End-to-End Analysis of Color Errors in a Soft-Proofing System

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Keywords: Color, Colorimetry, Error, Model, Proofing, Soft

Abstract: Cost-effective hardware and software accessories have been developed which transform a video display into a soft-proofing system. The accessories make system calibration highly automatic and provide the accuracy needed to support remote, networked proofing applications. The latter property is manifest in results of an instrumental, colorimetric analysis. Sources of color error are identified and analyzed quantitatively. They are compared to color errors associated with primarily software-driven calibration methods based on subjective judgments. The latter do not provide the accuracy needed for network applications.

Introduction

A system that is capable of supporting accurate, remote soft-proofing of color has been developed. The engineering prototype is a component of a system for accurate network color. Aspects of the system were the subject of a pair of papers at last year's Annual Technical Conference (Holub, 1999a and 1999b.) A more detailed treatment of the system has been published as US Patent No. 6,043,909 and international application no. WO 97/34409.

Successful, remote proofing in a networked environment requires fairly close color tolerances. If, for example, people at two sites wish to view an image on two video displays at their respective sites, it is important that the TriStimulus Values of colors displayed on the two monitors agree if the viewers are to be confident that they are seeing the same thing, physically. The individuals may have different perceptions, either as a matter of "taste" or of individual, biological differences, but well-calibrated colorimeters at either site should record substantially the same thing. Otherwise, debate between the individuals about whether "the red has too much yellow in it" (for example) is pointless. Measurements according to a device independent standard are preferred if not essential; colorimetry facilitates the use of quasi-uniform error metrics.

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The net color errors reported in this document are "end-to-end" in a soft-proofing system. The components of the net error are also examined, particularly an estimate of the error of conversion from CMYK to CIELAB for a proofing system and the errors incurred in using a monitor profile prepared with the assistance of Adobe's Gamma tool to transform pixels for display by ColorSync in Photoshop. The error analysis identified anomalies in the handling of certain colors by ColorSync and/or Photoshop or by the profile generated by Adobe Gamma. It also revealed limitations of visual methods of display calibration.

In "The Reproduction of Colour," Robert Hunt refers (p. 181 of the fourth edition) to a reproduction criterion, in which chromaticities and normalized luminance values are matched, as "colorimetric" reproduction. There is ample literature indicating that matching TriStimulus Values on two media is not, generally, a guarantee of identical appearance. Hunt, Nayatani, Land, Bartleson and Breneman and others made many contributions over the years to our understanding of surround effects, absolute luminance levels and related factors on tone and color reproduction. Therefore, matching TSVs between monitor and proof in a soft-proofing exercise need not result in the User's assent that the images on the different media are indistinguishable. However, the premise of this study is that the ability to match TSVs is a pre-requisite; lacking that, higher order corrections will be ineffective.

Accurate soft-proofing and matching of TSVs between monitor and proof are not new. What is novel is the means of establishing and maintaining monitor calibration. I have shown that the chromaticities of the monitor are stable over time. Once they have been measured carefully, a simple sensor is employed to establish and maintain the correct neutral balance and tone reproduction of the display; the latter are things that vary from day to day.

The sensor is both sensitive and linear; therefore, it has the capability to record the effects of "ambient" light reflected from the display screen, even at low levels. The effects of environmental illumination on the gamuts of different displays can be encoded in data structures used to coordinate color reproduction in an electronic color proofing network, as detailed in references cited previously. Over the nearly three-year life of the prototype, the calibration parameters of the simple sensor and its ability to bring the display to correct white balance and tone reproduction have proven remarkably stable, this despite the relatively crude manual procedures used to calibrate it in the first place.

The reference white for this analysis is the color of Iris proofing stock under nominal D5000 illumination in a Graphic Technologies Inc. (GTI) viewing hood. The sensor is programmed to make the monitor match the reference white. The sensor, under control of the host, measures gamma in order to make the tone reproduction of the physical monitor match what is assumed by the host computer software.

The first section of this paper summarizes measurements taken from the display to verify the accuracy of gamma correction and of overall errors of a monitor profile made with the assistance of Adobe Gamma. Color errors engendered by the profile are one component of system error.

The second section of the paper summarizes data on color errors of the calibration of the Iris ink jet proofing device and of the net error of soft proofing, estimated as the color differences between the hard copy and its soft proof representation.

The third section of the paper examines the sources of the errors observed in Part II. The figures based on color images employed in the study are available in a .pdf file available from the author. They may also appear on a CDROM version of these proceedings.

