Diagnostics for Digital Capture using MTF

Don Williams and Peter D. Burns
Eastman Kodak Company
Rochester, NY USA

Abstract

The modulation transfer function (MTF) has long been used as a diagnostic tool for analog image capture, by tracking frequency response caused by aperture, field position, or defocus optical phenomena. For digital capture, these factors still exist, in addition to a host of others introduced by detector motion, sampling, and image processing. Many of these problems can be identified via their MTF signatures and often can be quantified with complementary image analysis tools. Such techniques are useful for monitoring specification compliance and evaluating true imaging performance for digital capture. Using the slanted-edge MTF technique described in ISO 12233, a variety of MTF examples associated with characteristics from the above list are shown for several actual digital capture devices.

Introduction

The micro-imaging performance of capture processes has long been analyzed by way of the modulation transfer function (MTF). Fundamentally, it is the means by which the popular performance metrics of spatial resolution and acutance can be derived. When measured and interpreted with care, both of these singular metrics can serve their purpose well. In addition, the MTF morphology can be a strong indicator of imaging behavior that we typically do not associate with imaging resolution or acutance, *per se*. This allows the MTF to be a valuable clinical tool for capture devices that not only require an interpretation of their real resolution, but also call for insight into their image processing or hardware characteristics. This paper will give examples and offer explanations of MTF responses observed for several capture devices currently in the marketplace.

The power in using MTFs for such purposes lies largely in comparing observed results. Just as it is difficult to judge image quality with single stimuli, too little insight can be gained from measurement of a single MTF. Comparative MTF analysis exercising variables such as sampling frequency, color, image processing, orientation, spatial location, or manufacturer offer the greatest investigative clues. These include the emergence of subtle MTF ripples, dramatic modulation transfer changes at key spatial frequencies, or even unusual differences in channel specific MTFs. Like a characteristic drone or repetitive squeak from a worn machine, each of the above clues suggests information about the device's works.

Measurement and Reporting Methodology

The MTF measurements used in this paper were done with the slanted-edge edge gradient MTF technique as outlined in ISO 12233.[1] By allowing for easy calculation of micro-region, post-Nyquist frequency, and highly frequency resolved MTF data that typically requires no curve fitting, it provides an enhanced view of spatial frequency signatures particularly suited to digital image acquisition evaluation.[2]

Target frequency content and nonlinear input-output conditions were accounted for in all measurements. These measurements were derived from images of reflection targets with a 60% contrast modulation at a mean density of 0.75. For cameras, this data came from finished files having very low or no compression applied. Image data from reflection scanners had no compression applied at all. Also, no explicit curve fitting was applied to the graphics. All MTF plots are rendered as raw file connected points.

For cameras, we have chosen to label the MTF frequency axes in cycles/pixel. This is convenient because it aids in the understanding of the influence of image processing steps performed on the captured digital image. On the other hand, because image data from reflection scanners are usually compared with the source material, an absolute frequency scaling referred to that source was adopted.

The body of this presentation is separated into three sections. They are (1) resolution, (2) bi-directional characteristics, and (3) field behavior. They were chosen because of their predominance and influence on image quality as manifested through the MTF. Appropriately, we begin with the most contentious.

Resolution - Real and Otherwise

"Resolution can serve so many purposes
because it does not serve any of them very well. "

Brock[3] expressed the above sentiment more than 30 years ago and is perhaps more true today with digital capture than ever before. By referring to resolution in terms of number of pixels in the case of cameras, or through sampling frequency (i.e., pixels per inch - ppi) with scanners, the era of "pixel wars" has made "resolution" a vague term. To clarify our use, we look to history for guidance.

Using the Rayleigh criterion as a model,[4] the limit of resolution can be defined at that spatial frequency where an 81% peak-to-peak contrast loss is achieved. Figure 1 illustrates this for an idealized rectangular line-spread function at unity sampling for a square wave.

