Refined Slanted-Edge Measurement for Practical Camera and Scanner Testing

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Abstract

It has been almost five years since the ISO adopted a standard for measurement of image resolution of digital still cameras using slanted-edge gradient analysis. The method has also been applied to the spatial frequency response and MTF of film and print scanners, and CRT displays. Each of these applications presents challenges to the use of the method. Previously, we have described causes of both bias and variation error in terms of the various signal processing steps involved. This analysis, when combined with observations from practical systems testing, has suggested improvements and interpretation of results. Specifically, refinements in data screening for signal encoding problems, edge feature location and slope estimation, and noise resilience will be addressed.

Introduction

Slanted-edge analysis has been applied to the evaluation of digital cameras for several years.[1-3] The method has also been applied to film and print scanners, and CRT displays.[4] Each new application presents challenges to the use of the method. In this paper, we describe several improvements and analyses that are aimed at reducing measurement error and providing insight into several sources.

The slanted-edge analysis is based on the image (or system output) due to an input edge feature of high optical quality. Often the measured image modulus can be taken as an estimate of the MTF of the system. In other cases, the output modulation is divided by the input edge modulation frequency-by-frequency to yield the measured system MTF. We will refer to the single output modulation, normalized to unity at zero frequency, as the spatial frequency response (SFR), consistent with the standard. The ratio will be called the estimated or measured MTF.

The ISO Standard procedure[5] for camera resolution measurement is based on edge-gradient MTF analysis[6] methods. There are three basic operations; acquiring an edge profile from the (image) data, computing the derivative in the direction of the edge, and computing the discrete Fourier transform of this derivative array. The specific steps for the ISO 12233 method, which is used to derive a resolution measurement from digital image data, are shown in Fig. 1. If we interpret the slanted-edge spatial frequency response (SFR) measurement as an estimation problem, several sources of error can be seen as introducing bias and/or variation into the estimated SFR. For example, the standard and available software[7] do not require a precise alignment of the edge feature in the scene with image sampling array. This requires estimating the edge location from the data. An error introduced into the computed slope propagates as a bias error in the resulting SFR or MTF measurement.[3] Error is also introduced into practical measurements by pixel-to-pixel fluctuations. When making SFR measurements of image signal capture, the objective is usually to minimize the impact of this image noise.

Limiting Data Length

In many cases, careful selection of input image data can improve the measured SFR. Consider the number of sample points which are Fourier transformed, determined by the width of the input image for a near-vertical edge. We will call this the data length, *N*. For an ideal noise-free data set, if the *N* data extend beyond the edge, this merely increases the number of samples in the resulting SFR. This results in an interpolated, usually smooth, measurement.

For practical imaging systems, however, noise fluctuations on either side of the edge contribute both a positive bias and fluctuations to the resulting SFR. This effect is described by Blackman,[8] who addresses the general problem of image noise on MTF measurement. He suggests several methods for reducing the errors. In the present case of a flexible procedure based on a user-selected image data, however, we have the opportunity to avoid the problem by simple limiting the data length, *N*, to a region close to the edge feature. This applies to general statistical sources, such as shot-noise, and artifacts due to sampling, compression etc.

Figure 2 shows several SFR measurements for the same system, based on varying numbers of data. As *N* is reduced, the error is reduced. This simulation is for a device with a Gaussian point-spread function and the addition of spatially correlated image noise, typical of many systems. For noise sources with stationary statistics, it is possible to employ smoothing techniques to the estimate based on, e.g., $N = 256$. Limiting the data to an image area surrounding the edge feature often makes this step unnecessary. This is

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similar to a ‘windowing’ operation that is applied in a later stage of the algorithm, as shown in Fig. 1. Figure 3 shows the error in more detail as a difference from the noise-free case.

