Munsell Color Science Laboratory

Performance Evaluation of the Profile Maker Professional 5.0 ICC Profiling Software

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1. Abstract

Experiments were undertaken at the Munsell Color Science Laboratory to evaluate the colorimetric performance of camera, display and printer profiles produced through the Gretag Macbeth Profilemaker Pro ICC profiling software version 5.0. ICC profiles were generated for a Sinarback 54 M mega-pixel camera, an IBM T 221 LCD monitor and an Epson 7600 Ultrachrome inkjet printer. Errors were expressed in CIEDE2000 color-difference values. The camera profile showed the poorest colorimetric prediction capability with errors as large as 17.89 CIEDE2000 units over a test set. The display model was the most accurate with no error exceeding CIEDE2000 of 3.60 for its set of test colors. In between was the printer with a maximum error of 6.27 CIEDE2000. Smoothness of the color look up tables contained within the ICC profiles for each device was also investigated. Prediction results are listed below.

ΔE_{00}	Camera	Display	Printer
MEAN	3.65	0.83	1.62
MAX	17.89	0.04	6.27
MIN	0.50	4.14	0

Prediction errors for different device profiles

Color look up table smoothness investigations revealed that the camera ICC profile showed the greatest deviation from smoothness while the other profiles exhibited reasonable smoothness.

2. ICC Profiles for Digital Cameras

ICC profiles for digital cameras encapsulate information relating the device digital counts to CIELAB or CIEXYZ coordinates. Typical ICC mechanisms for describing these relationships include:

(a) One-dimensional look up tables followed by a 3x3 matrix transformation. This model is commonly referred to as the TRC-Matrix model.

(b) Use of a three dimensional Color Lookup Table (CLUT) surrounded by sets of one-dimensional lookup tables and possibly a 3x3 matrix.

Figure 1 shows the transform structure for the TRC-Matrix model. The advantages of such a structure is that the model is quite simple and does not significantly add to the file size of an ICC profile. A one-dimensional look up table, also known as Tone Response Curve or TRC, is used to create a linear relationship between one camera channel and CIEXYZ Tristimulus values. This is done separately for each channel of the camera. A matrix follows, transforming output of the one-dimensional look up tables to colorimetric coordinates.

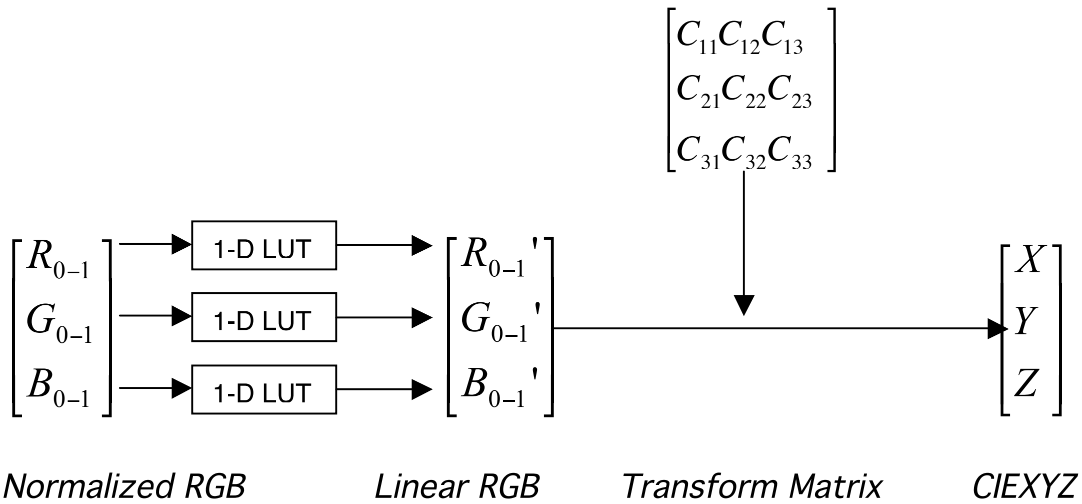


Figure 1. General structure of a TRC-Matrix transform.

The one-dimensional relationship between channel digital counts and tristimulus values can be a simple power-law function or a more complex function. The power-law function is often referred to as a gamma function. The coefficients of the matrix, $C_{11}...C_{33}$, can be determined through any one of multiple means. Linear regression or iterative optimizations are often employed to build the matrix for a camera profile.

Many cameras on the market, including the Sinarback 54 M used for this investigation, are designed with the criteria that the RGB signals they deliver adhere to the sRGB standard. This standard can well be described within a TRC-Matrix model. The sRGB calculation relating digital counts to XYZ is shown by equations 1 and 2. Equation 1 defines the conversion of sRGB scalar to linear sRGB values. This function can be easily encoded within the one-dimensional lookup tables of Figure 1. Equation 2 demonstrates the use of the sRGB matrix for converting between linearized sRGB values and XYZ values under D65 viewing conditions.

$$\begin{aligned} &if\ RGB_{Scalar} <= 0.04045, \quad RGB_{Linear} = RGB_{Scalar} * 12.92 \\ &otherwise, \quad RGB_{Linear} = ((RGB_{Scalar} + 0.055)/1.055)^{2.4} \end{aligned} \qquad (1)$$

$$\begin{bmatrix} 0.4124 & 0.3576 & 0.1805 \\ 0.2126 & 0.7152 & 0.0722 \\ 0.0193 & 0.1192 & 0.9505 \end{bmatrix} * \begin{bmatrix} R \\ G \\ B \end{bmatrix}_{LINEAR} = \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_{D65} \qquad (2)$$

For certain applications more degrees of freedom are desired than is available with a TRC-Matrix model. For such cases, ICC camera profiles may encode a transformation processing chain that includes a CLUT. One possible configuration for this transformation chain is illustrated in Figure 2.

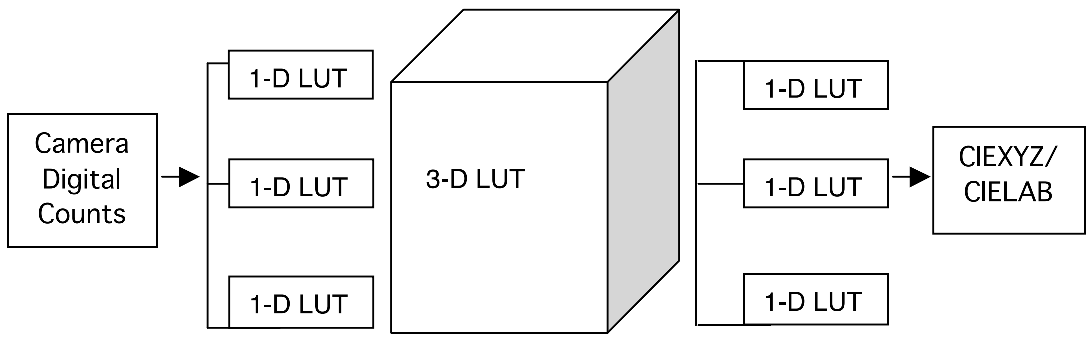


Figure 2. Example structure of a multi-dimensional look up table based transform.

