Tone-Transfer (OECF) Characteristics and Spatial Frequency Response Measurements for Digital Cameras and Scanners

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ABSTRACT

Measurement of the spatial frequency response (SFR) of digital still cameras by slanted-edge analysis has been established for several years. The method, described in standard ISO 12233, has also been applied to other image acquisition subsystems such as document and print scanners. With the frequent application of the method and use of supporting software, questions often arise about the form of the input test image data. The tone-transfer characteristics of the system under test can influence the results, as can signal quantization and clipping. For this reason, the original standard called for a transformation of the input data prior to the slanted-edge analysis. The transformation is based on the measured opto-electronic conversion function (OECF) and can convert the image data to a reference-exposure signal space. This is often helpful when comparing different devices, if the intent is to do so in terms of the performance of optics, detector, and primary signal processing. We describe the use of the OECF and its inverse to derive the signal transformation in question. The influence of typical characteristics will be shown in several examples. It was found that, for test target data of modest contrast, the resulting SFR measurements were only moderately sensitive to the use of the inverse OECF transformation.

Keywords: MTF, SFR, tone transfer, image quality

1. INTRODUCTION

The last few years have seen the development and adoption of several international standards for the evaluation of digital still cameras and scanners.[1] The method for evaluating image resolution performance is specified in ISO 12233 and uses a form of edge-gradient analysis[2,3] based on a slanted-edge target feature.[4,5] The analysis is based on the image (or system output) due to an input edge feature of high optical quality. Often the measured image modulation 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.

When measuring the MTF of an imaging system or image capture subsystem, it is common practice to first transform the observed output image data into an equivalent input exposure. For digital cameras and scanners, this is done by measurement of the input-output characteristic, called the opto-electronic conversion function (OECF) in ISO 14524.[6] The OECF describes the large-area relationship between input exposure and digital signal values. To transform the digital image data to corresponding effective exposure values we use the inverse of the OECF. While such transformations can have a significant effect on measurements of, e.g., image noise statistics,[7,8] it is often observed that their influence on the SFR results can be subtle. We start by describing the origin of the OECF characteristics for most digital cameras and scanners

1.1 OECF and Its Inverse

The shape of the OECF curve for a digital camera or scanner is largely determined by image processing after the initial signal detection by the image sensor array. The sensor has an approximately linear response in that the detected signal is proportional to the scene exposure as imaged by the lens. Digital images are delivered from the camera or scanner, however, with a tone transfer applied that compensates for the tone reproduction characteristics of common computer monitors. This large-area tone transformation is implemented via a lookup table and is part of a common color encoding specification for the interchange of digital images, sRGB.[9,10] Figure 1 shows a simple sequence of operations, where the above lookup table is part of the image-processing step.

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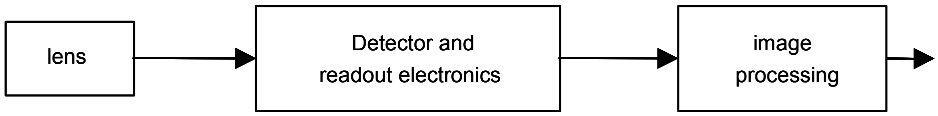

Figure 1: Elements of digital camera or scanner

A typical OECF characteristic that results from such a signal transformation is shown Fig. 2, where the image signal, *d*, is given by,

$$d = \left(k_1 e + k_2\right)^{1/\gamma}, \tag{1}$$

where k_1 and k_2 are constants, and γ is CRT gamma. The characteristic that would be used to transform digital signal values to corresponding relative scene exposure is shown in Fig. 2 as the inverse of the OECF. When evaluating a digital image acquisition system, we do not usually know the actual relationship between scene exposure and digital signal level. In addition, this relationship can change is a result of the adaptive nature of image processing, particularly for digital cameras. The OECF standard specifies the conditions to be used for the measurement of this characteristic.