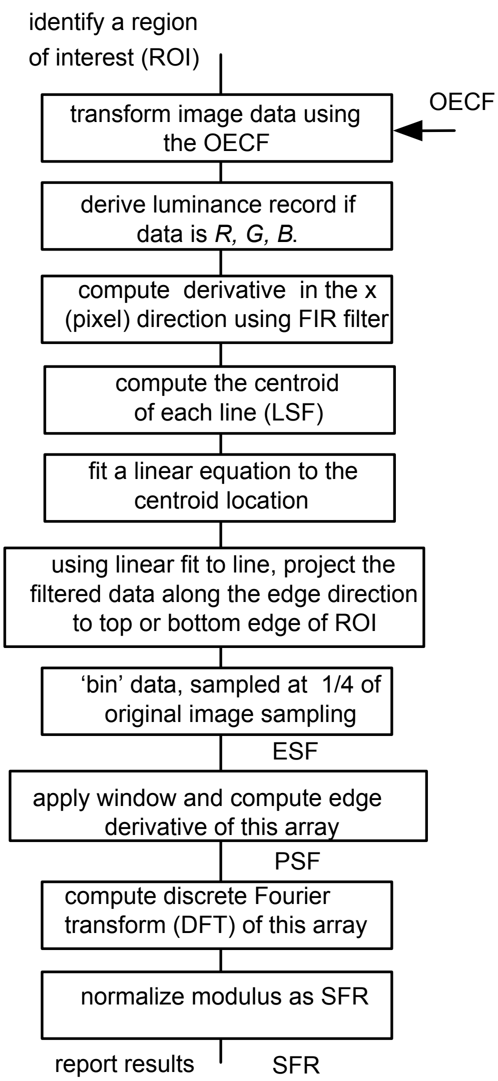

Figure 1. Description of the ISO 12233 spatial frequency response evaluation method. The edge is assumed to be oriented in a near-vertical direction.

Signal Clipping

The general conditions of approximately linear systems and continuous signal modulation transfer are usually cited as requirements for MTF analysis. In this context, the slanted-edge SFR method, can be viewed as an adaptation of established edge-gradient analysis for sampled systems and quantized digital images. The consequences of deviating from the assumptions for this adaptation, however, can easily be overlooked when practical testing is conducted. Admittedly, the use of low modulation target design (40% contrast modulation) helps considerably in controlling problems caused by uncorrected nonlinearities such as gamma look-up tables (LUT) or automatic contrast image processing.

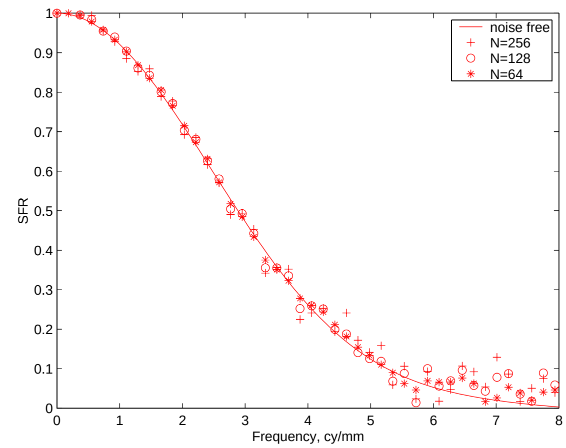

Figure 2: SFR measurements from simulated edge with image noise for varying data lengths

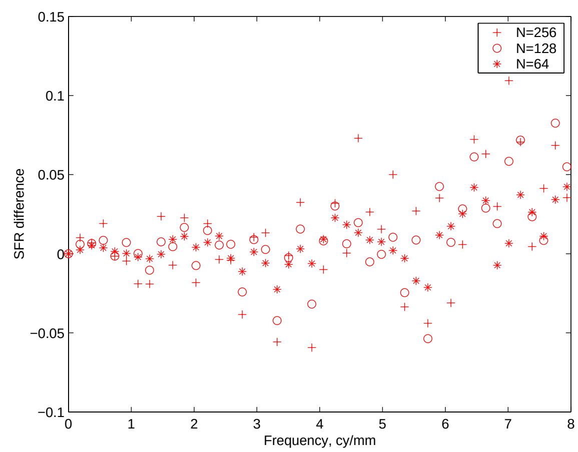

Figure 3. SFR measurement error for simulated edge with image noise and varying data lengths