Although in the illustration above the structure is shown delivering CIE color, ICC requires use of color spaces defined specifically for profile use. These are generically called *Profile Connection Space* (PCS). The illuminant corresponding to PCS is always D50. Thus, all ICC profiles are based either on measurements made under or derived for D50 conditions or for measurements that have been chromatically adapted to D50. PCS has three different potential encodings. There is a 16-bit direct encoding of D50 CIEXYZ. The second and third encoding are based on modified use of CIELAB equations. The difference is in the use of the normalization constants. In standard CIELAB, the normalization constants come from CIEXYZ measurements of a perfect reflecting diffuser under the illuminant. For ICC CIELAB, the normalization constants are the CIEXYZ values of media white under D50. These latter two ICC profile connection spaces are distinguished by bit length: one is an 8-bit encoding, the other is 16-bit.

An ICC profile is composed of a set of predefined fields called a *header* and a variable number of data structures known as *tags*. Each processing structure is stored within a tag in the profile. For a profile containing a TRC-Matrix processing chain, there is a single set of tags that describe the model. For a profile containing CLUT-based processing chains, there can be more than one CLUT structure. Each is designed for use under different *rendering intents*. Rendering intents are associated with different gamut mapping goals: perceptual, saturation, media-relative colorimetric, and absolute colorimetric. Each potential CLUT tag is associated with a signature that relates it with a particular rendering intent. Table I lists the CLUT signatures that may be encountered in camera ICC profiles.

Table I. Tags corresponding to multi-dimensional look up tables in a camera ICC Profile.

Tag Signature	Rendering Intent
AToB0	Perceptual
AToB1	Media-Relative Colorimteric
AToB2	Saturation

The rendering intent of interest for the purposes of this report is the absolute colorimetric intent wherein colors are defined with respect to the illuminant D50 and a perfectly reflecting diffuser for reflecting or transmitting media. CIELAB colors calculated for the absolute rendering intent are denoted using the notation $CIELAB_{D50}$ in the report. The $CIELAB_{D50}$ values are not readily available from the ICC profile and need to be derived from the CLUT corresponding to the AToB1 tag. The AToB1 tag contains media-relative CIELAB values denoted by $CIELAB_{Media\text{-}Relative}$. $CIELAB_{Media\text{-}Relative}$ values are defined with respect to the color of the media as opposed to a perfectly reflecting diffuser or transmitter. This is done in order to preserve highlight detail in image renderings. The formulae for conversion from $CIELAB_{Media\text{-}Relative}$ to $CIELAB_{D50}$ values are listed in the appendix.

2.1 Experimental Parameters

Table II lists the equipment and the experimental parameters used. The Profilemaker software was presented with the standard 24 Color Checker patches taken from the Color Checker SG target (see Figure 3) for building the ICC profile.

Table II. Experimental equipment and parameters for testing accuracy of the camera ICC profile.

Camera	Sinar 54 M
Lighting	Broncolor HMI-F1200 with off-axis illumination
Characterization Target	Standard 24 patches from Color Checker SG
Validation Target	116 remaining patches from Color Checker SG
Measuring Instrument	Gretag Macbeth Eye-One spectrophotometer

Figure 3(a). (Left) Color Checker Digital SG target; (b). (Right) Traditional 24-patch target found within SG, used to build the camera ICC profile.

The validation target consisted all colors in Figure 3(a) not common to Figure 3(b). This gives a total of 116 colors for validation.

The target and the object planes were positioned to be parallel to each other. The lighting used consisted of two HMI Broncolor HMI-F1200 lights. The target was uniformly illuminated with off-axis illumination from the two HMI lights. In order to obtain accurate characterization of the camera, all post capture processing options of the camera signal were turned off to the fullest extent possible. A live video image of the target was acquired in order to obtain best focus and exposure settings. Table III lists camera settings important to the experiment. Figure 4 shows the studio setup for image capture.

Table III. Sinar 54 M camera and software settings.

Setting	Value
F-Number	11
Speed	1/30
Gray-Balance	OFF
Curve	Linear
Precision	16-Bits

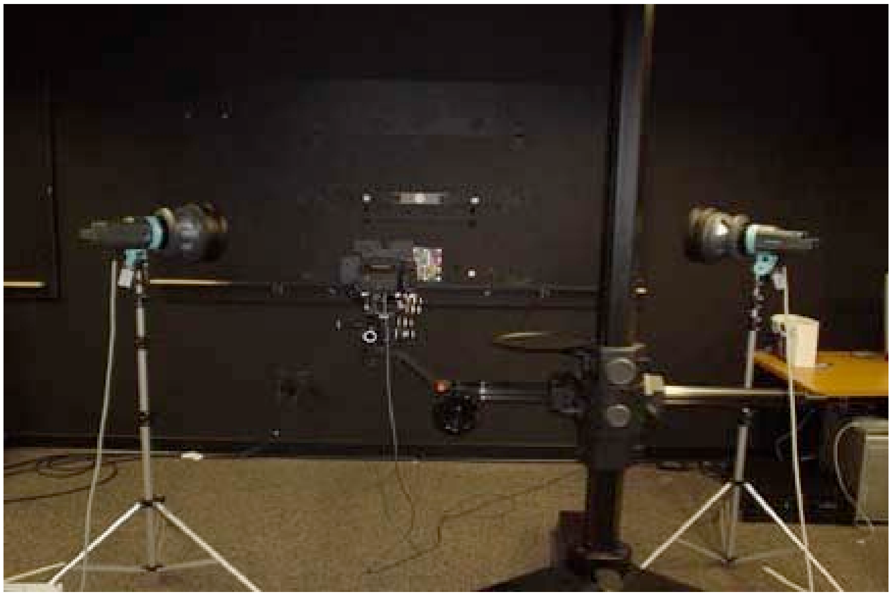


Figure 4. Sinar 54 M camera, SG target and HMI light positioning.