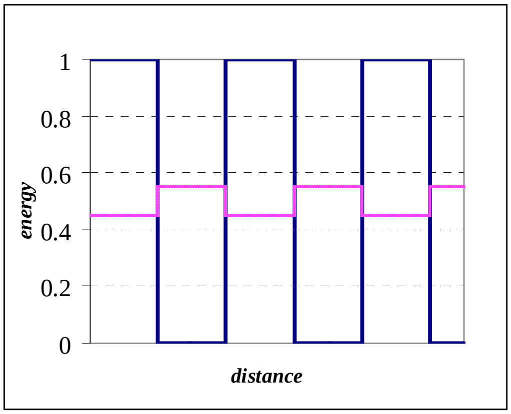

Figure 1. Idealized sampling and modulation loss for rectangular line spread function

The cited contrast loss is calculated in Eq. 1 through the quotient of the peak levels 0.45 and 0.55. Using the 100% modulated signal as a reference in Eq. 2, these values translate to a modulation transfer value of 0.10.

$$0.45 / 0.55 = 0.81 \qquad (1)$$

$$\frac{(0.55 - 0.45) / (0.55 + 0.45)}{1.00} = 0.10 \qquad (2)$$

Based on this analysis, one can then use a modulation transfer value of 0.10* as a nominal easy-to-use MTF-based resolution criterion that has a foundation in both science and history, and is unburdened by visual judgements or marketing hype. Though it cannot compare in analytical power to a complete MTF or acutance measure, it can act as a founded reality check to refute or support existing methods of resolution claims. To avoid confusion with other resolution metrics we will refer to this as the R_{10} criterion. A demonstration on applying it to digital cameras and scanners to interpret their real resolution follows.

In Fig. 2 are the visual MTFs of several 2 megapixel digital cameras. It is clear that they vary widely in shape and magnitude, despite being derived from cameras having the same number of sensor pixels. Which of these results then allow for passing the R_{10} reality test of a true 2 megapixel resolution camera?

The maximum useful frequency† for any sampled device is the Nyquist frequency of 0.5 cycles/pixel. So, if the first 0.10 occurrence in the MTF response is achieved at or beyond the Nyquist frequency, a resolution claim based on the number of total sensor pixels can be supported for that camera. This would be the case for cameras A & B.

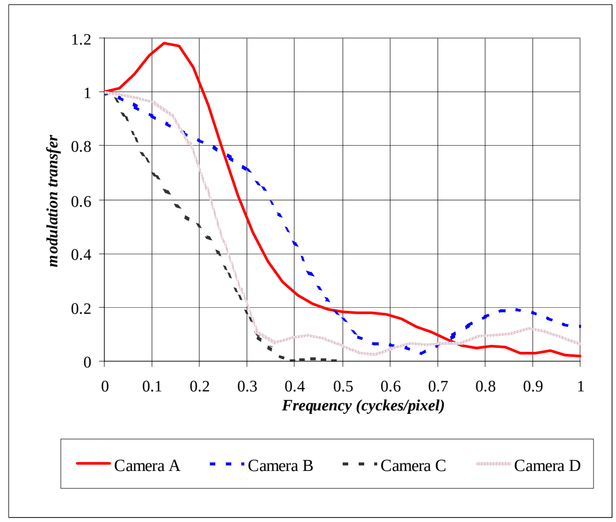

Figure 2. Visual MTFs for several 2 megapixel cameras

On the other hand, if the first 0.10 response occurs before the Nyquist frequency the claim can be refuted. This would be the case for cameras C and D where the first 0.10 response occurs at 0.35 cycles/pixel or 70% of its potential. Since these MTFs are equivalent in two dimensions however, the square of this latter value is multiplied by the total number of pixels to arrive at the effective R_{10} camera resolution. Doing so shows that cameras C and D are effectively 1 megapixel cameras.

This same approach can be taken for linear array scanners. The MTFs in Fig. 3 are a good case study for this class of devices. In Fig. 3 the fast scan MTFs at 300, 600, and 1000 ppi sampling are shown for an inexpensive native 600 ppi scanner. The corresponding Nyquist frequencies for these sampling rates are indicated with arrows. The MTF for the scanner's native sampling frequency of 600 ppi is both a normal and desired response. The response at the Nyquist frequency (≈ 0.20) indicates that it truly yields 600 ppi scans, albeit with a small risk of aliasing.

What is instructive though are how the 300 ppi and 1000 ppi MTFs compare with the native 600 ppi scan. Their relative behavior is classic examples of image processing effects. For instance, the 1000 ppi scan actually has a poorer MTF response than for 600 ppi sampling! Using the R_{10} criteria, the 1000 ppi scan is more in line with a 600 ppi scan, at best. This lowering of the MTF can easily be confirmed, via simulation, to the added influence of the linear interpolator used to build the 1000 ppi scan from the 600 ppi original.