Commonly overlooked sources of error are the non-linear effects of clipping and quantization. The former often occurs in consumer digital cameras where noise reduction, coring, or sharpening operators are applied. Because these operators are used more aggressively than LUT or auto-contrast features, they can have a profound effect on the measured SFR or MTF if clipping occurs. Examples of measured SFRs derived from clipped and non-clipped data using the same sharpening filter are shown in Fig. 4. Note the lack of agreement and odd rebounding behavior of the clipped data SFR at high frequencies. This is common and due to the introduction of ‘artificial’ edges by the signal processing.

To help identify these occurrences, an analysis of the histogram of the input image data values can be used. This can take the form of a statistical test alerting the user to clipped data when a threshold is exceeded.

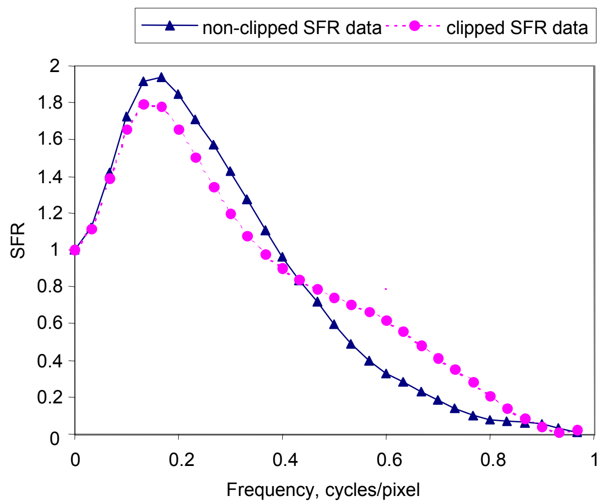

Figure 4. Measured SFR for image data with sharpening filter applied, with and without signal clipping

Analysis of Edge Displacement

One requirement for edge-gradient analysis is the use of a straight edge image feature, however, spatial distortion during image capture can challenge this condition. Since spatial distortion is not usually the object of the SFR measurement, it can be viewed as a source of bias error. When the edge-spread function (ESF) is estimated in the projection and binning steps of the procedure of Fig. 1, position variation can introduce a significant component into the measured ESF. Whereas the ESF and corresponding PSF are widened the resulting SFR is decreased, by Fourier transform properties.

Although edge distortion is a source of bias error for the SFR, the slanted-edge analysis lends itself to simple diagnosis of the problem. Just as the intermediate fitting equation for the edge location has been used to detect color misregistration,[9] residual errors for this fit can be used to detect and measure edge distortion. This is shown in Fig. 5 for two types of spatial distortion. The data were computed as part of the Matlab software, so they require no additional data acquisition or computation.

Figure 6 shows the reduction in measured SFR due to the above spatial distortion. It is suggested that similar plotting and subsequent analysis can be used during testing to diagnose the sources of unexpectedly low SFR results. Limits can be established for trends in this edge location array, based on acceptable SFR bias error caused by the introduction of this effective spread function.