Separately, spectral reflectance of the target was measured using the Gretag Macbeth Eye-One spectrophotometer with a 45/0 measuring geometry. Figures 5(a) and 5(b) show the Eye-One spectrophotometer and the Photo Research PR-650 spectroradiometer. The radiometer was used to measure the spectral power distribution of the HMI light source.

Figure 5(a). Eye-One Spectrophotometer; *(b). PR-650 Radiometer*.

The spectral power distribution of both the HMI light source used for image capture and the D50 illuminant which was utilized in computation of camera ICC profile are illustrated in Figures 6(a) and 6(b).

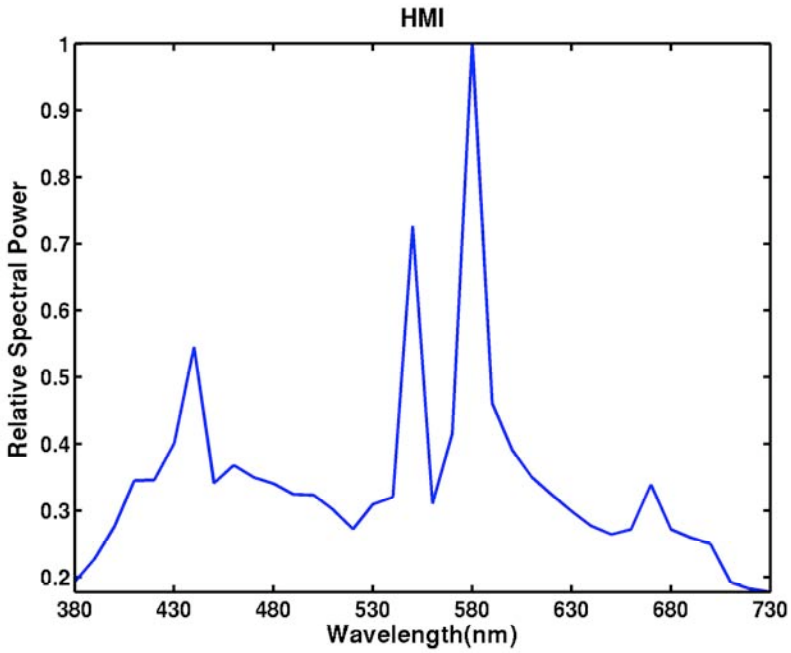


Figure 6(a) Relative spectral power distribution of the HMI light source.

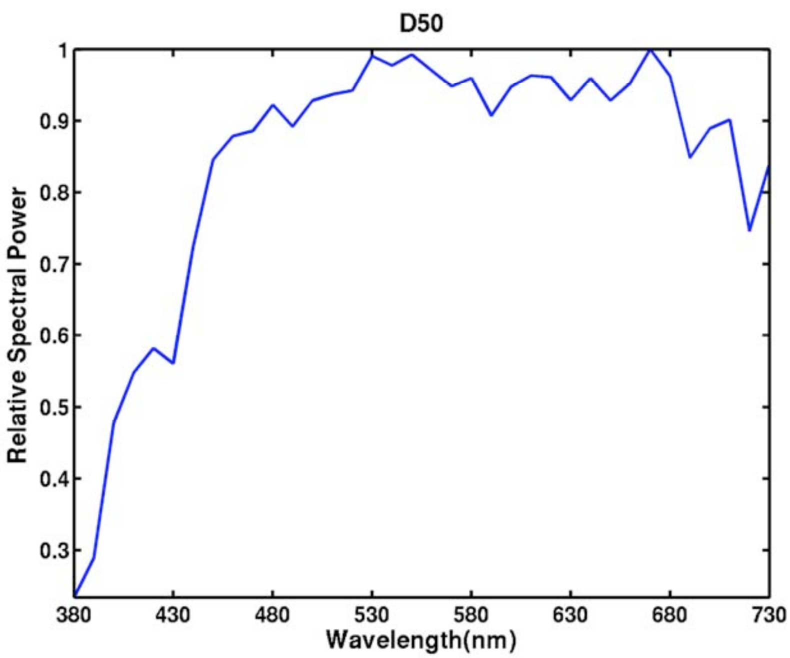


Figure 6(b) Relative spectral power distribution of the D50 illuminant.

2.2 Experiment

An image of the Color Checker SG target was captured using the Sinar 54 M camera. Prior to image capture it was ensured that camera parameters and controls as well as positioning of light sources, target and camera were in agreement with the guidelines described in the previous section. A portion of the captured image corresponding to the characterization target was then supplied to the Profilemaker software. Profilemaker relates the camera signals to CIELAB values for D50 viewing environment to build a CLUT based transformation structure.

Besides supplying the image of the target other options, which control the building of the transformation structure, also need to be set. The settings vary with the choice of 'Phototask Options' within the software. The 'Reproduction' option was selected, as it does not numerically distort the camera signals in any way in order achieve a particular effect. This is important when evaluating profile accuracy. The settings are listed in Table IV.

Table IV. Profilemaker camera profiling section settings.

Photo Task Option	Reproduction
Gray Balance Option	Use Camera Gray Balance
Exposure Compensation	20-30%
Saturation Adjustment	None
Fine Tune Shadows	None
Contrast Adjustment	None

After having performed the operations mentioned above the software delivered an ICC profile. The ICC profile encapsulates the color transformation structure and other parameters such as intended viewing illuminant etc. A listing of these tags is given in Table V. (See references for the interpretation and format of these tags). The profile size is a good indicator of the type of color transformation structure encapsulated within the profile. In this case the profile size was determined as 208 KB indicating the presence of a CLUT with sparse sampling of the input dimensions.

Table V. Camera ICC profile –Important tags and characteristics.

Tag	Data Type	Size (Bytes)	Nodes/Elements
Copyright	Text	42	Copyright by LOGO GmbH
Profile Description	Text	104	User specified file name
Chromatic Adaptation Tag	Signed Fixed 32	44	3x3 Identity Matrix
RGB Primaries	XYZ	60	3x3 Matrix
White Point	XYZ	20	1X3 Matrix
Black Point	XYZ	20	1X3 Matrix
r,g,b TRCs	curv	3012	1533 Nodes
A2B0	mft2	9934	15625 Nodes
A2B1	mft2	9934	15625 Nodes
A2B2	mft2	9934	15625 Nodes

Figure 7, below, shows a screen shot of the Profilemaker camera profiling section.

Figure 7. Screenshot of the Profilemaker camera section.