The MTF of the 300 ppi scan is notable because of its near equivalence to that of the 600 ppi scan. Though this is good in terms of "resolution", its potential for aliasing is very high because its Nyquist frequency is half that of the

* Similar values of 0.08 and 0.09 can be calculated for Gaussian and Lorentzian line-spread functions respectively.

† Though the slanted-edge approach allows MTF characterization and interrogation beyond the Nyquist frequency, the fact remains that the image information beyond this frequency is not exploitable.

600 ppi scan. Again, the 300 ppi MTF can easily be derived from the native 600 ppi scan by performing a simple 2X down-sample of the 600 ppi scan without application of a pre-filter. Though sub-optimal in terms of image quality, this technique can be very popular because of speed and simplicity.

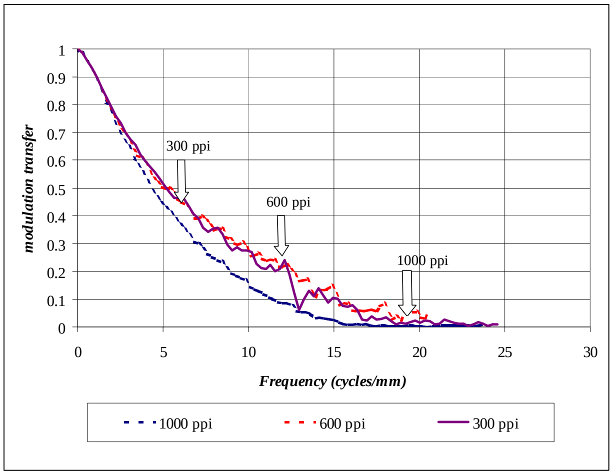

Figure 3. Fast scan MTFs for an inexpensive native 600 dpi flatbed scanner

In contrast, Fig.4 illustrates the MTF characteristics for a high-end native 3150 ppi flatbed scanner at the same sampling rates as for the 600 ppi scanner of Fig. 3. Notice the remarkable differences. Rather than simply down-sampling from the native sampling frequency without pre-filtering, the manufacturer has taken care to achieve consistent Nyquist normalized MTF shapes across different sampling frequencies. Such results are typical for scanners used in the demanding graphic arts community.

Parenthetically, the MTF for the above scanner did test accurately at its maximum native sampling frequency of 3150 ppi. As shown in Fig. 5, a response of 0.10 occurred almost exactly at the Nyquist frequency of 62 cycles/mm and is proof that this type of performance can be achieved if handled properly. Beyond this sampling rate, MTF performance began to decrease though, similar to that shown in Fig. 3.

Bi-Directional Characteristics

Bi-directional MTF differences are common with linear array scanners. These differences are often, but not exclusively, caused by the integration processes, either analog or digital, in the slow scan direction. Because this integration affects each color, one would expect to see some MTF loss in the slow scan direction relative to the fast scan for each color. Such behavior is illustrated in Fig. 6 for an inexpensive single-pass color flatbed reflection scanner at 300 ppi.

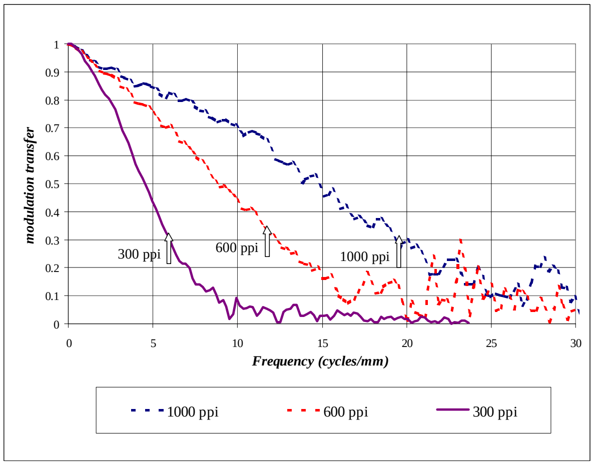

Figure 4. Fast scan MTFs for a high-end native 3150 dpi flatbed scanner

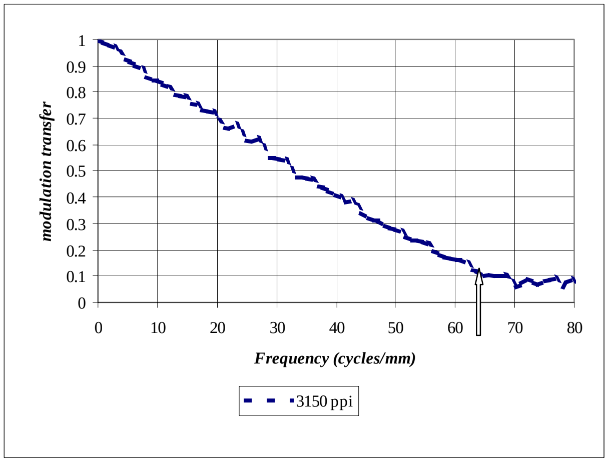

Figure 5. Fast scan MTF at a maximum native sampling frequency of 3150 ppi

Though optical performance could also cause this loss, in practice, optical characteristics do not vary as much with wavelength over the visible spectrum as those shown in Fig. 6.