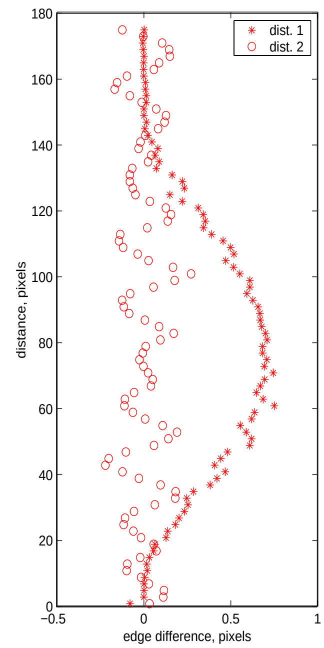

Figure 5. Edge displacement observed because of barrel lens (1) and(2) ripple type distortion

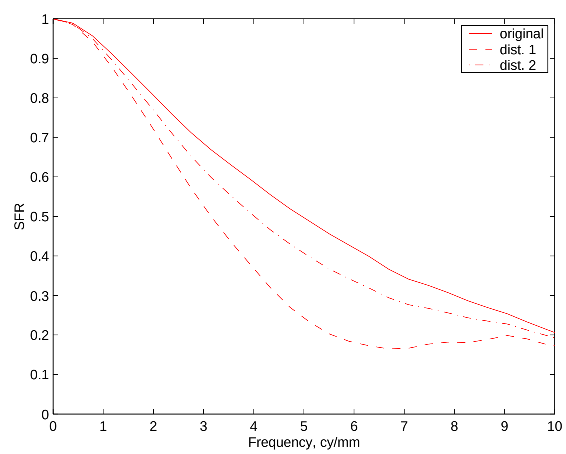

Figure 6. Measured SFR for undistorted edge and as described in Fig. 5

Slope Estimates from *a priori* Target Characteristics

The estimation of the direction (slope) of the edge has direct effect on the computed SFR,[3] as has been modeled in much the same way as microdensitometer aperture misalignment.[10] In the slanted-edge analysis, the processing of the image data by projection along the edge can be approximated by the synthesis of a slit of length m pixels. The effective MTF due to the slope error is[3]

$$T(u) = \frac{\sin(\pi\, ms\Delta u)}{\pi\, ms\Delta u}, \qquad (1)$$

where Δ is the original data sampling interval, s the slope misalignment error, and u the spatial frequency. The current ISO 12233 procedure, outlined in Fig. 1, computes independent edge slope estimates for each edge and color-record. It takes no advantage of target feature placement in calculating the edge slope. Pooling edge slope estimates, however, based on multiple image locations, color-records, and supplemental target features can used to improve the slope estimates. These, in turn, improve the precision of resulting SFR and MTF measurements.

For example, the proposed ISO 16067-1 target of Fig. 7, for scanner evaluation, is a monochrome target that includes two sets of parallel edges near its center for horizontal and vertical SFR estimates. The target also includes four fiducial marks, each consisting of a cross and circle. When this target is scanned, two SFR estimates/orientation/color are typically extracted. For many cases, in the absence of optical aberration, there are few reasons why the two vertical or two horizontal edges should differ in slope. Measured SFR results often do, however. These differences can frequently be tracked to minor differences in estimated slopes, due to image noise, dust, etc.

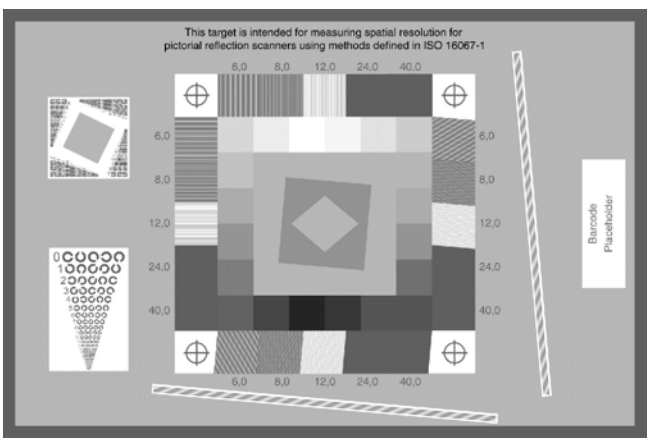

Figure 7. ISO scanner resolution target

This is illustrated in Fig. 8 for a monochrome scan of the ISO 16067-1 target. There are small differences between all of the estimates, making it unclear whether there are significant differences between horizontal and vertical directions. Using the same image data, but by pooling the common directional edge slope estimates, the directional MTF ambiguity is removed in Fig. 9. One now has a greater confidence that the directional MTFs are truly different.

