Capture Color Analysis Gamuts

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Abstract

A common method for obtaining scene-referred colorimetry estimates is to apply matrices to radiometrically linearized capture device signals, obtained either from digital cameras or scans of photographic film. These matrices can be determined using different test colors and different error minimization criteria. Since the spectral sensitivities of these capture media typically do not meet the Luther condition, the application of the matrices warps the spectral locus, as analyzed by the capture devices and media. The warped loci of spectral colors represent the boundary of the gamut of possible scene colors that can be estimated by the device. These gamuts tend to have roughly similar shapes for many popular capture devices and media, and often extend outside the true spectral locus in some areas and do not reach it in others. This observation leads to the conclusion that scene-referred color encoding primaries should be selected based on their coverage of the possible scene colors as analyzed, rather than on their coverage of the gamut of colors seen by the eye. The fact that the analysis gamuts extend significantly beyond the spectral locus in some cases also demonstrates the need for color processing systems to deal appropriately with such colors.

Introduction

Virtually all photographic films and digital cameras are sensitive to the entire visible spectrum, and therefore record all the colors the eye can see. In this sense their 'color gamuts' are the same as that of the eye. However, their spectral sensitivities are also almost always non-colorimetric, in that they do not meet the Luther condition. This means that there is no generally accurate transform from the captured or scanned signals to scene colorimetry estimates. Nevertheless, films and digital cameras are successfully used to take pictures of scenes and create digital image files. The color processing involves white balancing, scene analysis, color rendering, and color encoding. The full details of such processing are described elsewhere [1]; this paper will focus on scene analysis, or the estimation of scene colors from film scan or digital camera data, and the resulting 'capture color analysis gamuts'.

In scene analysis, a common approach is to first linearize the signals with respect to focal plane exposure for each capture channel, and then apply a matrix to estimate focal plane colorimetry. Flare may be estimated in order to remove it and get back to scene colorimetry estimates, but this step is not always performed. Sometimes the color rendering is designed to start with focal plane colorimetry estimates. In any case, the distinction between focal plane colorimetry and scene colorimetry is not relevant to this study. In this paper we will assume that the capture flare has been removed or is essentially zero and not make the distinction between scene colorimetry estimates and focal plane colorimetry estimates. This is consistent with the use of the monochromator to measure digital camera spectral sensitivities, as specified in ISO/DIS 17321-1 [2], because the field of view of the camera is illuminated with monochromatic light so the flare is also evenly distributed and therefore has no effect on the measurements.

While the linearization step may be non-trivial, it is deterministic in that there is a single correct linearization, which can be determined through careful measurement and inversion of the capture device/medium opto-electronic conversion function. In the film case this is more complicated, as it is first necessary to calibrate and characterize the scanner to produce the desired film densities. Then the measured film densities must be matrixed to the analytical densities that correspond most closely with the exposure collected by each film layer. The film linearization is finally accomplished by inverting the analytical density characteristic curves.

It is also necessary to obtain linearized capture device/medium channel integrated exposures in order to obtain accurate spectral sensitivity measurements (which are used to calculate the various color analysis matrices). The correctness of the linearization and resulting spectral sensitivity measurements can be verified by predicting the result of analyzing various colors using the camera, the linearization determined, and the matrix. The chances of inaccurate measurements producing accurate predictions are very small. Consequently, in this report the assumption will be made that the linearization and spectral sensitivity measurements are correct, recognizing that there will always be some small error and degree of uncertainty.

Unfortunately, it is the matrix from capture device exposure to colorimetry that is indeterminate. Since the capture devices and media do not see the world with the same spectral sensitivities as the eye, there is no 1:1 mapping from capture device response to scene colorimetry. It is therefore necessary to decide on some matrix to use based on selected test color spectral characteristics and some error minimization criterion. Weights can also be assigned to the test colors, or to the various dimensions of the color space in which errors are minimized. Generally it is desirable to choose test colors that to the extent possible represent the spectral characteristics of the scenes to be captured, and to choose error minimization color spaces that minimize perceptual errors. There are a number of considerations and caveats to these choices which have been discussed elsewhere [3]. For this work several methods will be used to determine different matrices in each case. The point is to show a variety of results and look for commonality, rather than to try to evaluate the appropriateness of some matrix for some application.

