Slanted-Edge MTF for Digital Camera and Scanner Analysis

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Abstract

The development and adoption of standards for the evaluation of digital camera resolution has helped foster the widespread use of slanted-edge-based analysis. In addition, the form of these evaluation methods suggests their use in imaging system analysis and design. The standards-specific methods and algorithms, however, are not intended for direct MTF evaluation, but if care is taken to avoid bias and minimize random error, the methods can successfully be used for this purpose.

In this paper the influence of several variables are discussed. Specifically, the effect of color misregistration, edge location estimation, data-record length and image noise on the measured MTF are addressed.

Introduction

The development and adoption of standards [1] for the evaluation of digital camera resolution has helped foster the widespread use of slanted-edge-based analysis. The form of these evaluation methods suggest their use in imaging system MTF analysis and design. We address the method, and the specific ISO algorithm, as an estimation procedure. In this way, several sources of measurement error are seen as introducing bias and random error. In this paper, the focus will be on describing the form of several types of bias error.

The optical transfer function (OTF) and its modulus, the modulation transfer function (MTF) have long been used to describe image signal transfer in, e.g., optical and photographic systems [2,3]. Several measurement methods have been described, based on periodic signals, random noise, and other features. In the past, edge-gradient methods have shown the advantages of target simplicity and a small test image area, but the disadvantages of alignment sensitivity and noise bias.

Historically, edge-gradient methods were applied using a scanning microdensitometer. The method, outlined in Fig. 1, usually calls for the scanning the image of an edge feature in a direction perpendicular to the edge, with a slit aperture also aligned in the direction perpendicular to the edge. An edge profile is then derived from the data, often with noise reduction, such as by averaging edge traces. From this edge-spread function, a point-spread function is computed, either by a discrete first derivative or by a parametric fit to the data. The discrete Fourier transform of the point-spread function is then computed, with its modulus recorded.

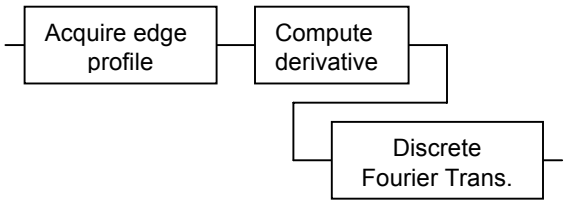

Figure 1. Edge-gradient analysis steps

If the input edge feature used is of sufficiently high optical quality, in terms its edge modulation, then the above measured modulus can be taken as estimating the MTF of the system whose output provided the data. If this is not the case then the output modulation can be divided by the input target modulation frequency-by frequency to yield the system MTF. When no account is taken of the input edge modulation, the measured modulus can still provide a useful measurement relative to the input target edge and other relevant operating conditions. We will refer to the result based on a single measurement as a spatial frequency response (SFR), and one corrected for the input modulation (or error modeled as an effective MTF) as an MTF.

Slanted-Edge Analysis

For the evaluation of digital imaging systems, the above edge-gradient method was modified [4] to allow its use with actual image data, rather than those acquired via a separate instrument. The use of a slanted, or skewed edge was proposed, in conjunction with corresponding data processing. One property of this modified method made it particularly useful for evaluating digital still cameras (DSC), reduction of aliasing caused by sampling of the color signals by the color filter array.

The ISO 122333 [5] standard for the evaluation of spatial frequency response (SFR) of digital cameras is based on the above slanted-edge method, and shown in Fig. 2. First, the region of interest (*m* lines, *n* pixels) surrounding the edge is selected and transformed to compensate for the camera photometric response. This is done via the opto-electronic conversion function (OECF). A luminance array is then computed as a weighted sum of red, green, and blue image records at each pixel. The edge location and direction

are then estimated from this luminance array via a linear equation. This is found after taking a one-dimensional discrete derivative and finding the centroid for each data line. The image data for all pixels are projected along the direction of the edge to form a one-dimensional 'super sampled' edge-spread function. The four-times oversampling accomplished by this step reduces the influence of signal aliasing of the measured SFR. After application of a Hamming window, the discrete Fourier transform is computed. The normalized modulus is then taken as the SFR.