Figure One illustrates the processing of image data and serves as an outline of sources of color errors. At the top, the goal of the exercise is called out, viz., the matching of chromaticities and normalized Luminance values of images between two reproduction media. CMYK image data were proofed on a large-format Iris. The resulting images constituted physical proofs for both visual and instrumental comparison. On the large sheet with the selection of images was written a CMYK calibration image. The latter had known CMYK values at each patch. The print was measured with a Gretag SPM 100 in such a way that the spectrum of the proofing stock under the GTI source could be substituted for that of the illuminant employed by the Gretag instrument in making the measurements.

A mathematical model of the relationship between the ink values and color measurements was prepared so that color, in CIELAB coordinates, could be calculated for each possible ink value. An ICC standard formatted profile was based upon the model. Possible sources of error in the CIELAB pixel values returned by the profile include rendering variations of the Iris proofing device, the measurements of color, inaccuracies of the model and quantization and interpolation errors due to the profile and cmm.

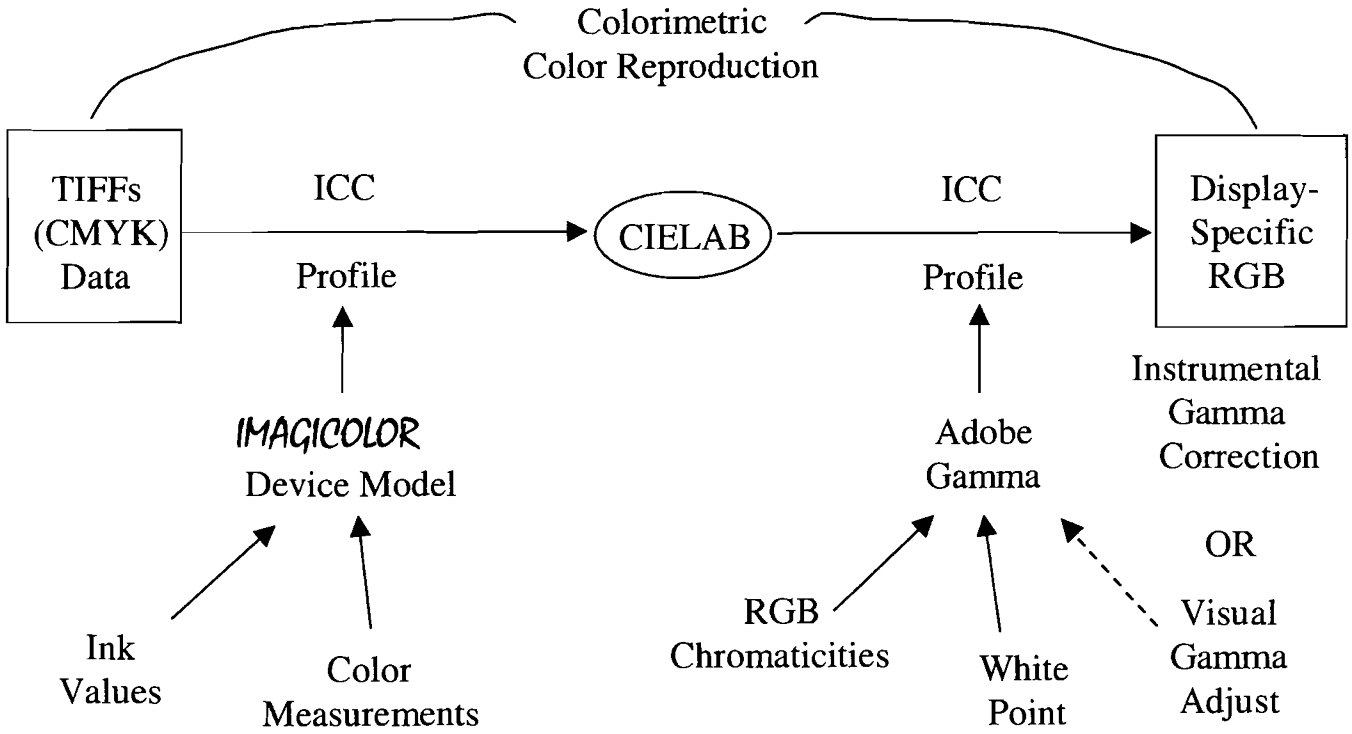

Figure One shows the dataflow and color processing of the experimental prototype schematically.