This paper reports on the observed characteristics of the capture color analysis gamuts resulting from a number of capture devices/media, and scene analysis color matrices. These gamuts are also compared to several common primary sets used for additive RGB color encodings, to see which might be best suited for scene-referred image data.

Approach

The following capture devices and media were used for the evaluation:

1. Kodak 5218 tungsten balanced motion picture color negative film
2. Kodak 5246 daylight balanced motion picture color negative film
3. BetterLight digital scanning back (trilinear RGB separation filter sensor)
4. Megavision digital camera back (professional frame transfer CCD CFA sensor)
5. Nikon D70 digital camera (professional CCD CFA sensor)
6. Canon 20D digital camera (professional CMOS CFA sensor)

The Kodak 5218 color negative film was assumed to be exposed using the ISO 7589 Studio Tungsten illuminant [4], which closely approximates the spectral power distribution of the tungsten-halogen lighting for which the film is balanced. The Kodak 5246 film and digital cameras were assumed to be exposed to D55 illumination, which corresponds to typical daylight illumination. However, some of the methods used to determine matrices are independent of the adopted white used for capture.

The spectral sensitivities for the films were obtained from Kodak [5] and multiplied by the spectral transmittances of the ISO 7589 standard lens. The spectral sensitivities for the digital cameras were measured using a monochromator as specified in ISO/DIS 17321-1, with the camera lens in place.

The following methods were used to calculate color analysis matrices:

- The LS error minimization is a fitting of the capture spectral sensitivity curves to the CIE 2 degree observer color matching functions. Errors at each wavelength in XYZ space are minimized to derive the matrix that produces the smallest sum of squared errors. The matrix is independent of the scene adopted white.
- The WPPLS error minimization is similar to the LS error minimization, but with the matrix row sums constrained to preserve equi-energy white.
- The RGB error minimization is a white point preserving least squares minimization of the spectral colors (monochromatic colors) performed in a color space based on monochromatic primaries at 450, 540 and 620 nm, an equi-energy white point, the sRGB color component transfer function, and with the spectral errors weighted by the adopted white spectral power distribution. With this method, the scene adopted white is mapped to equi-energy white in the error minimization color space.
- The DNG matrices are the camera RGB to D65 XYZ matrices found in Adobe DNG [6] files for the Nikon and Canon cameras. It is assumed that these matrices are determined either by the camera manufacturer or by Adobe using unspecified methods.

It should also be noted that while the methods used to calculate the matrices are reasonable, they are probably not optimal. Specifically, if the spectral characteristics of the scenes to be captured are known (or can be reasonably assumed), they can be used in the matrix determination to achieve more accurate scene colorimetry estimates. There are also other options for error minimization color spaces, such as those based on CIECAM02. This paper does not address the question of how to determine the best scene analysis matrix to use. It assumes some simple choices and then looks at the characteristics of the resulting capture color analysis gamuts.

Results

The spectral sensitivities, and x,y chromaticity plots of the capture color analysis gamuts for each of the capture devices/media are shown in figures 1-6. In these figures the blue triangle indicates the sRGB primaries [7], the red triangle indicates the Adobe RGB (1998) primaries [8], and the yellow triangle indicates the RIMM RGB primaries [9]. However, It should be noted that each of these encodings has a specified white point chromaticity (D65 for sRGB and Adobe RGB, and D50 for RIMM RGB) which will not necessarily match the chromaticity of the scene adopted white after applying the above matrices. To produce values appropriate for encoding using these standard encodings, it would be necessary to combine the camera RGB to XYZ matrix with a chromatic adaptation matrix from the scene adopted white, or in the case of the RGB error minimization method from the equi-energy adopted white, to the encoding white point chromaticity, in addition to applying the encoding color component transfer function. Also, as sRGB and Adobe RGB are output-referred, color rendering processing will typically be applied to scene-referred values to produce the desired output-referred colorimetry before encoding (as discussed in reference 1). Several observations can be made from the figures:

- Current capture devices and media deviate significantly from colorimetric capture, and this is reflected in the large differences between the spectral locus as presented to the camera, and the spectral locus as analyzed.
- The more traditional film and color separation filter analysis methods tend to produce more 'conservative' color analysis gamuts which do not extend much outside the spectral locus.
- The film spectral sensitivities, combined with a color analysis matrix, 'spectrally gamut map' the spectral locus to a triangle that appears to be well-suited to subsequent color rendering to various real reproduction media.
- Current digital camera color analysis gamuts can extend significantly outside the spectral locus and even outside the XYZ primary triangle, but do not extend into the pure cyan region of colors that is not covered by the RIMM RGB primary triangle.