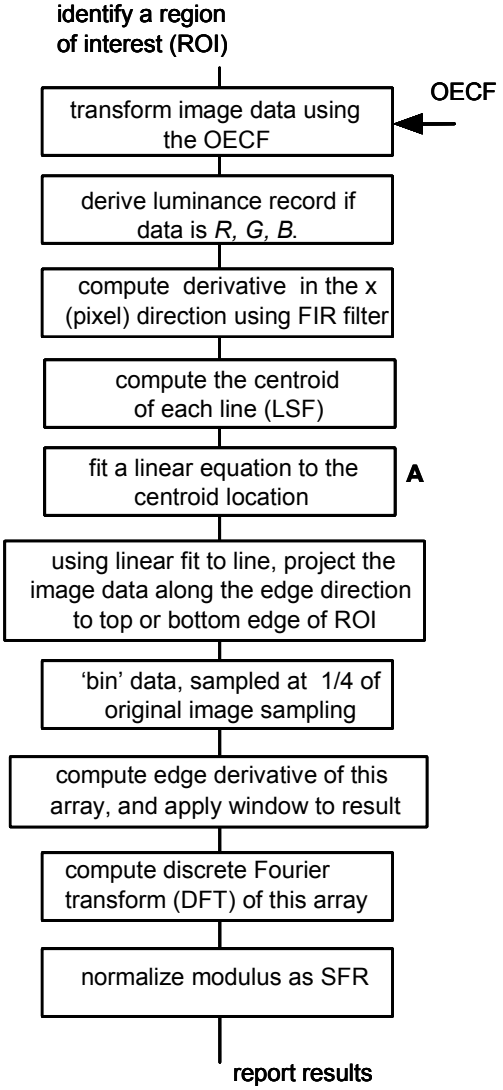

Figure 2. Description of the ISO 12233 spatial frequency response evaluation method. The edge is assumed to be oriented in a near-vertical direction. This figure has been edited to correct an error in the published PICS 2000 Proceedings.

A software implementation of the ISO procedure [5] has been evaluated [6] and found to provide a robust SFR measurement, largely insensitive to edge angle and ROI selection. With its success, however, the method is finding application beyond DCS evaluation [7-12]. It is now common to compare multistage imaging system performance using the slanted-edge techniques. In addition, results from different methods and equipment are likely to be compared in terms of 'MTFs'. To aid in such analysis, it is useful to understand the influence of key measurement parameters on the resulting SFR or MTF.

Skew MTF

As shown in Fig. 2, a key step in the SFR computation is the determination of the location and direction of the edge feature. These two parameters are estimated from the data, and are subject to variation. The estimation of the direction (slope) of the edge will have direct effect on the computed SFR, and can be modeled in much the same way as microdensitometer aperture misalignment [12,13]. When scanning an edge or other one-dimensional feature with a misaligned (skewed) slit aperture, Jones described this in terms of an effective MTF cascaded with the actual edge modulation function,

$$T_{skew}(\omega) = \frac{\sin(\pi L \tan(\phi)\omega)}{(\pi L \tan(\phi)\omega)}, \qquad (1)$$

where L is the slit length, ϕ the angle of misalignment, and for small angles $\tan(\phi) \cong \phi$.

In our case, we do not use a scanning slit, but the processing of the image data by projection along the edge can be approximated by the synthesis of a slit of length m pixels. Equation 1 can now be expressed as

$$T_{skew}(\omega) = \frac{sin(\pi m s \Delta\omega)}{(\pi m s \Delta\omega)}, \qquad (2)$$

where Δ is the original sampling interval, and s is the slope error in the estimate at point A in Fig. 2. This is related to the misalignment angle as $s = \tan(\phi)$.

Figure 3 shows the effective skew MTF for several values of slope estimation error, and a data array (height) m = 100. Note that this source of error introduces a negative bias error into the computed SFR or MTF derived from it. The bias increases with the number of data scan lines, m. For many digital camera and scanner evaluations, edge slope errors of less than 0.5 degrees are achievable.

Discrete Derivative

Determination of a point-spread function from an edge-spread function requires computing the first derivative with respect to distance. With sampled data, the continuous derivative is replaced with a difference equation, such as

$$\text{two-point}: f_i' = f_i - f_{i-1}$$
$$\text{three-point}: f_i' = \frac{f_{i+1} - f_{i-1}}{2} \qquad (3)$$

These operations, seen as digital filtering with arrays [-1, 1] and [-0.5 0 0.5], approximate a continuous derivative operation. The effect on the SFR is to cascade an additional MTF whose form depends on the width of the array [4, 14],

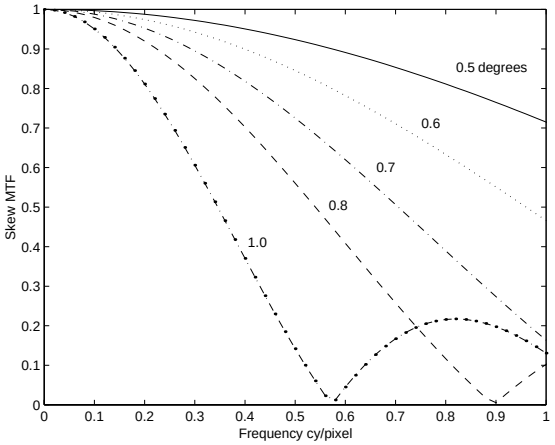

Figure 3. Skew MTF caused by various levels of angular error. The number of lines of data, m = 100.