The accuracy of the profile was tested in two different ways:
(a) Test of profile accuracy in predicting the characterization target used to build the profile.
(b) Test of profile accuracy in predicting the validation target whose colors are independent of the characterization target.

The purpose of test (a) was to ascertain that the prediction errors for the characterization dataset are low, as is usually expected from such a dataset. The prediction errors for test (b) can be expected to be higher than that of test (a) within certain limits. The flowchart in figure 8 outlines the methodology for determination of the prediction error for any given target.

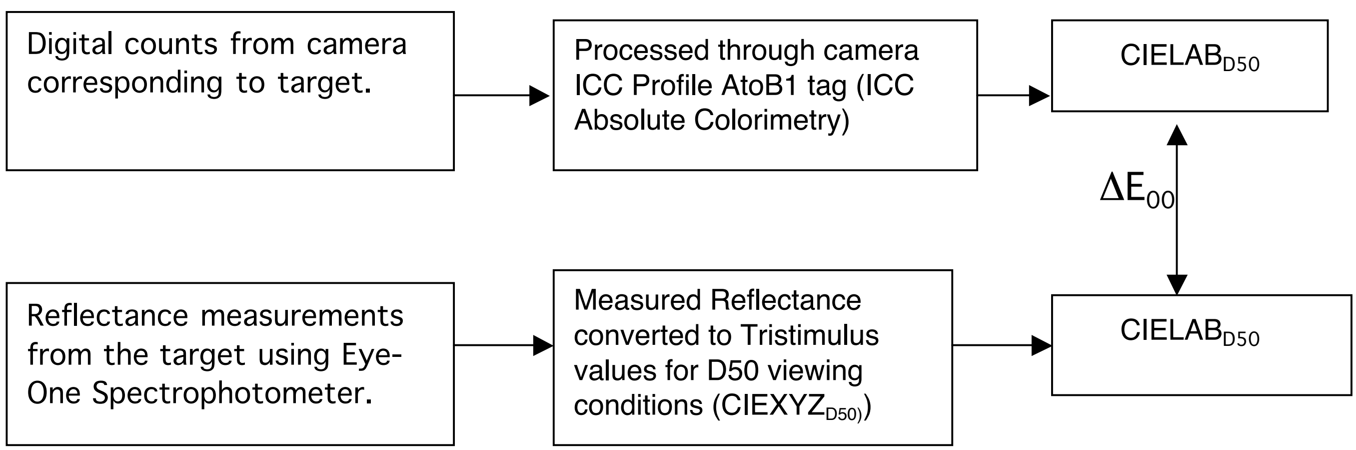


Figure 8. Workflow for evaluating camera ICC profile prediction error.

Processing of camera digital counts through the ICC profile was accomplished in MATLAB using the following steps:

(1) Import ICC profile using the function 'iccread'.
(2) Create color transformation structure using data in the ICC profile using the function 'makecform' and specifying the transformation to be of the type 'AtoB3'.
(3) Normalize camera digital counts between 0-1.
(4) Apply the color transformation structure created in step (2) to values from (3).

The output from step (4) is $CIELAB_{D50}$, which are stored in the camera ICC profile CLUT.

2.3 Results

Following the top route of the flowchart described by Figure 8 CIELAB values were estimated for the photographed targets. These estimates were compared to values derived through the bottom route of figure 8. Average, maximum and minimum differences between predicted and measured values appear in Table VI.

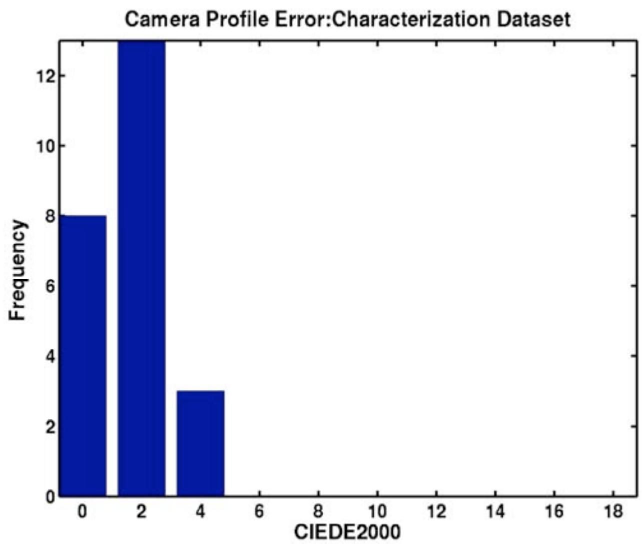
Table VI. Camera ICC profile prediction errors.

ΔE_{00}	Characterization	Validation
MEAN	2.41	3.65
MAX	5.29	17.89
MIN	0.82	0.5

Figures 9(a) and 9(b) give the error distribution histograms as for the two datasets. From table VI, the mean and the maximum errors for the characterization dataset are high.

An important reason for this is the use of relatively few data points in the construction of a very large uniformly sampled CLUT. Table V indicates that the number of nodes in the CLUT is 15625. These were built using just 24 data points. This means that almost every node has been estimated via interpolating or extrapolating from the 24 characterization patches. The farther in three-dimensional space the nodes are from any of the 24 original points the higher the likelihood of increased prediction error. To obtain an increased sampling for the purposes of building the profile and thereby achieve better accuracy, all the colors of the Digital Color Checker SG shown in Figure 3 could have been used. This was avoided deliberately as the 24 patches selected for building the profile correspond to the Gretag Macbeth Color Checker target. The Color Checker target is popularly used for building camera ICC profiles and hence the decision to use 24 patches.

For the validation target a higher prediction error than that of the characterization target was expected. The maximum error for the validation set is of the magnitude 17.89 CIEDE2000. Figure 10 shows the a*-b* and L^*-C_{ab}^* shift plots for the validation set from measured $CIELAB_{D50}$ coordinates to ICC profile predicted $CIELAB_{D50}$ coordinates.