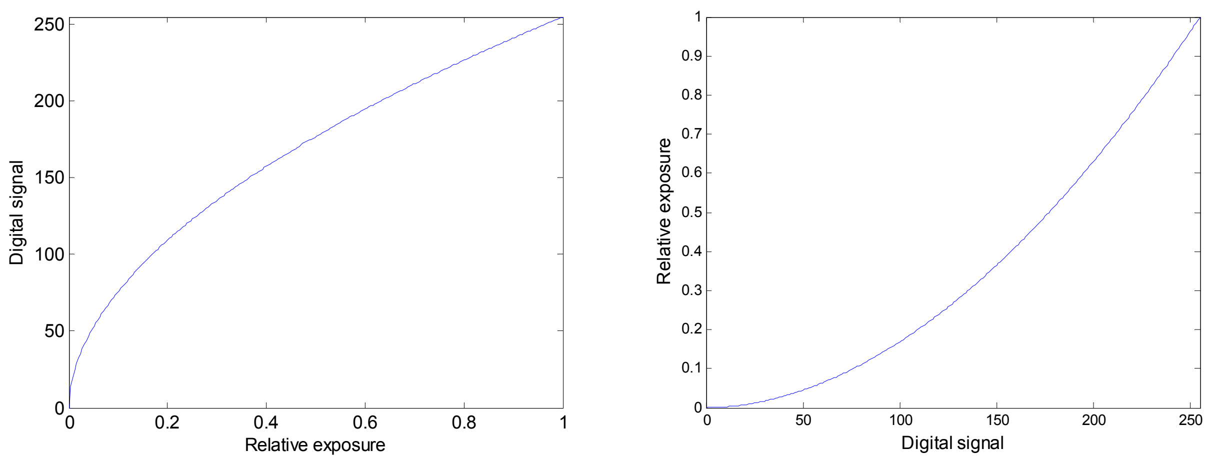

Figure 2: Example OECF and its inverse (right)

The OECF and its inverse are usually nonlinear functions, therefore, we would expect that transforming digital image data, prior to estimating the SFR, would change the result from that computed without the transformation. Under certain conditions, the lens and detector combination can be modeled as a sampling step with a combined point spread function. Ignoring signal quantization, the combination of this first step with a second nonlinear OECF transformation constitutes what is often called a weakly nonlinear system. The signal transfer for such systems is often analyzed in the Fourier transform domain using a functional series,[11] where the optical transfer function would be the first (linear) member. While such a description will not be addressed here, it can provide a way to predict the introduction of signal components at the output at different (usually higher) frequencies than were present in the input exposure. When this is unwanted output from a linear system, it is often called harmonic distortion.

We will address the influence of the OECF transformation on the measured SFR in the context of practical measurements. The effect of the inverse OECF can be described in terms of the bias error introduced into the SFR measurements by the signal processing that specifies the OECF characteristics.

2. SFR AND OECF

2.1 Noise-Free Case

Consider the case where slanted-edge analysis is performed in order to estimate the SFR or MTF. If the preferred procedure is to first transform image data to an effective exposure via a lookup table, the error introduced can be investigated by direct calculation. We first address the noise-free case.

A noise-free slanted-edge image file was generated and stored as an 8-bit encoded monochrome image file. In keeping with common practice in MTF measurements, care was taken in specifying the contrast of the edge feature. We would expect that, the higher the edge contrast, i.e., the wider the range of input signal values high to low, the greater the influence of the OECF on the computed SFR. We will define the large-area modulation contrast of the edge feature in percent as

$$c = \frac{100\left(s_{\max} - s_{\min}\right)}{s_{\max} + s_{\min}}, \tag{3}$$

where $s_{\max}$ and $s_{\min}$ are the maximum and minimum signal values for the edge image feature, respectively. In each case, the mean signal value was set at the center of the range,

$$\frac{s_{\max} + s_{\min}}{2} = 128 .$$

For each condition computed, the test file was transformed using several lookup tables, was shown in Fig. 3. The functional form of the transformation was, as in Eq. (1), with k_1 and k_2 equal to one and zero, respectively. The values of γ were chosen to span the range of likely transformations. In addition, the particular values correspond to common in color image processing. For example, 0.45 and 2.2 correspond to the transformation and its inverse, which is used for the default display on a computer monitor for Microsoft operating systems.

