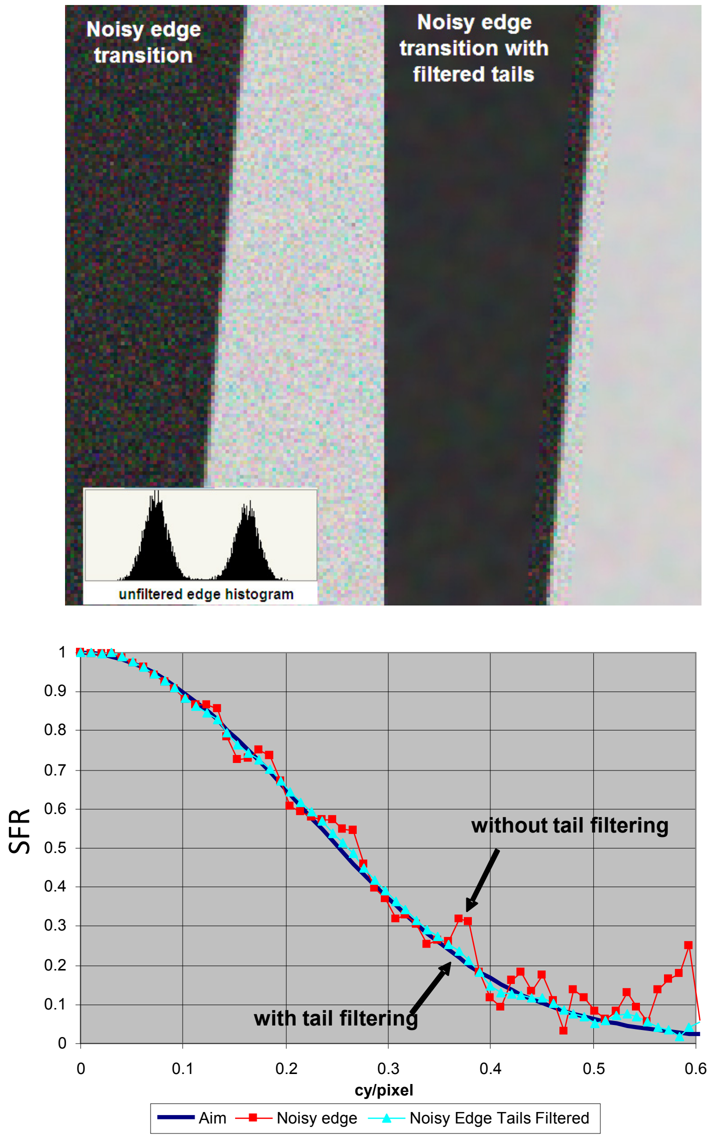


Figure 3: Example of spatial filtering image ROI data near an edge feature (upper) regions with and without filtering (contrast is increased for display here, (lower) corresponding SFR results for the luminance record

2.2 Analyzing and reducing bias

As shown in Fig. 1, the first two steps of EGA involve computing an edge profile vector, and then its derivative. This results in an estimated line-spread function (LSF). This LSF is based on the computed average profile across the (assumed) straight edge. In order to compute the profile, the slanted-edge algorithm finds the edge location and slope by fitting a linear equation to the edge locations (row-by-row) within the ROI data. This works well when the edge feature is straight. However if the edge is distorted, e.g. due to optical aberration, this will introduce error into the resulting SFR. We should note that the SFR is not intended to be a measure of (influenced by) spatial distortion.

SFR results from two distorted edge images are shown in Fig. 4 [5]. As we see, both large-scale barrel, and a more random type of edge displacement lead to significant reduction in the measured SFR. While the presence of a distorted edge can introduce bias into the measurement, the slanted-edge algorithm also provides a method for reducing this error. As described above, the slanted-edge method relies on fitting a linear equation to the edge location data. If we fit a higher-order polynomial, e.g. a second-order function, certain types of slowly varying distortion can be compensated for.