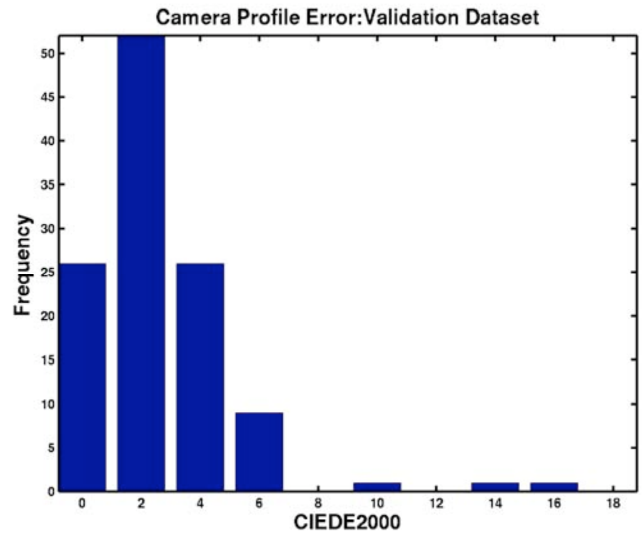


Figure 9(a) Characterization dataset ICC profile prediction error.

9(b) Validation dataset ICC profile prediction error.

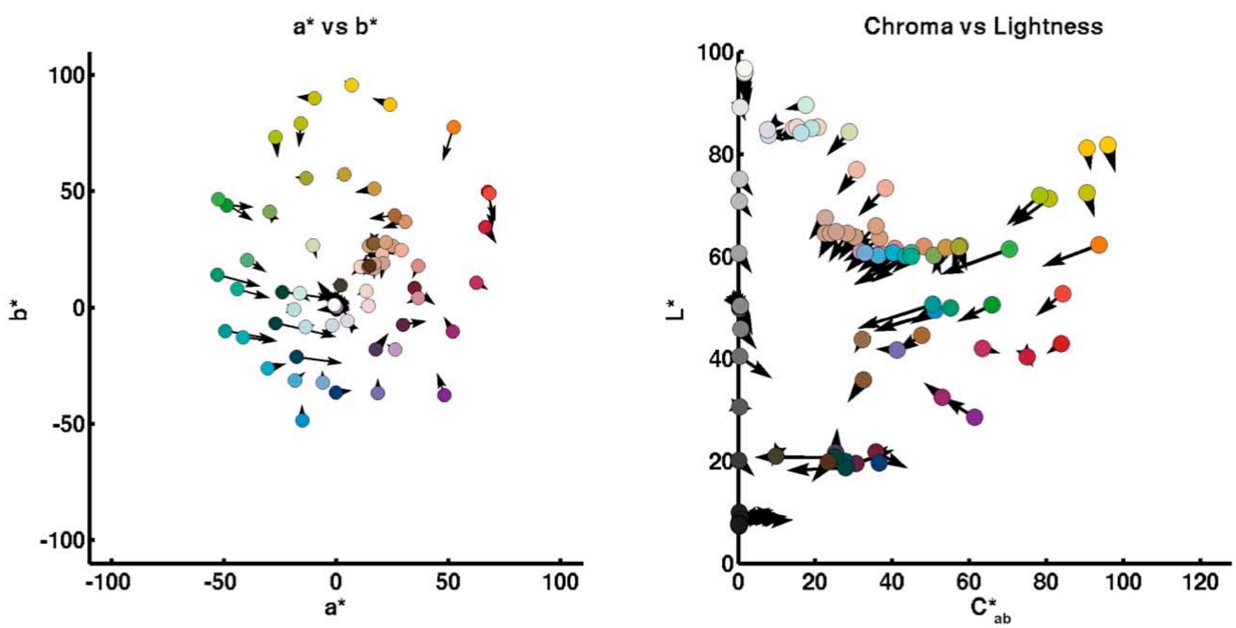
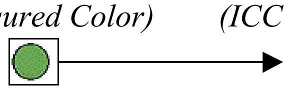


Figure 10.Change from measured color to ICC profile predicted color.
(Measured Color) (ICC profile predicted color).



The colors in Figure 10 represent actual colors of the color checker SG target reproduced to the closest approximation for graphing purposes. Some patterns are noticeable from the plots in Figure 10. In the figure on the left which shows deviations from measured color in a*-b* plane, there is a noticeable trend of colors in lower regions of a* to be over predicted. This means that combinations of green and blue colors corresponding to negative a* and b* will be reproduced to be less greenish or have an increased a* component. From the figure on the right there is a consistent pattern for a majority of the colors to be under predicted in both L* and C_{ab}*. Thus this will lead to colors being reproduced darker and less chromatic than those present in the original scene.

2.3 Color Look Up Table Smoothness

CLUT smoothness was examined in this section. The CLUT corresponding to the AToB1 tag was extracted from the camera ICC profile. The CLUT was smoothed using a three-dimensional Gaussian function. A three-dimensional Gaussian with symmetry in all directions has the mathematical representation shown by equation 3.

$$f(x,y,z) = 1/2\pi\sigma e^{-[x^2+y^2+z^2]/\sigma^2} \tag{3}$$

x, y, z- Red, green and blue digital counts, input to the CLUT.
σ - Standard deviation of the Gaussian function.
f (x, y, z)-Output of the CLUT in CIELAB coordinates.

Using the three-dimensional Gaussian defined in equation 3 to filter the camera CLUT, x, y and z dimensions represent the input channels of the CLUT and 'σ' represents the standard deviation. A readily available discrete implementation of the function represented by equation 3 was used from MATLAB: *smooth3*. Prior to application of the smoothing function, CLUT values were normalized between 0-1. In order to quantify smoothness the original and smoothed CLUTs were differenced creating a three-dimensional measure of 'unsmoothness'. Figure 11 shows a plot of differenced CIELAB values between smoothed and unsmoothed CLUTs the differenced values between the smoothed and the unsmoothed for a grid of RGB input values.