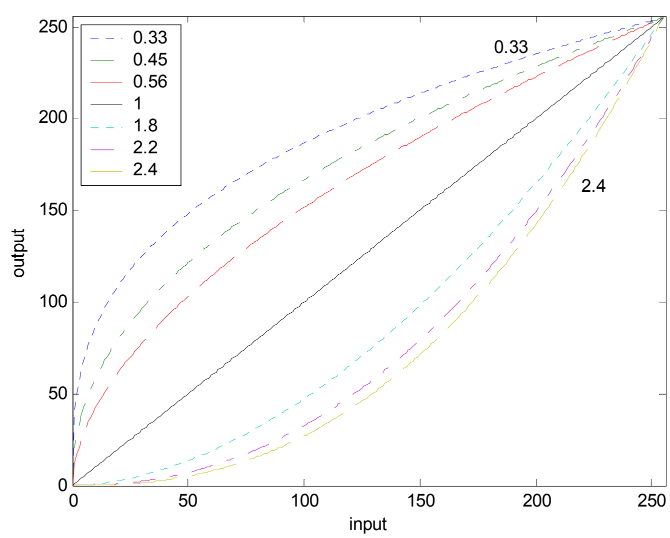

Figure 3: OECF transformations, where γ varies from 0.33 to 2.4

Following the transformations indicated in Fig. 3, the image arrays were used as input for the slanted-edge SFR computation.[12] The results for 40 and 80% input edge modulation contrast are plotted in Fig. 4. As anticipated, we note that the nonlinear transformations increase the computed SFR at higher frequencies. The magnitude of the increase also varies with input edge contrast. Table 1 gives the difference in computed SFR, on a [0,1], scale because of the OECF transformations when evaluated at the half-sampling frequency for three modulation contrast values.

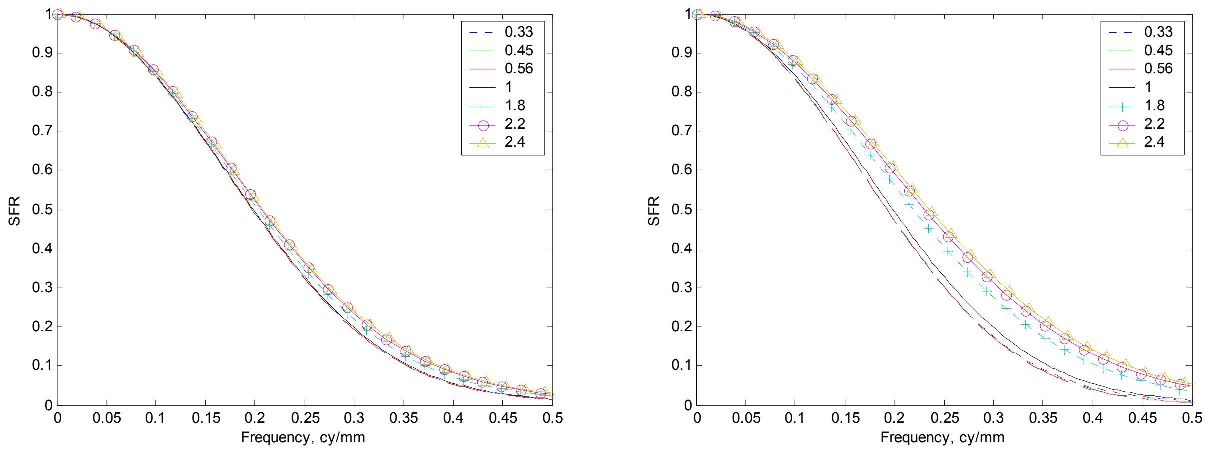

Figure 4: SFR results for a noise-free Gaussian edge images after the transformations of Fig. 3. The left plot is for the 40% edge modulation contrast, and the right, 80%.

Table 1: Difference in SFR for the noise Gaussian edge at the half-sampling frequency (0.5 cy/pixel) introduced by OECF lookup table for the γ values of Fig. 3 and three edge-modulation values, ($\gamma = 1$ case is reference).

			Gamma, γ			
Modulation	0.33	0.45	0.56	1.8	2.2	2.4
40%	–0.0018	–0.0019	–0.0019	0.0075	0.0121	0.0146
60%	0.0091	0.0059	0.0033	0.0197	0.0306	0.0360
80%	–0.0018	–0.0049	–0.0064	0.0222	0.0341	0.0400

2.2 Digital Camera and Scanner Examples

The above results for noise-free Gaussian edges indicate that for moderate contrast edges, introduction of an inverse OECF transformation introduces small changes to the computed SFR or MTF. To see whether equivalent results would be observed in practical device evaluation, the experiment was repeated for a digital still camera and desktop scanner. The consumer digital still camera was used to capture a digital image of a 1 m × 1 m printed target with 40% modulation contrast edge features (measured in reflectance factor). The target, shown in Fig. 5, is the currently proposed ISO target for scanner resolution evaluation. The camera was used in its normal automatic mode without the use of the flash. The target included a series of gray steps that can be used to derive the camera OECF. Our objective, however, was not to estimate the OECF from the camera data, but to investigate the sensitivity of the SFR measurement to a range of lookup table transformations. As before, the original image data was taken as providing the reference-measured image SFR. The digital file was used, following the selection of a vertical edge as the region of interest, and the slanted-edge analysis was completed for each of the six gamma transformations of Fig. 3. The results are shown in Fig. 6, where the overall shape of the SFR indicates the presence of a sharpening filter in the camera image processing. The moderate contrast of the target helped ensure that no clipping of the digital image was observed.