The chromaticities of the Red, Green and Blue channels of a CRT-type display were measured with a PR700 spectroradiometer, made by Photo Research. It has telescopic optics and a view-finder and measures light with 2 nm spectral resolution, "seeing" objects more or less the way a human would. RGB chromaticities and the similarly measured chromaticity coordinates of the Iris proofing stock were used in two ways:

First, they were used to determine a 3X3 matrix that embodied the relationship between XYZ values (derived from CIELAB pixel coordinates in the usual way) and device-specific RGB values (not yet gamma-compensated) required to realize the color on the display. When combined with a separate gamma correction function for the display, a simple, mathematical model of the color reproduction performance of the display is obtained. It was used as a check on the accuracy of an ICC profile that was employed by ColorSync and Photoshop in rendering on the display. It was also used in computing the target values sought by the simple sensor and host computer in holding the display at the correct white point. In other words, it was part of the method of calibrating the sensor which automates the control of white balance.

Second, they were fed to Adobe's Gamma ("AG") utility, which used them to make an ICC profile for the display. "AG" also provides a subjective tool that enables the User and host computer to correct for discrepancies between the gamma assumed by the software and the tonal gradation function of the physical display. The resulting "gamma compensation" function is incorporated by default into the ICC profile. The calibrated sensor measures the physical tone reproduction characteristic of the display directly and data so derived were also used to calculate a compensation curve (applied through graphics LUTs) whose performance was compared (see Tables 1 through 4) to the subjectively derived function. This is suggested by the "OR" at the right of Fig. 1.

Potential sources of error on the right side of Fig. 1 include measurements, model inaccuracy, errors of subjective judgment, incorrectly computed profile, quantization and interpolation errors, and errors of the sensor that may include imperfect calibration and incomplete compensation for device drift. Kodak's cmm was used in ColorSync, with a colorimetric rendering intent.

Part I: Color Errors of Neutral Balance and Tone Reproduction

Two CIELAB test images were prepared in Photoshop. One consists of a neutral scale ranging from $L^* = 100$ to $L^* = 30$ in steps of 10 L^* units. The other consists of nine patches of various, arbitrarily-selected colors. Facsimile representations of the two images appear in color Plates 1 and 2, available on the CDROM version of these Proceedings. The images were displayed, in Photoshop, using the AG-generated monitor profile, and measured by the PR

700. The patches were "zoomed up" so that the patch color was measured full screen. This doesn't mean that the PR 700 was "looking at" the whole screen, only that adjacency effects on the monitor were minimized by displaying a given color full-screen.

Data are assembled in four tables, below. Two tables are devoted to each of the synthetic, CIELAB images. The first pair of tables (Tables 1 and 3) reflect data from the AG profile based only on the subjective tonal correction curve. The second of each pair of tables (Tables 2 and 4) is based on measurements following execution of a simple application. The app writes a correction function to LUTs in the graphics controller which corrects for differences between the gamma functions for the three channels assumed by the software and those existing in hardware, based upon tonal gradation readings by the sensor.

AG also assumes that the physical display's white balance is consistent with what the User gives it as white point - in ***all four*** tables, the simple sensor was used to insure that the assumption was correct. The point of the comparisons is to show how quickly color accuracy can deteriorate with wrong assumptions. AG was given excellent data on chromaticities and white point and the display was made to conform with the assumed white point. The errors are substantially larger when generation of the tone reproduction function was handled by AG, rather than by sensor-mediated corrections.

Column headings in Tables 1 and 2 have the following significance. L* nominal is the value assigned to the patch when the image was defined in Photoshop. The patches corresponding to the first column entries are labeled in Plate 1. The second column gives the L* values measured with the PR700. Maintenance of gray balance along the tone scale is an important aspect of gamma correction. Therefore, the u',v' chromaticities (of the CIE 1976 Uniform Chromaticity Scale) of each patch are entered in the third and fourth columns; these are presented instead of x,y because of their greater uniformity and the fact that they contribute to the calculation of ΔE^*uv, shown in the rightmost column. Each of the components of ΔE^* are also shown.