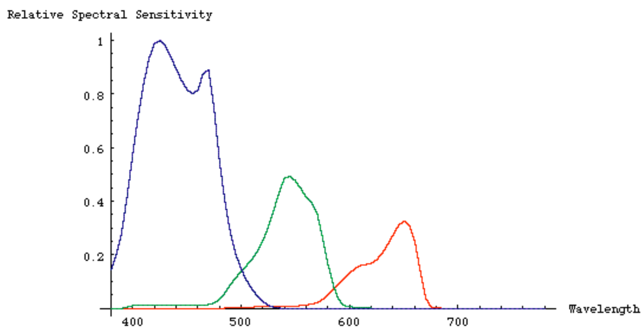

Figure 1a: Spectral sensitivities for 5218 motion picture negative film

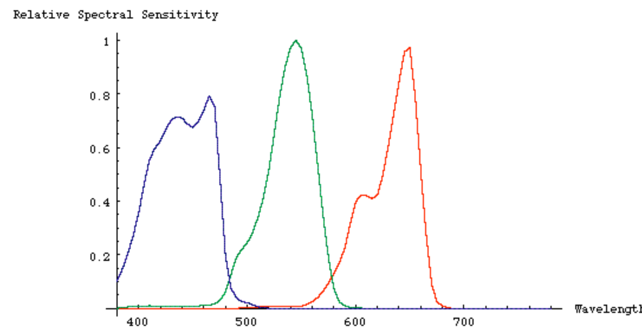

Figure 2a: Spectral sensitivities for 5246 motion picture negative film

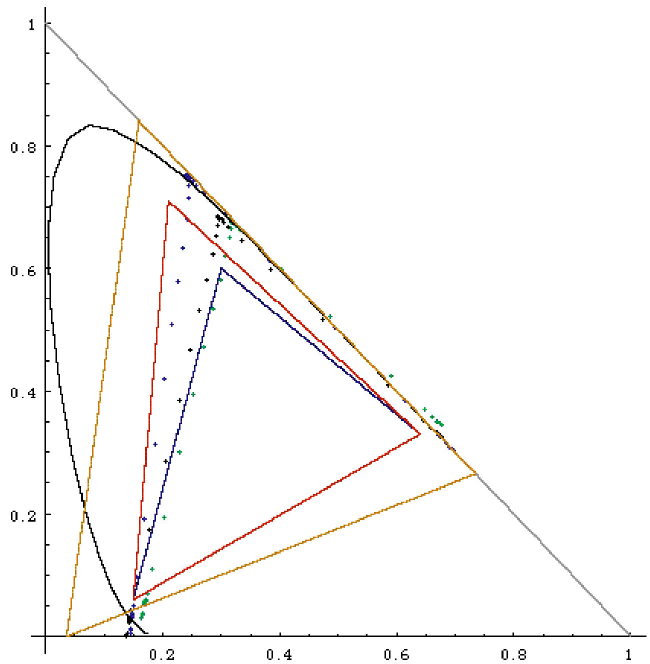

Figure 1b: Capture color analysis gamuts for 5218 motion picture negative film (LS matrix-black dots, WPPLS matrix-green dots, RGB error minimization matrix-blue dots)