A similar target was used to evaluate the digital scanner. For most scanners, the user can control the tone-transfer introduced by the driver software, unlike most digital cameras. The parameter labeled "gamma" actually operates as an inverse gamma, or gamma correction. A value of, e.g., 2.2, will invoke a transformation with a gamma of 0.45, since it is intended to apply the inverse of the default computer monitor characteristic. This was approximately the OECF observed while using the scanner. The results of the slanted-edge analysis following the signal transformations are shown in Fig. 7. In this case, there was very little bias introduced into the resulting SFR up to the half-sampling frequency.

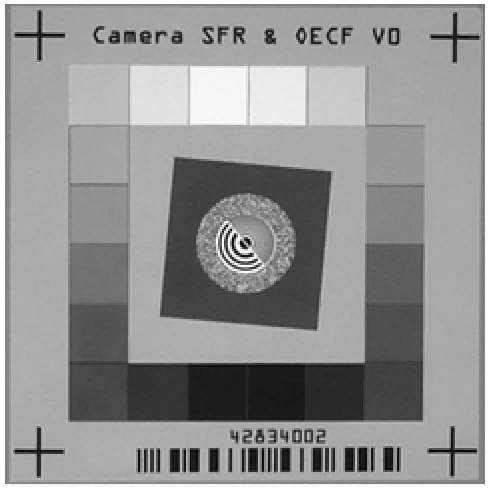

Figure 5: Target used for digital camera and scanner evaluation (*Courtesy of D. Williams, Eastman Kodak Company*)

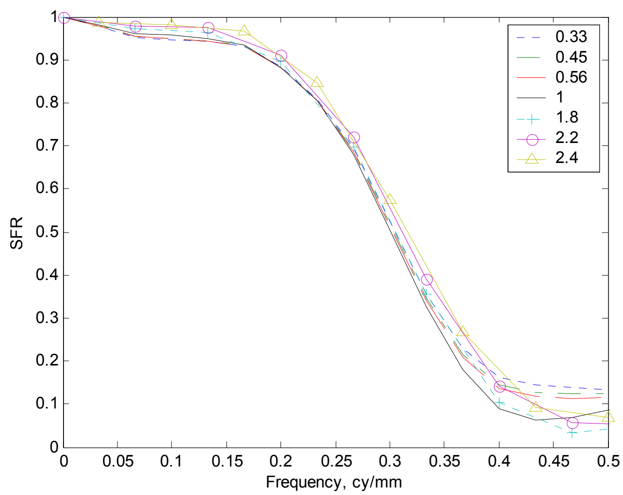

Figure 6: SFR results for a digital still camera based on a 50% edge modulation contrast

3.0 SUMMARY

When making MTF measurements for digital still cameras or scanners, the ISO standards recommend transforming the test image data to an effective exposure signal space. This is often helpful in reducing the influence of differing signal processing between units under test. To do so, however, usually requires the measurement of the tone-transfer characteristics of the device. In this paper, we have investigated the variation in the resulting SFR and MTF measurements that is introduced by typical lookup table processing. Results indicate that the bias errors incurred by either not making the inverse OECF transformation, or making an inaccurate one, are often not a serious problem. This is particularly true for input test target edge features of moderate contrast. This, together with the desire to avoid image clipping, is the motivation for the development of the new ISO targets used in our camera and scanner evaluation. By analyzing such errors (or approximations) as sources of measurement bias and variation, they can be compared with other sources of measurement variability

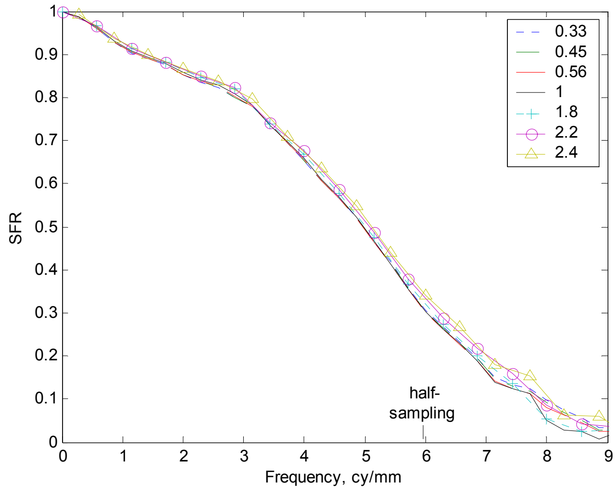

Figure 7: Desktop scanner example 300 dpi sampling 40% modulation contrast

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** Upated Matlab software currently available at:* http://burnsdigitalimaging.com/software/