Comparison of Tables 1 and 2 reveals that tonal and white balance errors are greater when the visual gamma correction of Adobe Gamma is used. Overall errors in the case of sensor-mediated correction are very acceptable except for colors at or below L* = 30. This is because the lack of neutral balance at the dark end of the **physical** monitor overwhelms the ability to correct by way of LUTs. Generally, there are two physical controls available on each channel, one for gain and one for bias or offset. The settings of offset controls in each of the

TABLE ONE

NEUTRAL SCALE ERRORS WITHOUT PROTOTYPE SENSOR-MEDIATED TONAL CORRECTION

L nominal*	*L* measured*	*u'*	*v'*	*delta u**	*delta v**	*delta L**	*delta E*uv*
100.0	100.00	0.208	0.483	0.000	0.000	0.000	0.000
90.0	90.26	0.208	0.481	0.469	-2.112	0.260	2.179
80.0	79.96	0.207	0.480	-0.208	-3.015	-0.040	3.022
70.0	69.42	0.207	0.477	-0.361	-4.693	-0.576	4.742
60.0	58.91	0.206	0.477	-1.225	-4.518	-1.092	4.807
50.0	48.15	0.205	0.475	-1.753	-5.008	-1.849	5.619
40.0	36.74	0.204	0.472	-1.911	-5.015	-3.259	6.279
30.0	25.40	0.203	0.472	-1.552	-3.632	-4.599	6.062

TABLE TWO

NEUTRAL SCALE ERRORS *WITH* PROTOTYPE SENSOR-MEDIATED TONAL CORRECTION

L nominal*	*L* measured*	*u'*	*v'*	*delta u**	*delta v**	*delta L**	*delta E*uv*
100.0	100.00	0.208	0.482	0.000	0.000	0.000	0.000
90.0	90.69	0.207	0.482	-0.354	0.589	0.687	0.972
80.0	80.65	0.209	0.482	0.944	-0.210	0.653	1.167
70.0	70.71	0.209	0.482	0.827	-0.092	0.706	1.091
60.0	60.56	0.209	0.483	0.787	0.709	0.563	1.200
50.0	50.98	0.210	0.483	1.458	0.663	0.981	1.878
40.0	40.67	0.209	0.484	0.793	0.899	0.665	1.371
30.0	31.41	0.212	0.485	1.592	1.388	1.407	2.538

TABLE THREE

DISPLAY COLOR ERRORS WITHOUT PROTOTYPE SENSOR-MEDIATED TONAL CORRECTION

L* Defined	a* Defined	b* Defined	delta L* meas - def	delta a* meas - def	delta b* meas - def	delta E*ab
100.0	0.0	0.0	0.000	0.000	0.000	0.000
48.0	12.0	-19.0	-2.234	0.411	-4.495	5.036
80.0	10.0	41.0	-0.180	-0.533	-1.431	1.538
15.0	5.0	14.0	-5.396	-0.173	-0.661	5.439
51.0	-17.0	10.0	-2.573	-1.484	-2.712	4.021
33.0	-34.0	17.0	-4.938	1.249	-1.052	5.201
32.0	53.0	-14.0	-0.804	-3.213	-1.977	3.857
55.0	2.0	46.0	-2.069	-0.906	0.288	2.277
40.0	5.0	-22.0	-3.495	1.465	-4.769	6.091
65.0	-12.0	22.0	-1.123	-1.246	-2.154	2.730

TABLE FOUR

DISPLAY COLOR ERRORS *WITH* PROTOTYPE SENSOR-MEDIATED TONAL CORRECTION

L* Defined	a* Defined	b* Defined	delta L* meas - def	delta a* meas - def	delta b* meas - def	delta E*ab
100.0	0.0	0.0	0.000	0.000	0.000	0.000
48.0	12.0	-19.0	0.877	-1.129	1.241	1.893
80.0	10.0	41.0	0.245	-1.141	-0.113	1.173
16.0	5.0	14.0	1.590	-1.513	-1.000	2.412
51.0	-17.0	10.0	0.474	0.692	0.160	0.854
33.0	-34.0	17.0	-0.698	2.853	-0.367	2.960
32.0	53.0	-14.0	1.418	-1.195	0.253	1.872
55.0	2.0	46.0	0.464	-0.470	0.564	0.868
40.0	5.0	-22.0	0.596	0.125	1.167	1.316
65.0	-12.0	22.0	0.504	-0.451	0.930	1.150

three channels determines the gray balance in the shadows and influences gamma as well. In the prototype monitor, gain controls are available. These are used in cooperation with the sensor, to adjust the highlight white to the desired chromaticities. However, controls were not available to me for the offsets of the channels. Therefore, the prototype was limited to LUT-mediated corrections in the shadows and shadow errors are larger than would otherwise be the case.