A common artifact in color flatbed scanners not explicitly revealed, but present, in the device of Fig. 6 is spatial misregistration of the color channels. A procedure to measure this channel misregistration from captured images via slanted edge protocols are described in reference 5. For linear array devices, these errors occur almost exclusively in the slow scan direction and may be tracked to poor alignment procedures or shoddy scanner components and design. In order of decreasing cost, the solutions to this are prevention, correction, or denial. Unsurprisingly, inexpensive scanners choose the latter and ignore the problem while very expensive high-end scanners are designed and manufactured with sufficient care to prevent misregistration all together. In between these two lies the correction solution. By knowing or automatically detecting registration errors, a software solution to color mis-registration can be implemented through interpolation. Of course, any interpolation method brings with it, its own frequency response. We believe this is the cause for the lower MTF behavior of the red and blue channels for the moderately priced single-pass pre-press scanner of Fig. 7.

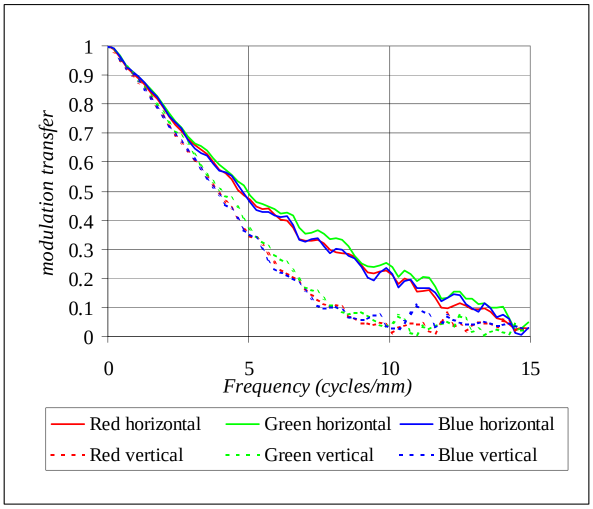

Figure 6. Bi-directional MTF behavior likely due to integration

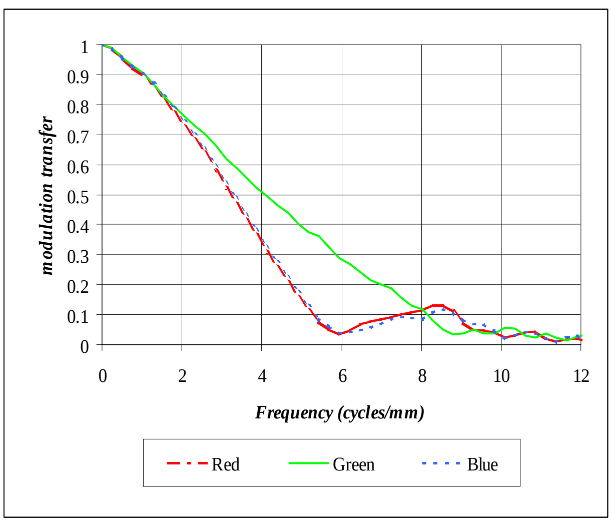

Figure 7. 300 ppi slow scan MTFs for a linear array scanner showing no color misregistration.

This conclusion was drawn in the context of the following supporting observations from Fig. 7.

(1) No color misregistration was detected in the slow scan direction. This is unusual for today's linear array scanners.

(2) The slow scan MTFs for the red and blue channels were significantly lower than the green and are virtually identical. Because visual acuity is most affected by the green response, the prudent engineering choice for lossy registration correction would be with the red and blue channels.

(3) The fast scan RGB MTFs (not shown) do not exhibit this behavior and were virtually identical in response to one another.

(4) The first zero crossing of the red and blue MTFs occur at the Nyquist frequency. This suggests that some form of digital processing has occurred.