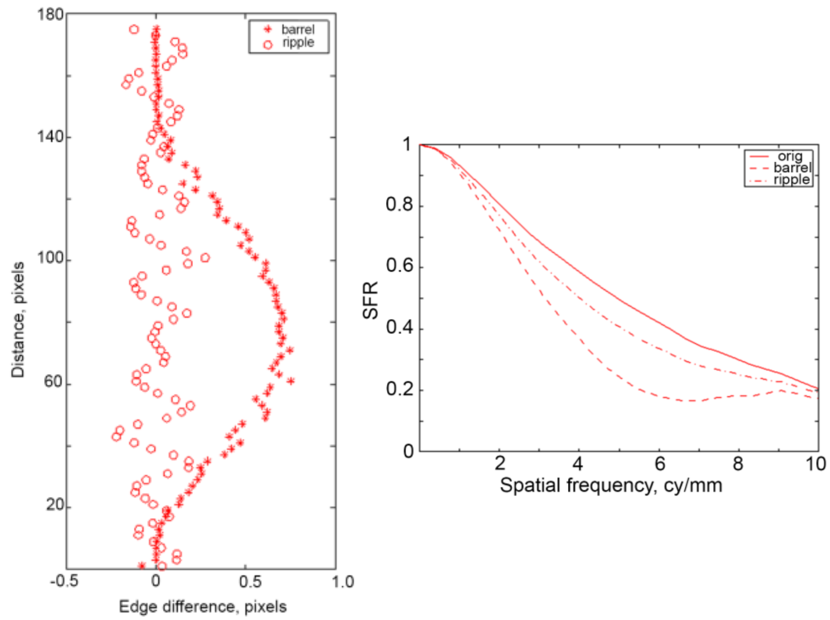


Figure 4: Example of the influence of optical distortion of camera edge-SFR measurements [5]. (a) Edge displacement observed because of barrel lens and ripple type distortion. (b) Measured SFR for undistorted edge. Sampling is at 400 ppi.

Figure 5 shows an example of a computed curved edge, similar to those captured with a lens exhibiting geometric distortion at the edge of the optical field. When the usual, standard linear fit is used to compute the SFR, this causes the result to underestimate the intended results. When a second-order polynomial equation is fitted to the edge, however, the SFR result is restored to the ideal, or correct, measurement. This polynomial edge-fitting is not included in any ISO standards, but is implemented in several software tools [1] and is likely to be considered in future editions of ISO 12233. An informal evaluation of the polynomial edge-fitting approach from three practitioners, working independently, showed extremely good accuracy and consistency between them.

[1] Information on a Matlab implementation is available from PDB.

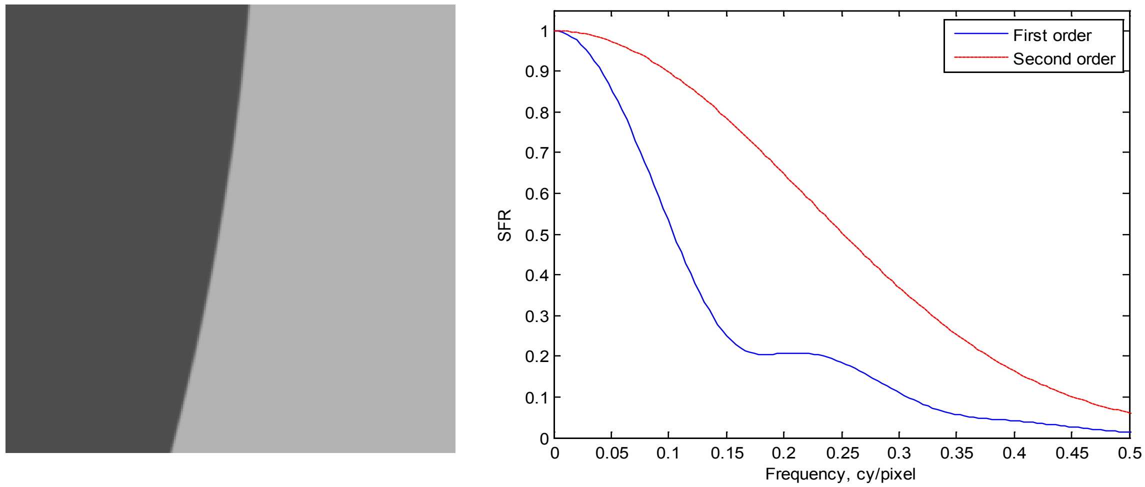


Figure 5: (left) edge ROI with spatial distortion leading to a curved edge-feature, and (right) computed SFR following the usual linear (first-order), and quadratic (second-order) fit to the edge.

3. NEW APPLICATIONS

Since its development for the evaluation of digital camera resolution, the slanted-edge SFR method has been applied to several other imaging applications. The following presents a summary of several, with a brief discussion of each.

3.1 Scanner resolution

Perhaps the most obvious second application for the ISO 12233 edge-SFR method was for the evaluation of digital scanner resolution. This was adopted as ISO 16067 [7]. The details of the slanted-edge algorithm follow the digital camera resolution standard closely.