The organization of Tables 3 and 4 is slightly different. Patches labelled 1 through 9 in Plate 2 correspond to the nine rows following the white reading in the tables. The first three columns give the CIELAB coordinates assigned to the patches when the image was defined in Photoshop. The next three list the differences between measured and defined values and the last column holds the overall delta E*ab. The choice of CIELUV vs. CIELAB for color-error reporting in Tables 1 through 4 is purely a matter of convenience in data analysis. Units of the two, approximately-uniform color spaces can be viewed as interchangeable for our purposes.

The average ΔE*ab over all nine, non-white patches in Table 3 is 4.02, compared to 1.61 in Table 4. Note that the largest errors in Table 4 tend to occur at low lightness values (at or below L* = 30) and to have a large L* error component. Although the average error in Table 4 is satisfactory, it will be possible to improve upon it when control of the offsets in the physical monitor is added to the prototype. In summary, Part I has taken a first look at the adequacy of the profile prepared by Adobe's Gamma utility.

Part II: Color Errors of Soft Proofing

A collection of color transparencies ("chromes") were scanned at a commercial shop on a Leaf 45. The RGB TIFF images were stored on CD as were CMYK TIFF images prepared from them using Adobe Photoshop 4.0 separation settings believed to yield good results on a large-format Iris Proofer. A half-dozen or more images (CMYK TIFF) were ganged on a single sheet of proofing stock along with a CMYK image consisting of tint blocks of known CMYK values. The latter is a calibration image of some 300 patches. 256 of the patches represent all combinations of four levels (0, 25, 50 and 100 % dot) of each of the colorants.

The printed images were all cut from the large sheet. The calibration target was measured carefully, using a Gretag SPM 100 spectrophotometer, so that the spectrum of the GTI lamp reflecting off the proofing stock could be substituted for the spectrum of the instrument's lamp. The colors of the patches were then calculated in CIELAB coordinates in a spreadsheet. The relationship between the CMYK inkings and the CIELAB colors was modeled, yielding equations which predict the color of an arbitrary inking. The accuracy of the model was checked by using it to calculate the colors of the inkings in the calibration image. The calculated values were compared to the actual measurements. The average error was 1.1 ΔE*ab units. The largest error was 3.2 ΔE and the second largest was 2.6. The accuracy of the model appears to be within the natural variation of the Iris proofer and measurement equipment and is small enough to support confident, remote, soft-proofing. The foregoing result regarding model accuracy is consistent with that reported by Holub (1989) for a variety of marking devices and technologies.

One of the images was a transparency version of the IT8 scanner calibration target. In the course of preparing it in Photoshop, the maximum density patches from the dye and dye overprint scales were copied, enlarged and pasted back into the image over the manufacturer's logo in the gray surround along the bottom edge of the target (see Plate 3.) The gray background ("patch #1 in Plate 3) was measured on both hard proof (in the GTI hood) and soft proof (on the display) as were the cyan, magenta, yellow, red (MY), green (CY) and blue (CM) patches. In this case (unlike the original measurements of the printed calibration target) all measurements were made with the PR 700. On the display, patches were magnified so that the colors were full-screen. In the case of the hard proof, a baffle was used to reduce the susceptibility of the instrument to flare effects from the surround of the patch being measured. The baffle did not seem to make a significant difference.

The foregoing is a test of the ability to meet a colorimetric reproduction criterion (matching TSVs) between the two media, using an experimental setup based on the simple sensor of the prototype, as described above. The errors reported in Table Five are "end-to-end." In this case, the errors are expressed as CIELUV color differences. One ΔE in CIELUV is very similar to one ΔE in CIELAB. Column headings in Table 5 have the following significance: Column 1 gives the color name of the patches identified as #1 ("gray"), #2 ("cyan,") etc. in Figure 3. Columns 2 and 3 give the differences in u' and v' for the proof measurement minus the monitor measurement. The next three columns hold the individual components of the color error and the last column holds ΔE*uv.

Both visually and instrumentally, the cyan patch (#2) rendered on both hard and soft proofs were very close. However, the foregoing metameric cyans are very different, spectrally, a fact that is illustrated in Figure Two. Given the difficulty of the experiment, the difference in instruments and the difference in illumination geometry employed for measuring hard copy in calibration and verification phases, the errors seem acceptable. However, the size of the errors for some patches, especially red, magenta and blue, warranted closer examination. Note that instrumentally-mediated tonal correction was employed throughout the experiment of Part II.