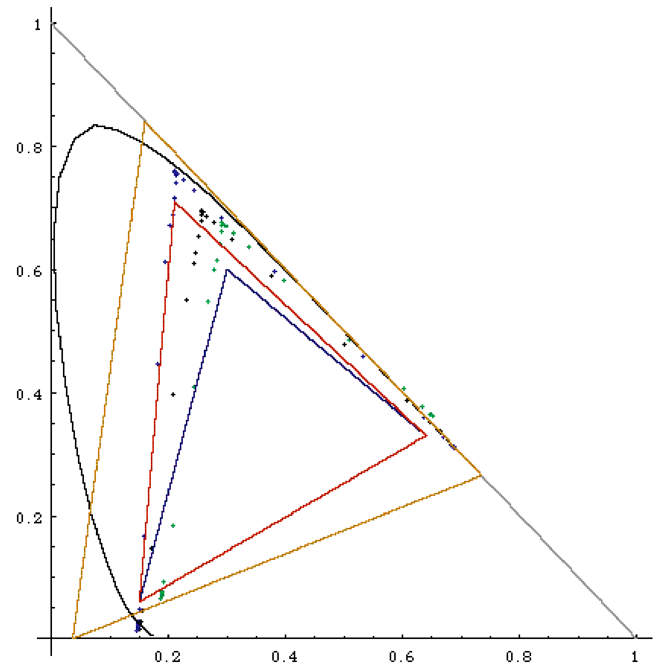

Figure 2b: Capture color analysis gamuts for 5246 motion picture negative film (LS matrix-black dots, WPPLS matrix-green dots, RGB error minimization matrix-blue dots)

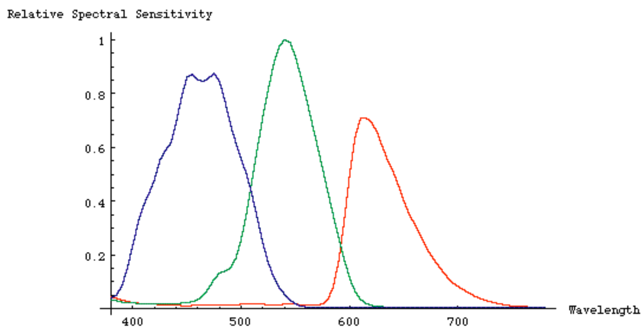

Figure 3a: Spectral sensitivities for a BetterLight digital scanning back

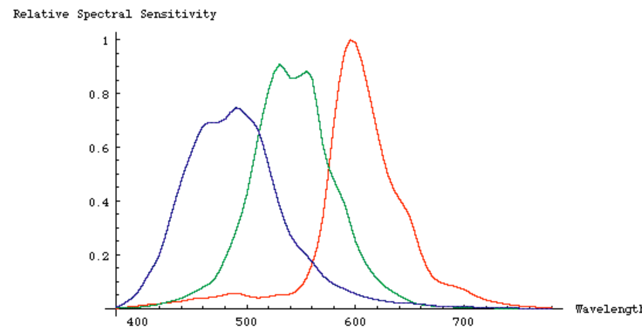

Figure 4a: Spectral sensitivities for a Megavision digital camera back

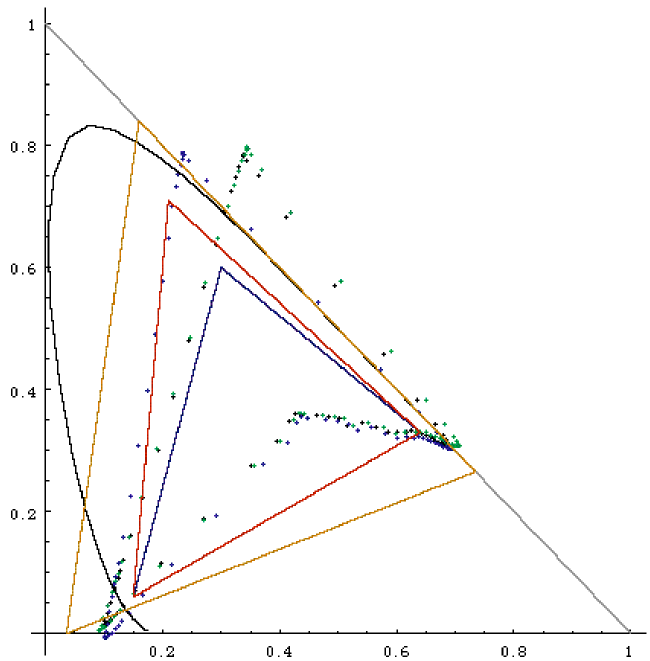

Figure 3b: Capture color analysis gamuts for a BetterLight digital scanning back (LS matrix-black dots, WPPLS matrix-green dots, RGB error minimization matrix-blue dots)