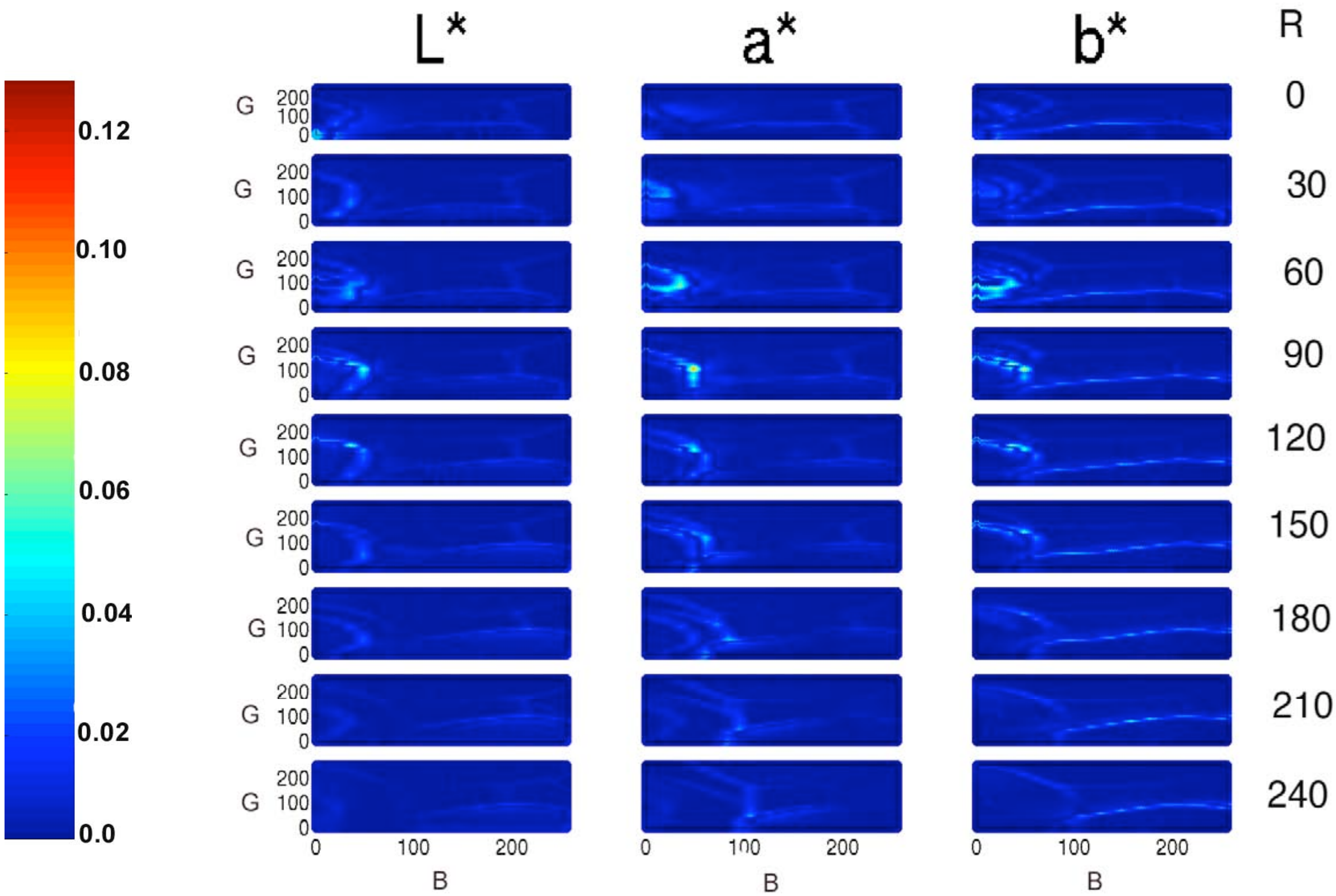


Figure 11. Unsmoothness metric for evaluating camera CLUT. Colorbar on the left indicates level of unsmoothness. A higher level indicates a greater deviation from smoothness Each row of the plot represents residual CLUT value (difference between smoothed and unsmoothed CLUT) evaluated for a grid of green and blue digital counts at constant red digital count. The value of the constant red digital count is indicated by column R toward the right side of the plot. The colorbar on the left indicates the extent of unsmoothness present at a particular combination of blue and green digital counts.

From Figure 11, areas where sharp topographical changes take place can be seen. A horseshoe shaped region is noticeable for all the plots where lower blue digital counts occur. This indicates an unsmooth lookup for a combination of green and blue colors at lower blue values. The maximum deviation from smoothness occurs consistently in regions near the center of the horseshoe pattern, indicating region of highest discontinuity in the CLUT. A constant ridge can also be observed at lower green values.

The unsmoothness in the look up tables can cause prediction errors. Linear interpolation performed in these regions will result in erroneous output. Therefore the unsmoothness of the camera CLUT can be considered to be a possible contributor to the higher prediction errors seen for combinations of blue-green colors.

3. ICC Profiles for Liquid Crystal Displays

Most commonly available monitors today are either a Cathode Ray Tube (CRT) or a Liquid Crystal Display (LCD). CRT device physics is fairly well approximated by the TRC-Matrix model shown in Figure 1. LCD physics are more complex. The three dimensional stage of an LCD model is more complicated than can be described by a matrix. There are two dimensional and three dimensional non-linear aspects to the color rendering characteristics. In order to obtain good estimates of colorimetry from device digits, a CLUT is often used in an LCD profile.

In contrast to the camera ICC profile, the LCD ICC profile contains CLUT structures that are defined for transformation from device digits to colorimetry and vice-versa. The camera ICC profile contains CLUT structure defined only from device digits to colorimetry. The inverse transformation structure is similar to that shown in Figure 2 with the exception that for transformation from colorimetry to device digits the direction is reversed. The tags associated with different transformation directions and rendering intents are listed in Table VII. *AtoB* tags indicate transformation from device digits to colorimetry. *BtoA* tags transform from colorimetry to device digits.

Table VII. Tags corresponding to multi-dimensional look up tables in an LCD ICC profile.

Tag Signature	Rendering Intent
AToB0	Perceptual
AToB1	Media-Relative Colorimteric
AToB2	Saturation
BToA0	Perceptual
BToA1	Media-Relative Colorimteric
BToA2	Saturation

3.1 Experimental Parameters

The Profilemaker software has two options for defining the dataset that is used when characterizing LCDs:

(a) Use the standard chart supplied with the software. This chart consists of 99 colors.

(b) Use a user defined custom chart that can consist of any number of colors.

Both options were exercised. The custom chart consisted of a 16X16X16 sampling of the RGB cube, giving 4096 colors. The custom chart used for this experiment and the standard 99-patch charts are described in the appendix section of this report. Table VIII lists the experimental parameters.

Table VIII. Experimental equipment and parameters for testing accuracy of the camera ICC profile.

Display	IBM T221 LCD display
Calibrated White Point	D50
Room Conditions	Darkened-No External Light Interference
Characterization Target 1	Standard 99 patches from the Gretag LCD chart
Characterization Target 2	Custom 4096 patches generated by the experimenter
Validation Target	Characterization Target 2
Measuring Instrument	Gretag Macbeth Eye-One

The room was adequately darkened to ensure exclusion of all possible sources of flare. The measuring instrument used was the Gretag Macbeth Eye-One spectrophotometer with a 45/0 measuring geometry. When measuring emissive devices, such as an LCD, the Eye-one functions in a spectroradiometic mode as the internal light source is not used for the measurements. The measurements were recorded in 10 nm intervals with a range from 380-730 nm. The colors from the selected chart were automatically displayed on the screen by the Profilemaker software and the measurements from Eye-One recorded automatically to a Gretag Macbeth native file format used in building the ICC profile. Figure 12 shows the setup for the experiment. Emission spectra of the LCD primaries are shown in the appendix.