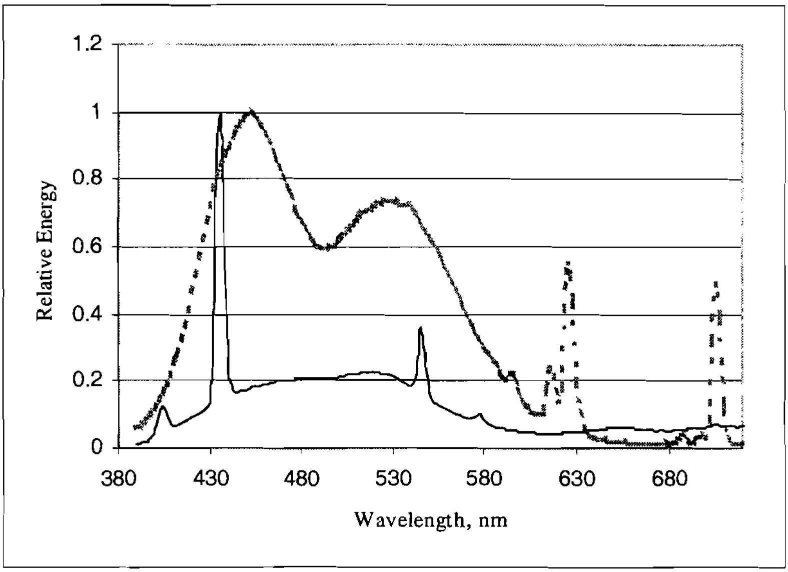

Figure Two is a plot of the spectra of metameric cyans, the dashed line representing the video display and the solid line the hardcopy proof in a reflection viewer. Each spectrum was normalized to its maximum value.

Part III: Further Dissection of Net Color Errors

When the patches were magnified for measurement, it was noticed that most exhibited the kind of mottling (random spatial variation of color values) that would be expected with a scanned image. However, the red (especially), magenta and blue patches did not. They were completely homogeneous fields, suggesting that their colors were being clipped. I used Photoshop's eye-dropper tool to sample the RGB values that were supposedly being displayed and found that the values (which did not vary across the patches in question) all appeared to be well within gamut for the display. In the case of the red patch, R, G, B = 207, 59, 50. In order to be close to the edge of the gamut, at least one of the foregoing coordinates would have to be at, or close to 255 or 0. Although it does not seem likely that the errors are a result of processing performed in prototype hardware or software, I undertook the experiments described below in an attempt to isolate sources of error.

TABLE FIVE

COLORIMETRIC REPRODUCTION CRITERION APPLIED TO HARD/SOFT PROOF MATCH

IT8 Image	proof u' - mon u'	proof v' - mon v'	delta L*	delta u*	delta v*	delta E*uv
Gray	0.000	0.000	0.426	-0.354	0.000	0.554
Cyan	-0.001	0.001	-0.220	-0.562	0.402	0.725
Magenta	0.006	0.001	0.381	4.070	0.621	4.135
Yellow	0.002	-0.001	1.379	1.780	-1.780	2.870
Red	0.013	0.000	-0.773	8.889	0.276	8.927
Green	0.001	0.001	0.530	0.480	0.480	0.861
Blue	-0.007	-0.003	-0.461	-2.544	-1.066	2.796

TABLES SIX AND SEVEN

VERIFICATION OF COLORANT MIXTURE MODEL ON SELECTED IT8 IMAGE PATCHES

IT8	L* meas	a* meas	b* meas	delta L*	delta a*	delta b*	delta E*ab
Cyan	61.57	-25.72	-32.24	-1.14	0.56	-1.43	1.91
Magenta	53.45	47.99	-16.42	0.89	1.28	0.82	1.76
Yellow	92.66	-6.98	83.98	1.92	-1.13	-1.10	2.49
Red	52.24	60.67	47.64	0.21	0.32	1.38	1.43
Green	53.30	-49.36	35.48	0.12	-0.29	-0.72	0.78
Blue	25.98	21.36	-41.74	-0.01	-1.14	1.61	1.98