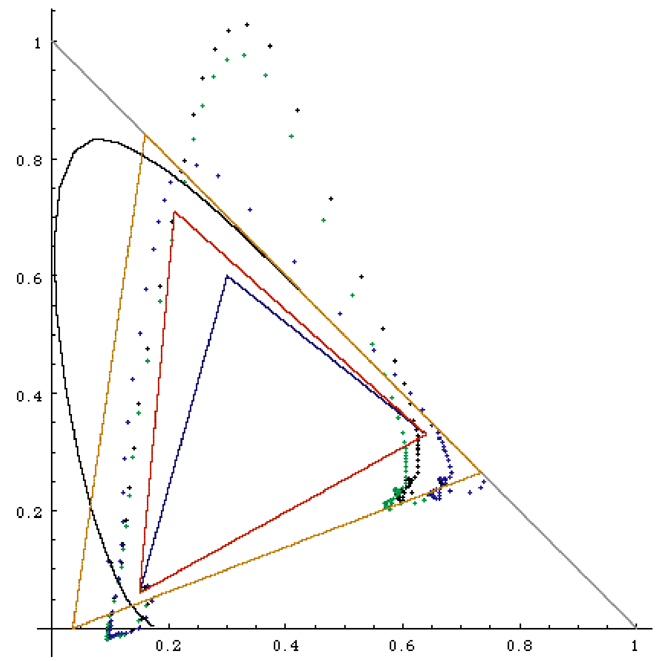

Figure 4b: Capture color analysis gamuts for a Megavision digital camera back (LS matrix-black dots, WPPLS matrix-green dots, RGB error minimization matrix-blue dots)

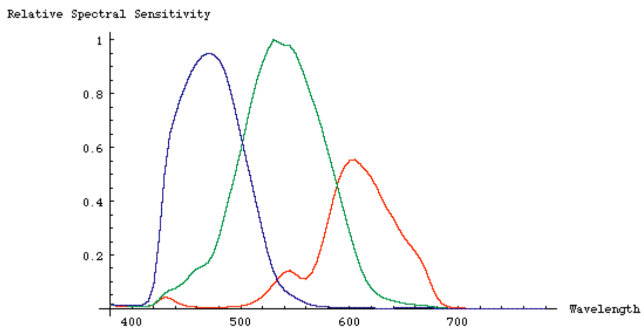

Figure 5a: Spectral sensitivities for a Nikon D70 digital camera

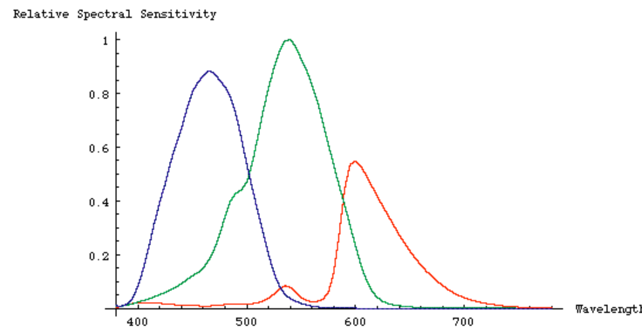

Figure 6a: Spectral sensitivities for a Canon 20D digital camera

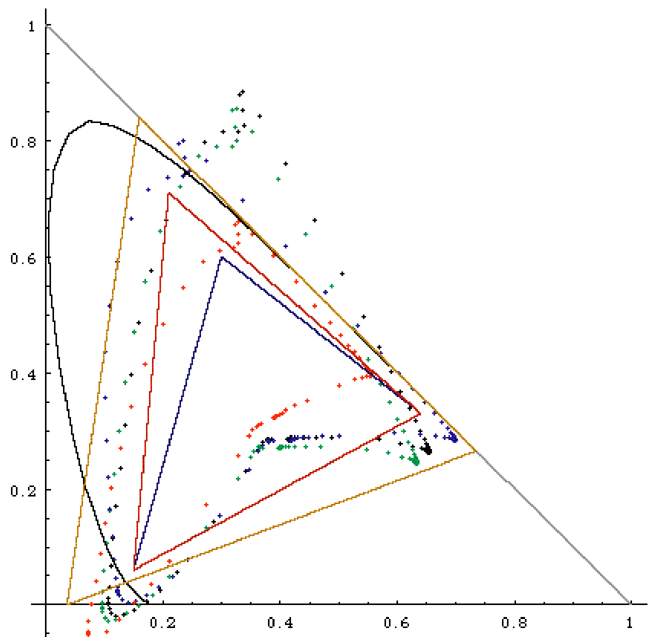

Figure 5b: Capture color analysis gamuts for a Nikon D70 digital camera (LS matrix-black dots, WPPLS matrix-green dots, RGB error minimization matrix-blue dots, DNG D65 matrix-red dots)