While the authors cannot confirm the above conclusion with certainty, the following example of MTF behavior from a color sequential array scanner having explicit registration correction toggling is offered. It was this particular example that prompted our speculation on the scanner MTFs of Fig. 7.

Shown in Fig. 8a are the bi-directional MTFs for the color sequential array scanner mentioned above. The registration correction option is toggled off. While the color channel MTFs for both directions are effectively identical, a ¼ pixel registration error was measured for the horizontal component of the red channel. This figure was independently confirmed via the scanner's software when an identical scan was performed with the registration correction toggled on. The scanner's registration option performed well in this second scan. The registration error was completely removed for the horizontal component of the red channel, albeit at the cost of a lower MTF response. This is illustrated in Fig. 8b. All bi-directional color MTFs are the same as those in Fig. 8a except for the horizontal red component, which is noticeably lower. It is undeniable that the registration option caused this.

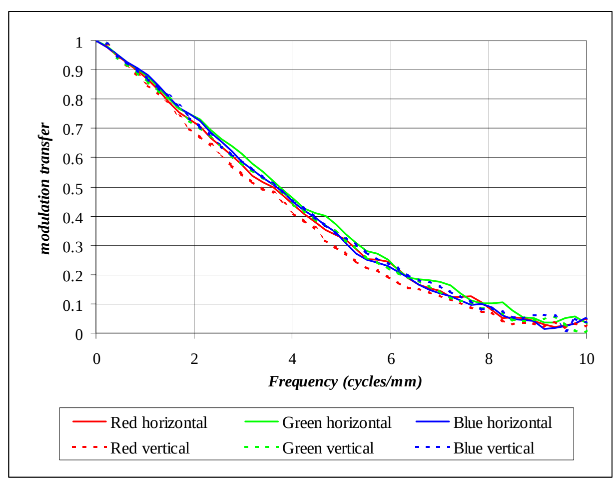

Figure 8a. Bi-directional color MTFs for a color sequential array scanner - registration correction OFF

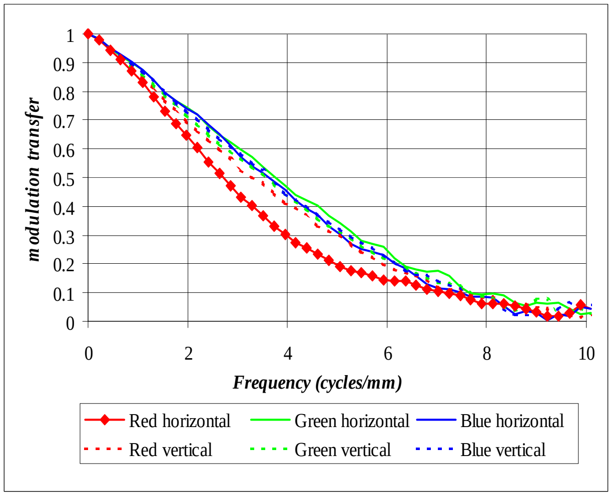

Figure 8b. Bi-directional color MTFs for a color sequential array scanner - registration correction ON

Finally, directional MTF differences are also frequently found in consumer digital cameras and are often the result of one-dimensional sharpening in the fast readout direction of the sensor array. This is sometimes referred to as a "hardware sharpen" because it can be quickly implemented in camera hardware. Since such implementations usually do not allow for line buffering required for two-dimensional sharpening, directional MTF differences occur. An example of this is shown in Fig. 9 for two differently branded 2 megapixel cameras.

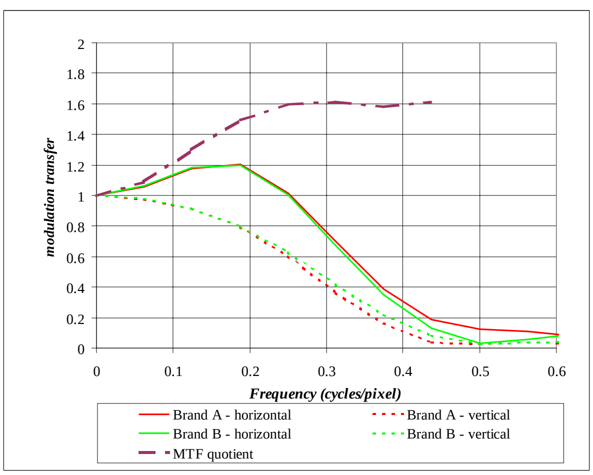

Figure 9. Bi-directional visual MTFs for 2 differently branded 2-megapixel cameras

The results of Fig.9 can be revealing in two ways. One, the near identical directional MTFs for two differently branded randomly chosen cameras is uncanny. This could be an indicator of either a common chip set or common manufacturer. Secondly, the quotient of the horizontal and vertical MTFs can yield the frequency response of the sharpening process, and in turn, give clues to the sharpening kernel size, coefficients, or gain. This quotient is plotted in Fig. 9.