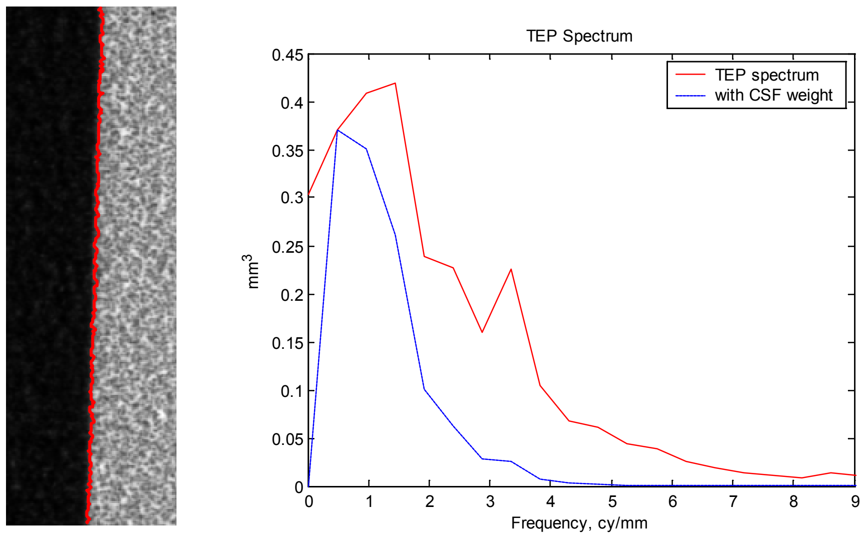
3.2 Color registration

The original digital camera resolution method called for the slanted-edge SFR computed from a luminance-weighted image array. This meant that differences between the color-records for a digital camera were lost. An early Matlab implementation (sfrmat) of the SFR method, however, was the first widely available tool to compute and report results for all color-records and the computed luminance. Since the slanted-edge SFR was computed for each record, the edge fit parameters could be used to report position differences between the edge locations. Burns and Williams described [8] how these parameters can be used to report and interpret these as color channel (mis-)registration values, and used as a summary measure for lateral chromatic error. This is now common practice.

3.3 Printer image quality

ISO/IEC 13660 [9] defines methods for assessing printer resolution performance. In this standard, slanted edge gradient analysis is specified as one basis for evaluating this image quality attribute. Specifically, slanted EGA is cited for two distinct uses. One is for calibrating digital scanners/cameras for their use as instruments in collecting image data from printed targets. The second is for analyzing the image data of printed edge content from printers being evaluated. A recent paper [10] also addresses printer resolution measurement by this method. Another effort, ISO/IEC PDTS 29112 [11], is also defining new methodologies for assessing printer performance; resolution and edge raggedness being two of the included performance metrics.

The edge finding and profile computation steps of the slanted-edge method were adopted in an adaptation for the measurement of a different image quality parameter, edge raggedness [12]. When modifying the method, attention focused on the automated edge-finding step, due to the influence of halftone patterns in digital prints. This was addressed by modifying the edge detection method for each line of the data array. Fig. 6 from Ref. [12] shows the result of the spectrum of the tangential edge profile (TEP). This TEP noise-power spectrum [13] is the spatial variation of the edge expressed as a function of spatial frequency. Rather than an image-signal parameter, as is the SFR, this TEP spectrum is viewed as an image distortion measure. The visibility of this edge variation, or raggedness, is modeled using a visual weighting, the contrast sensitivity function (CSF), as indicated in Fig. 6.



a. b.

Figure 6: (a) Scanned inkjet print with detected edge added, and (b) TEP noise-power spectrum and visual, contrast sensitivity function, weighting for 33 cm viewing distance [11]

3.4 Optical flare measurement

We previously discussed how the selection of the input data (ROI) can be used to reduce the influence of image noise. For some applications, however, including the extended ‘tails’ of the edge can be important. This is the case for the measurement of optical flare. In this measurement it is important not the truncate the edge because a measure of optical flare is derived from the measured SFR for low spatial frequencies. The SFR method was adapted, and applied to digital scanner flare in Ref. [14].

3.5 Process monitoring and quality assurance

A sampling frequency normalized method to report limiting resolution is the sampling efficiency. It was introduced in Ref. [15], and is described in detail in the second edition of ISO 12233. Briefly, it is the ratio of two frequencies, the quotient of the 10% SFR frequency to the half sampling frequency. An example of its derivation from an SFR is shown in Fig. 7. The 10% SFR frequency is 0.44 cycles/pixel leading to a sampling efficiency of 88%. The sampling efficiency has proven very useful for quality control and benchmarking purposes for mass digitization efforts. For example this has been adopted in the cultural heritage community where a variety of sampling frequencies are used, depending on usage and object content. Notably, it is specified as a summary resolution metric in the Federal Agency Digitization Guideline Initiative (FADGI), a standardization and digital capture guideline initiative of the U.S. Library of Congress [16, 17].