ERRORS COMMITTED BY MONITOR PROFILE ON IT8 PATCHES

	L* meas	a* meas	b* meas	delta L*	delta a*	delta b*	delta E*ab
cyan	62.19	-23.74	-26.78	-0.81	2.26	4.22	4.85
magenta	52.84	40.76	-14.63	-0.16	-6.24	2.37	6.68
yellow	90.76	-8.02	85.22	-0.24	-2.02	0.22	2.05
red	50.39	51.96	40.36	-1.61	-8.04	-5.64	9.95
green	50.83	-44.39	31.49	-2.17	4.61	-4.51	6.80
blue	25.59	19.62	-33.41	-0.41	-3.38	9.59	10.17

Before describing the experiments, I review the pixel processing that occurs in the course of displaying the soft proof. For this analysis, I returned to Photoshop 4.0, where I believe I have better understanding and control of what is going on. To open an image for soft-proofing, I selected IMPORT TIFF IMAGE WITH COLORSYNC PROFILE from the FILE menu. In the profile selection menu, I chose the profile prepared from the Iris Proofer calibration and the profile of the monitor prepared with Adobe Gamma. The former converts CMYK pixels of the TIFF-s image into CIELAB coordinates. The latter may be presumed to control what happens as Photoshop (or ColorSync) converts CIELAB to RGB for display. As part of the set up, the gamma correction function of Tables 2 and 4 was written to the LUTs. I did not prepare different versions of either the Source or Destination Profiles based on possible rendering intents.

It is entirely possible that the patches showing large errors in Table 5 were flat because they were out-of-gamut for the Iris proofing process, not for the monitor. Recall that the original separation of the scanned images of this study was performed in Photoshop 4.0, where out-of-gamut colors may have been clipped. However, it is not apparent why this should result in larger errors than those observed in Tables 2, 4 and 5 due to the dataflow described. The original TIFF-RGB versions of the images were opened in Photoshop and the eyedropper used to see if patches 2 through 7 (Plate 3) were out-of-gamut. They were, except for yellow, which was nearly so.

The first experimental question that I considered was whether the Iris model produced particularly large errors for some of the colors of Table 5, especially red. To examine this, I read out the C, M, Y and K values of patches 2 through 7 from the TIFF-s image displayed in Photoshop. These were processed through the colorant-mixture model (that was used to build the CMYK-CIELAB profile) to yield predicted, or "model" CIELAB values. The patches on the physical proof were then measured in the GTI viewer, using the PR700, as in Table 5.

Results are assembled in Table 6, where the first column gives the patch identifier and the next three columns the measured CIELAB coordinates. The following three columns hold the components of color error, measured values less the model predictions. The last column is ΔE^*ab. The average error over the 6 patches is 1.72 color difference units. While this is larger than the 1.1 ΔE^*ab average estimated for the model from the calibration target measurements, it does not suggest the larger errors quoted in Table 5. In particular, the red patch error does not stand out. Furthermore, this verification involved measuring the color samples 2 years after the original proofing and calibration with a different instrument, illumination and a somewhat different measurement geometry than used in the original calibration. From this perspective, the average error is quite satisfactory.

The results of the experiment summarized in Table 6 show that the larger of the errors reported in Table 5 are not due to a localized failure of the Iris model. The next experiment considers errors that result from display transformations. The model-predicted CIELAB values of the six, colored, IT8 patches were used to create a new test image in Photoshop 4.0. In organization, the test image resembles that of Plate 2, except that it has only 6 patches. The new image was displayed and the patches measured as before. Results appear in Table 7.

Column headings and row labels in Table 7 are as in Table 6. The convention of subtracting the nominal CIELAB coordinates (those used to define the test image) from the measured values was followed again. (The nominal values are not shown in Table 7 but can be inferred.) Some error is to be expected given the limited precision with which CIELAB values can be specified when creating an image in Photoshop. Nevertheless, the errors are unexpectedly large. The monitor profile performed well on many colors in this study, but failed on these.

The next step in the analysis was to test the validity of the calibration data given to Adobe Gamma (the application which made the monitor profile.) Because there were several possible sources of error (including the AG profile, ColorSync, the Kodak cmm and processing in Photoshop,) I did *not* make a profile. Rather, I referred to the mathematical model of the monitor alluded to in the Introduction.

The calibration data for the monitor model consists of chromaticities of the R, G and B channels, the white point to which the monitor was balanced by the prototype sensor and the measured tone reproduction of the physical display. The CIELAB values used to define the test image of Plate 2 (where the monitor profile performed reasonably well) and those calculated by the colorant mixture model for selected patches from the IT8 image (where it did not) were transformed through the mathematical model to yield the RGB triplets that should appear on the monitor. These were compared to the RGB coordinates read from the image using the Photoshop eyedropper tool. Results are assembled in Table 8.