Field Behavior

Most of the examples given so far have shown somewhat unconventional uses of MTF as it explicitly relates to digital capture. In each, on-axis, in-focus, fixed-aperture optical constraints are presumed. For most consumer digital cameras though, the latter two variables are typically not under user control. This leaves the off-axis MTF behavior at ones disposal for analysis.

MTF responses can vary dramatically with off-axis field conditions, especially for consumer cameras that are cost driven. Because of the small target feature, edge gradient analysis is ideally suited for characterization of these conditions by allowing for multiple targets in a single-frame capture. This latter condition is of practical importance by removing the ambiguity of frame-to-frame image processing or exposure variability. The MTF responses at three different field conditions for a 2-megapixel consumer camera are offered as an example in Fig. 10. These MTF plots are for a camera with sharpening included in the imaging path. Though there is a tendency to think of the taking lens as the source of these off-axis effects, the reader is reminded that color filter array lenslets can also dramatically suppress MTF responses. Both lenslet and taking lens contributions are reflected in the plots of Fig. 10.

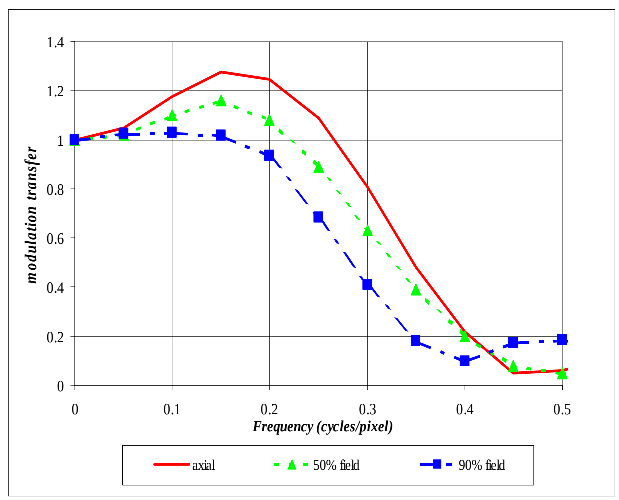

Figure 10. The MTF responses at three different field conditions for a typical 2-megapixel consumer camera

Conclusion

A number of MTF examples from existing digital image capture devices have been presented along with an interpretation of their characteristics. This has included the analysis of resolution, channel misregistration correction, integration, sub-sampling, sharpening, interpolation, common chip sets, and off-axis field behavior. While not offering conclusive evidence of all suspected causes, MTF signatures can provide suggestive clues on image processing or hardware configurations. An R_{10} resolution proposal for using MTF to better quantify the effective resolution of digital capture devices derived from a Rayleigh criteria has also been offered and demonstrated.

Acknowledgements

The authors wish to thank several sources of digital capture device data used in this article. They include Bruce Pillman and Matthew Johnson of Eastman Kodak Company, Bill Comstock of Harvard University's Widener Library, Phil Michel of the Library of Congress, and Steve Puglia of the National Archives.

References

1. ISO 12233:2000 Photography-Electronic still picture cameras -Resolution measurements.
2. P. D. Burns, Slanted-Edge MTF for Digital Camera and Scanner Analysis, *Proc. PICS*, IS&T, pg. 135-138, (2000).
3. G. Brock, Selected Readings in Image Evaluation, *J. Imaging Sci. Technol*., 40, 120 (1966).
4. M. Born and E. Wolf, *Principles of Optics*, 6th ed., Pergamon Press, Oxford, 1980, pg. 333-335.
5. P. D. Burns and D. Williams, Using Slanted Edge Analysis for Color registration measurement, *Proc. PICS*, IS&T, pg. 51-53, (1999).

Biographies

Don Williams received both B.Sc. and M.Sc. degrees in Imaging Science from RIT, and works in Imaging 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.

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, where he is a member of the adjunct faculty. After working for Xerox, he joined Eastman Kodak's Imaging Research and Development organization. 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