Figure 12. IBM T221 monitor and Eye-One setup for the experiment.

3.2 Experiment

The standard 99 patch and the custom 4096 patch characterization targets shown in appendix were supplied to the Profilemaker software to generate two different ICC profiles. The only user defined settings in the Profilemaker LCD profiling section were the white point which was set to a default value of D50 and the profile size, which was set to 'large'. The specification of a large profile size in the Profilemaker software sets the CLUT size to 33x33x33 entries. Table IX lists some of the important tags generated contained within the display profile for the LCD.

Table IX. LCD ICC Profile –Important tags and characteristics.

Tag	Data Type	Size (Bytes)	Nodes/Elements
Copyright	Text	42	Copyright by LOGO GmbH
Profile Description	Text	119	User selected filename
Chromatic Adaptation Tag	Signed Fixed 32	44	3x3 Identity Matrix
RGB Primaries	XYZ	60	3x3 Matrix
White Point	XYZ	20	1X3 Matrix
Black Point	XYZ	20	1X3 Matrix
r,g,b TRCs	curv	52	Stored Gamma Values
A2B0	mft2	221854	35937 Nodes
A2B1	mft2	221854	35937 Nodes
A2B2	mft2	221854	35937 Nodes

Figure 13 shows a screen shot of the Profilemaker software's LCD profiling section. The accuracy of both profiles was validated using the flowchart illustrated in Figure 14. The default white point was set to D50 even though the preferred white point for displays is D65. D50 was chosen as it corresponds to the ICC standard illuminant and is better suited for computation of profile prediction errors. The processing of digital counts corresponding to the target was accomplished in MATLAB as described in section 2.2. The output from the color transformation structure created in MATLAB this case was $CIEXYZ_{D50}$ values. These were then converted to $CIELAB_{D50}$ values and compared to $CIELAB_{D50}$ values obtained from measurement of a given target off the LCD screen.

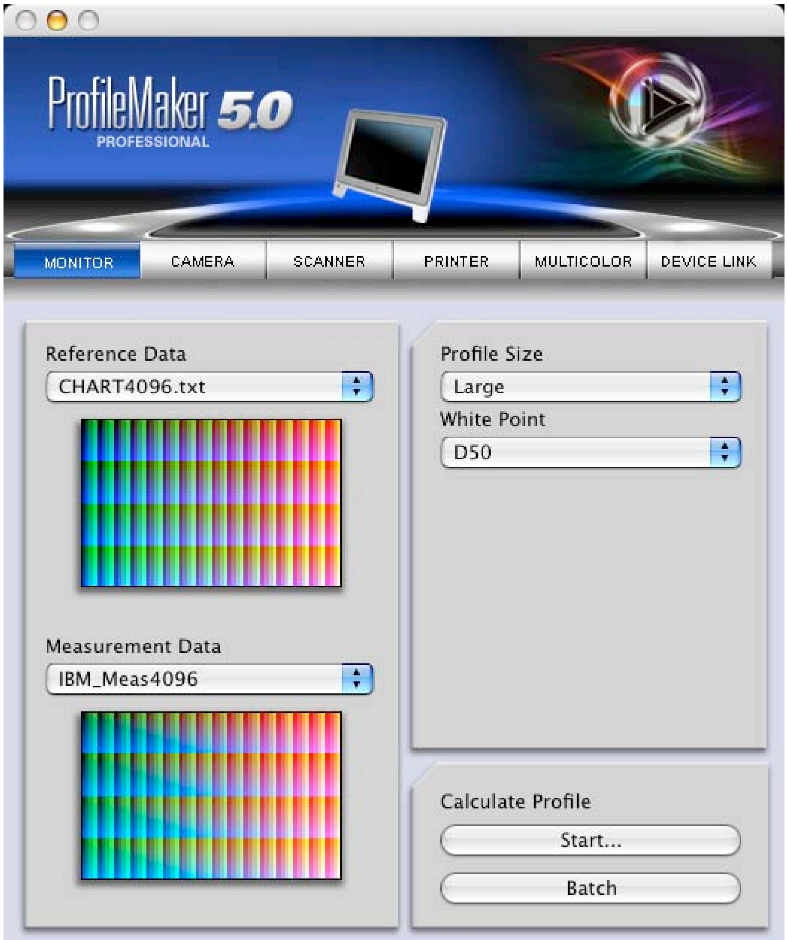


Figure 13. Screenshot of the Profilemaker camera section.

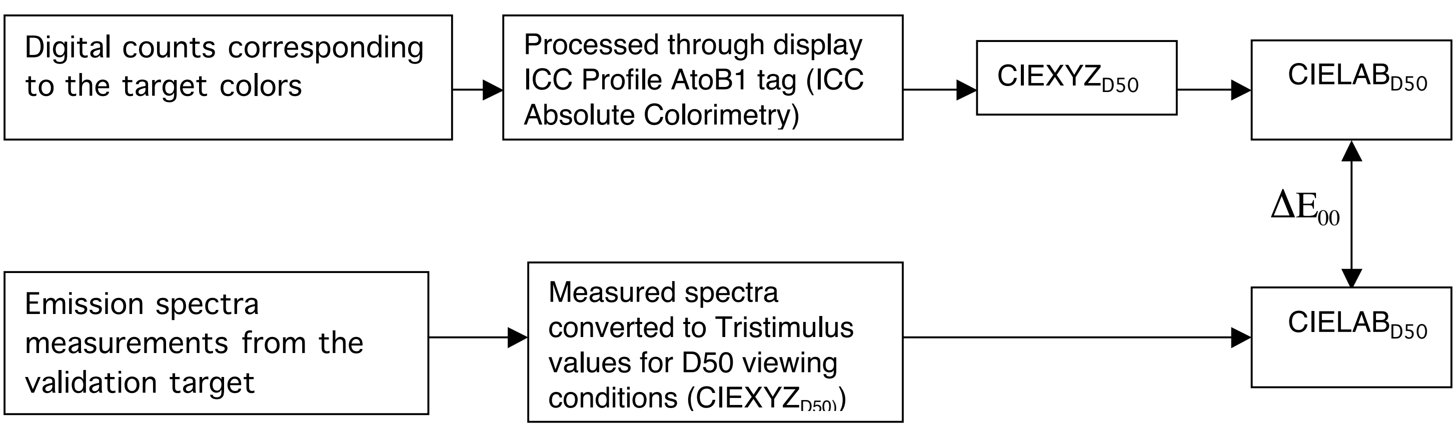


Figure 14. Workflow for evaluating LCD ICC profile prediction error.