$$T_{deriv}(\omega) = \frac{\sin(\pi\delta k\omega)}{\pi\delta k\omega}, \qquad (4)$$

where δ is the data sampling interval and k is the equal to 1 for the 2-point derivative, and 2 for the 3-point version. As has been pointed out in the literature, this operation attenuates (negative bias) the high frequency values of the computed SFR. For the ISO method, which does not correct for this effect, the discrete derivative is computed from data that is four-times oversampled, $\delta = \Delta x/4$. This means that the bias introduced is much smaller than if the operation were performed on the originally sampled data. Figure 4 shows the effective MTF caused by this discrete derivative calculation. The frequency axis, cycle/pixel, is in terms of the original image sampling.

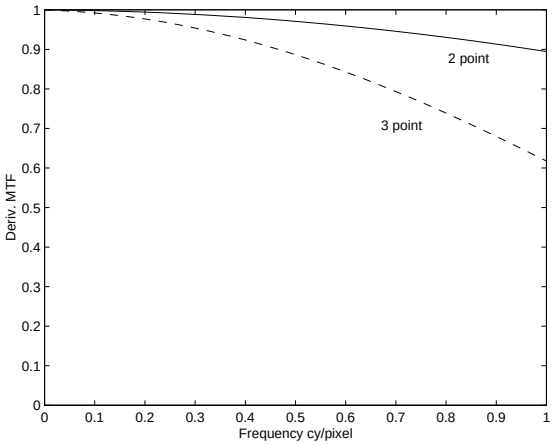

Figure 4. MTF caused by computation of the edge gradient by a finite difference. The 3-point difference [-0.5 0 0.5] *is used in the ISO procedure.*

Image Noise

The presence of image noise in the image introduces both a variation and positive bias into the measured SFR [17]. The use of multiple scans, *m*, of data reduces the source of error (in approximate proportion to *m*) but will usually not eliminate it. Often benchmarking studies [6] of simulated image noise levels provide guidance in the interpretation of measurement results. Levels of stochastic noise can be estimated from uniform image areas and interpreted in terms of a signal-to-noise ratio [4,6]. Although the error introduced by the image noise will vary with edge modulation (signal), data size, and noise correlation, acceptable results can be obtained without requiring replicate measurements, or other data smoothing techniques. Figure 5 shows a result of simulating uncorrelated gaussian noise, added for three levels. When expressed as a pixel signal-to-noise ratio (edge difference/rms noise) the plotted data sets are for SNR = 12.5, 25, 50, bandlimited input image data and m = 128 lines. These results are consistent with those reported by Williams, and provide guidance to acceptable noise levels for these measurement conditions. For the eight-bit encoded image the lowest noise level, seen to introduce a modest bias, corresponds to an rms value of 3.0, added to the edge data (min = 50, max = 200).

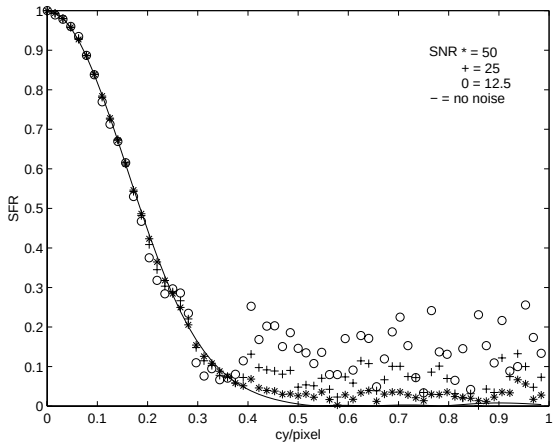

Figure 5. SFR based on 128 x 64 data, for three levels of image noise. Noise is zero-mean, normally distributed and spatially uncorrelated

Conclusions

By examining the various steps of the slanted-edge gradient analysis, several sources of error can be understood as introducing bias into the resulting SFR or MTF. Working equations, however, can be adapted from previous microdensitometer-based image evaluation methods. In addition, sensitivity of the methods to other image characteristics, e.g., non-stochastic error caused by quantization or image compression, can be investigated via simulation.

Acknowledgement

Many thanks to Don Williams for his contributions to this and related works.

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Biography

Peter Burns studied Electrical and Computer Engineering at Clarkson University, receiving his BS and MS 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 Imaging Research and Development organization. A frequent contributor to IS&T conferences, his technical interests include; system evaluation, simulation, and the statistical analysis of color error in digital and hybrid systems. peter.burns@kodak.com