The column headings in Table 8 have the following significance: Columns 2 through 4 are the CIELAB coordinates used to define the test images. The next three are the RGB equivalents as calculated by the monitor model. The last three are the RGB triplets read from the image with the Photoshop eyedropper tool. Column one consists of row labels; the rows correspond to white, then the six patches from the IT8 target, then the nine patches from Plate 2. Inspection

TABLE EIGHT

RGB IMAGE VALUES FOR THE MONITOR PROFILE VS. MODEL

	L*	a*	b*	R mod	G mod	B mod	R prof	G prof	B prof
W	100	0	0	255	255	255	255	255	255
C	63	-26	-31	62	167	206	74	164	198
M	53	47	-17	182	84	156	172	88	151
Y	91	-6	85	248	231	30	244	230	0
R	52	60	46	210	56	51	194	64	54
G	53	-49	36	54	148	60	57	144	63
B	26	23	-43	65	51	128	65	51	116
#1	48	12	-19	120	106	145	118	106	140
#2	80	10	41	230	189	120	224	189	125
#3	15	5	14	51	39	25	51	41	15
#4	51	-17	10	99	130	103	101	127	104
#5	33	-34	17	29	93	52	22	89	53
#6	32	53	-14	132	0	99	122	0	96
#7	55	2	46	148	128	49	144	127	51
#8	40	5	-22	88	92	129	89	91	124
#9	65	-12	22	148	163	116	148	162	119

TABLE NINE

COLOR ERRORS OF MONITOR MODEL

	L* meas	a* meas	b* meas	delta L*	delta a*	delta b*	delta E*ab
cyan	62.83	-25.34	-30.64	-0.17	0.66	0.36	0.77
magenta	53.35	46.48	-16.11	0.35	-0.52	0.89	1.08
yellow	91.21	-6.35	84.32	0.21	-0.35	-0.68	0.80
red	52.78	59.61	45.39	0.78	-0.39	-0.61	1.06
green	52.45	-47.35	35.17	-0.55	1.65	-0.83	1.93
blue	26.17	22.76	-40.54	0.17	-0.24	2.46	2.48

of the figures reveals that the differences between model and profile RGBs are generally greater for the IT8 patches (where the monitor profile doesn't work well) than for the patches from Plate 2 (where it works adequately.) This doesn't appear to be a monitor gamut problem, since only patch #6 (from Plate 2) is slightly out of gamut for the monitor.

The concluding step of the analysis involved creating yet another test image in Photoshop – this time an RGB image of the IT8 patches using the RGB values computed with the model. The difference between this image and the one used for the analysis of Table 7 is this: For Table 7, the test image was defined with CIELAB values calculated by the ink mixture model. What was displayed (I believe) was the result of processing of the CIELAB values by the profile made by Adobe Gamma and by ColorSync. For Table 9, the test image was defined with RGB triplets calculated from the same CIELAB values used in Table 7, but using the mathematical model of the monitor. The monitor model substituted for the profile, Photoshop, ColorSync and the cmm used by it in converting CIELAB to RGB. Since the image is in RGB coordinates, no special system processing was needed for display.

Measurements of the RGB test image are assembled in Table 9, along with color difference data relative to the nominal values, using the format of Tables 6 and 7. Color errors of Table 9 are now acceptable, having an average value of 1.35.

Summary

Table 5 summarized an end-to-end analysis of soft-proofing system color errors. Several patches exhibited undesirably large errors and suggested anomalous processing somewhere in the system. The model which converts CMYK to CIELAB was re-verified at the troublesome colors and found *not* to be the source of the unusual errors. Analysis of color errors due to the calibration data and mathematical model of the display showed that they were adequate. Therefore, the evidence points to a problem of monitor profile generation by Adobe Gamma or in the use of profiles by ColorSync, the Kodak cmm and/or Photoshop. It was not the purpose of this study to assign blame; therefore, the analysis was concluded with the demonstration of feasibility summarized below. Nevertheless, the results point to a real difficulty confronting Users.

The results demonstrate that a properly calibrated, simple and inexpensive sensor can be used to enforce a colorimetric criterion of color reproduction on a video display, automatically. Given models of color reproduction by network devices of sufficient accuracy, remote proofing of color is feasible. The design of the sensor opens the door to remote video proofing by enabling automatic measurements of the effects of ambient illumination as those effects would be appreciated by a human observer.

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