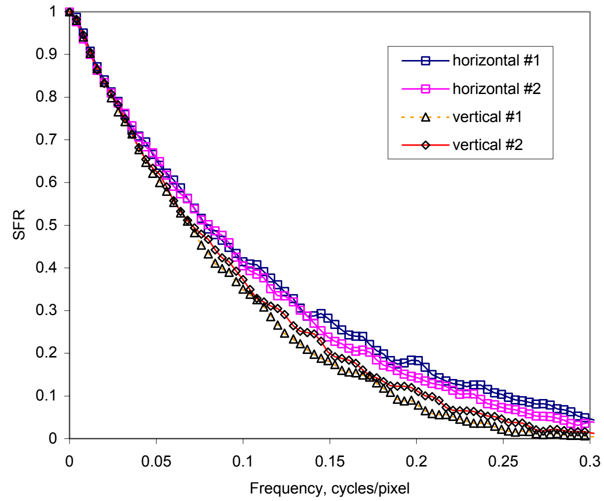

Figure 8: SFR measurements from independent edge slope estimates for the same device

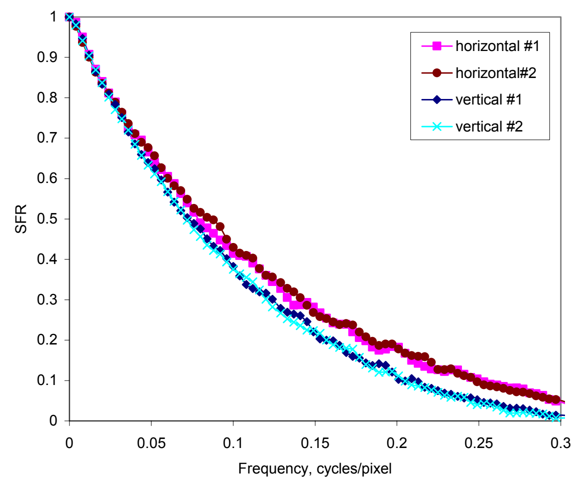

Figure 9. Improved results based on pooled slope estimates

Conclusions

The performance of slanted-edge analysis for digital imaging devices can be improved by reducing and identifying conditions that lead to measurement errors. Limiting the extent of image data used for the analysis, and detecting the presence of clipped signal are simple but effective measures. While spatial distortion, due to optical aberration or position errors reduce the measured SFR, its presence can be detected by examining intermediate derived edge location data, already computed as part of the procedure. As usually practiced, the slanted-edge analysis is applied without using knowledge of the target configuration. Information about the surrounding target features can be used to reduce the propagation of slope error to the measured SFR.

References

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Biographies

Peter Burns studied Electrical and Computer Engineering at Clarkson University, receiving his B.Sc. and M.Sc. degrees. In 1997, he completed his Ph.D. in Imaging Science at Rochester Institute of Technology. After working for Xerox, he joined Eastman Kodak Company, where he works in Electronic Imaging Products, Research and Development. A frequent contributor to imaging conferences, his technical interests include; system evaluation, simulation, and the statistical analysis of error in digital and hybrid systems. peter.burns@kodak.com

Don Williams received both B.Sc. and M.Sc. degrees in Imaging Science from RIT, and works in Electronic Imaging Products, Research and Development at Kodak. His work at Kodak focuses on quantitative signal and noise performance metrics for digital capture imaging devices and imaging system simulations. He has been active for several years in the development of imaging standards, and currently co-leads the PIMA/IT10 effort for both digital print scanner (ISO 16067-1) and digital film scanner (ISO 16067-2) resolution measurement. Mr. Williams is also a frequent contributor and advisor on digitization fidelity issues for the library and museum communities.