3.6 Information content from natural edges

A number of workers have used edges in natural images to evaluate (spatial) information content. An example of this is for determining the necessary scanning resolution for collections of film negatives. This is illustrated in Fig. 8. The highlighted edges were selected manually for evaluation [18]. The frequency associated with 10% SFR value was used as the measure of limiting information content. A statistical analysis of multiple measurements was then used for determining the final scanning resolution. This process can be extended to include automatic edge-feature selection [19, 20].

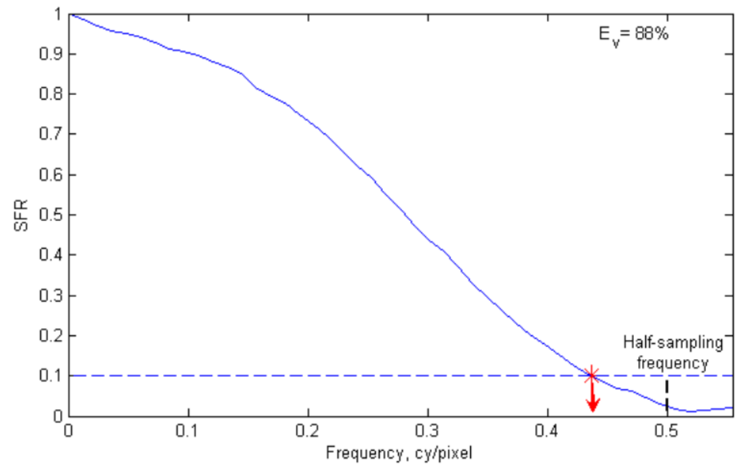


Figure 7: 10% SFR calculation and the resulting sampling efficiency, E_v, of 88%

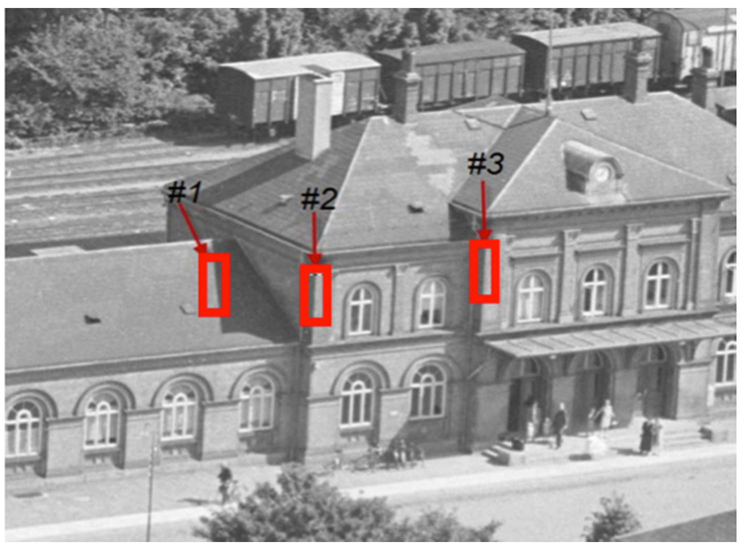


Figure 8: Scene shadows from building corners used to gauge image content (4" x 5" aerial negative, courtesy of the Danish Royal Library)

4. FUTURE WORK

A number of other improvements to the current slanted edge SFR technique have been suggested but not effectively demonstrated or tested, several being optimization methods. For certain applications it may be reasonable to constrain the color channel edge slope estimates for each color. Implementing search algorithms for more consistent ROI selection or optimal edge angles and curvature selections has also been considered. Finally, benchmarking accurate SFR estimates at other than near-vertical and horizontal directions has been suggested for a number of years. This requires creating a series of digitally unambiguous edge artifacts that have known SFR responses at arbitrary angles.

5. CONCLUSIONS

The international standard for measuring digital camera resolution, ISO 12233, was adopted over a decade ago. Since then the slanted edge-gradient analysis method has been improved and applied beyond digital camera evaluation. As for any statistical estimate, careful selection of input test data can reduce measurement variability. In addition, an intermediate operation, the finding the edge feature, can be modified to reduce the bias error introduce by optical distortion. Although initially applied to digital camera (lens and detector) performance, the method has now been adopted for a range of applications. This has led to adaptation of the basic method, for e.g., printers, quality assurance and optimization of image processing. It popularity lies in its simplicity, ease of use, and freely available software implementations. We continue to encourage others to make suggestions for improvements, and will continue to share these with the greater digital imaging community.

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