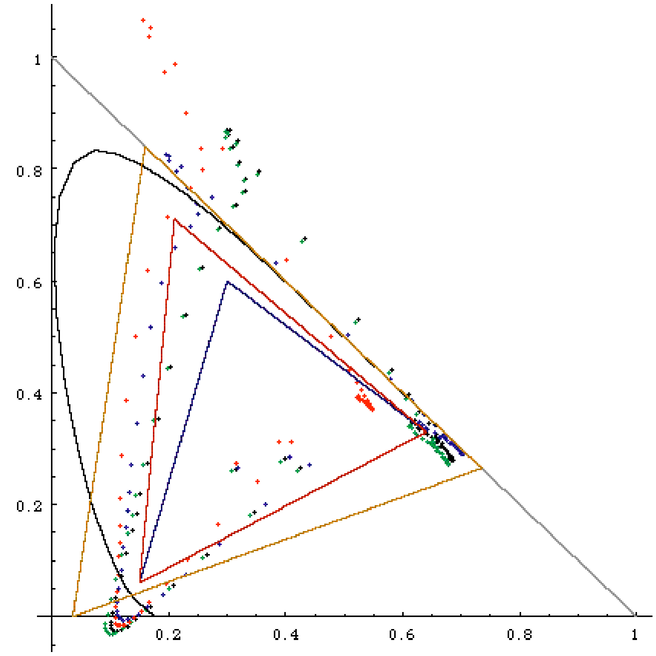

Figure 6b: Capture color analysis gamuts for a Canon 20D digital camera (LS matrix-black dots, WPPLS matrix-green dots, RGB error minimization matrix-blue dots, DNG D65 matrix-red dots)

Conclusions

It is apparent that current popular capture devices and media deviate significantly from colorimetric analysis, but at the same time are commercially successful. This is probably because the acceptability of the results is at least as dependent on the accuracy of the white balance, and the pleasingness of the color rendering. Film, and the color separation filters used on the trilinear scanning camera, tend to be more restrained in analysis, with film mapping all possible scene colors into gamuts that are mostly within the spectral locus and for the most part triangular. This can make things easier for color rendering algorithms. Digital camera analysis gamuts are more variable, but still tend to be roughly triangular in shape, resulting in extremely chromatic cyan colors not being included. It was interesting to note that no capture device/medium or matrix tested produced analyzed chromaticities outside the RIMM RGB primary gamut but within the spectral locus. On the other hand, some analyzed colors were outside the spectral locus and XYZ primary triangle. This indicates that the RIMM RGB primaries are as suitable as XYZ for the encoding of scene-referred colorimetry, as analyzed using current technologies. This is useful knowledge in that there are other advantages to using the RIMM RGB primaries, such as for tone curve color rendering. It is also clear that it is necessary for digital color systems to be able to deal appropriately with colors that are analyzed to be significantly outside the spectral locus, or even the XYZ primary triangle.

References

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[4] ISO 7589:2002, Photography -- Illuminants for sensitometry -- Specifications for daylight, incandescent tungsten and printer

[5] http://www.kodak.com/US/en/motion/products/negative/index.jhtml

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[7] IEC 61966-2-1:1999, Multimedia systems and equipment - Colour measurement and management - Default RGB colour space - sRGB

[8] http://www.adobe.com/digitalimag/adobergb.html

[9] ISO/TS 22028-3, Photography and graphic technology -- Extended colour encodings for digital image storage, manipulation and interchange -- Part 3: Reference input medium metric RGB colour image encoding (RIMM RGB)

Author Biography

Jack Holm is the principal color scientist in the Office of Strategy & Technology for Hewlett-Packard's Imaging & Printing Group. He is vice-chair of the International Color Consortium, chair of the US TAG for ISO TC42 (Photography), and technical secretary for IEC TC 100 TA2 (Multimedia systems & equipment - Color measurement & management). He has been active in color imaging research for over a decade, and was a primary contributor in the development of color processing for HP digital cameras. Previously he served as a digital photography consultant, and on the faculty at the Rochester Institute of Technology.

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