3.3 Results

Table X lists the results for testing the accuracy of profiles built using the standard chart as well as the custom chart on a combination of datasets. The CIEDE2000 color difference metric is computed for $CIELAB_{D50}$ values obtained through the top and bottom routes of the flowchart shown in Figure 14.

Table X. LCD ICC profile prediction errors.

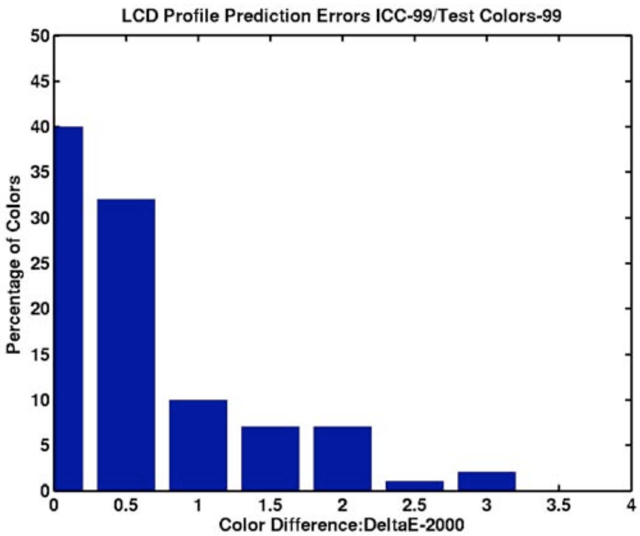
ΔE_{00}	Calibration:n=99 Verification:n=4096	Calibration:n=4096 Verification:n=99	Calibration:n=4096 Verification:n=99
Mean	0.83	0.98	0.46
Min	0.07	0	0.01
Max	3.51	3.46	3.3

The mean and the maximum error for predicting the 99 colors chart through the two different profiles are very similar to each other allowing for reasonable tolerances. This is evidenced from values noted in the first and second columns of Table X. The mean error for predicting the 4096 colors test chart through the profile built by same chart is also quite low indicating good profile performance.

The above observations show that for the case of LCD profiles increasing the number of physical measurements supplied to the Profilemaker software for building the ICC profile does not increase the prediction accuracy of the ICC profile. The reasons for this are two-fold:

(a) Most importantly, the 1-dimensional look up tables, which shape the data input to the 3-dimensional CLUT (see Figure 2) are defining the input space quite linearly with respect to output of the CLUT. Hence, data are linearly shaped leading to a significant reduction in interpolation errors, which would otherwise take effect while interpolating on non-linearly related data.

(b) The colors contained within the smaller target are optimally determined for building initial structure of the CLUT. Other nodes developed from this initial structure by extrapolation or interpolation, will not cause significant error in prediction.



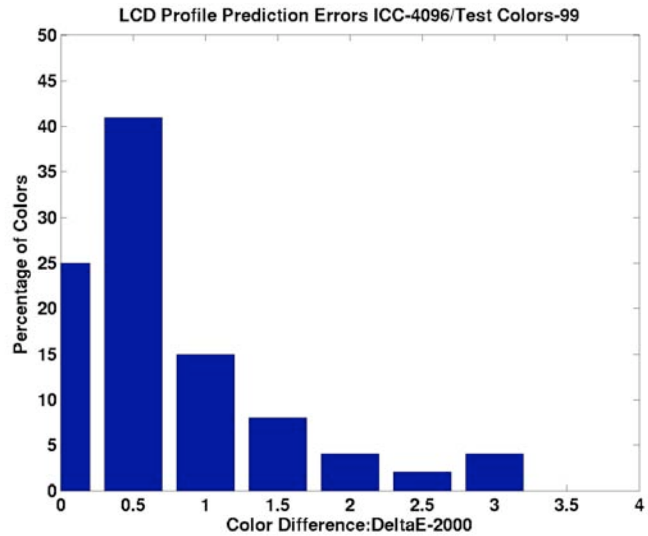
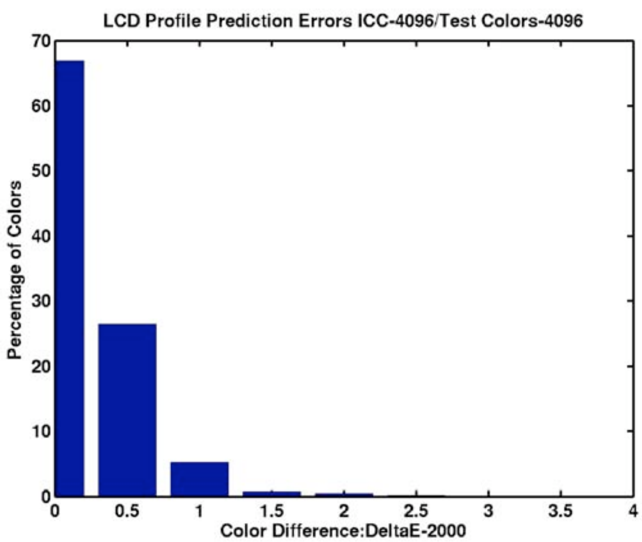


Figure 15(a) LCD profile prediction error.
Calibration: n=99.
Verification: n=99.

(b) LCD profile Prediction Error.
Calibration: n=99.
Verification: n=4096.



(c) LCD profile prediction error.
Calibration: n=4096.
Verification: n=4096.

Regardless of the minor differences in performance of the profiles built from different charts, all the profiles give a mean prediction error below 1.0 CIEDE2000. For images, this is below human visual threshold. The Profilemaker software thus delivers LCD ICC profiles, which are capable of giving a very accurate prediction of the device's responses from device digits to colorimetry.

3.4 Color Look Up Table Smoothness

The LCD ICC profile's smoothness in the direction from device digits to colorimetry was tested in this section. The procedure is similar to that described in determining the smoothness of the camera ICC profile CLUT. Figure 16 shows a visual metric for unsmoothness plotted on the same intensity scale as the camera CLUT. This was done in order to obtain a relative comparison between the two device's ICC profile CLUT smoothness.

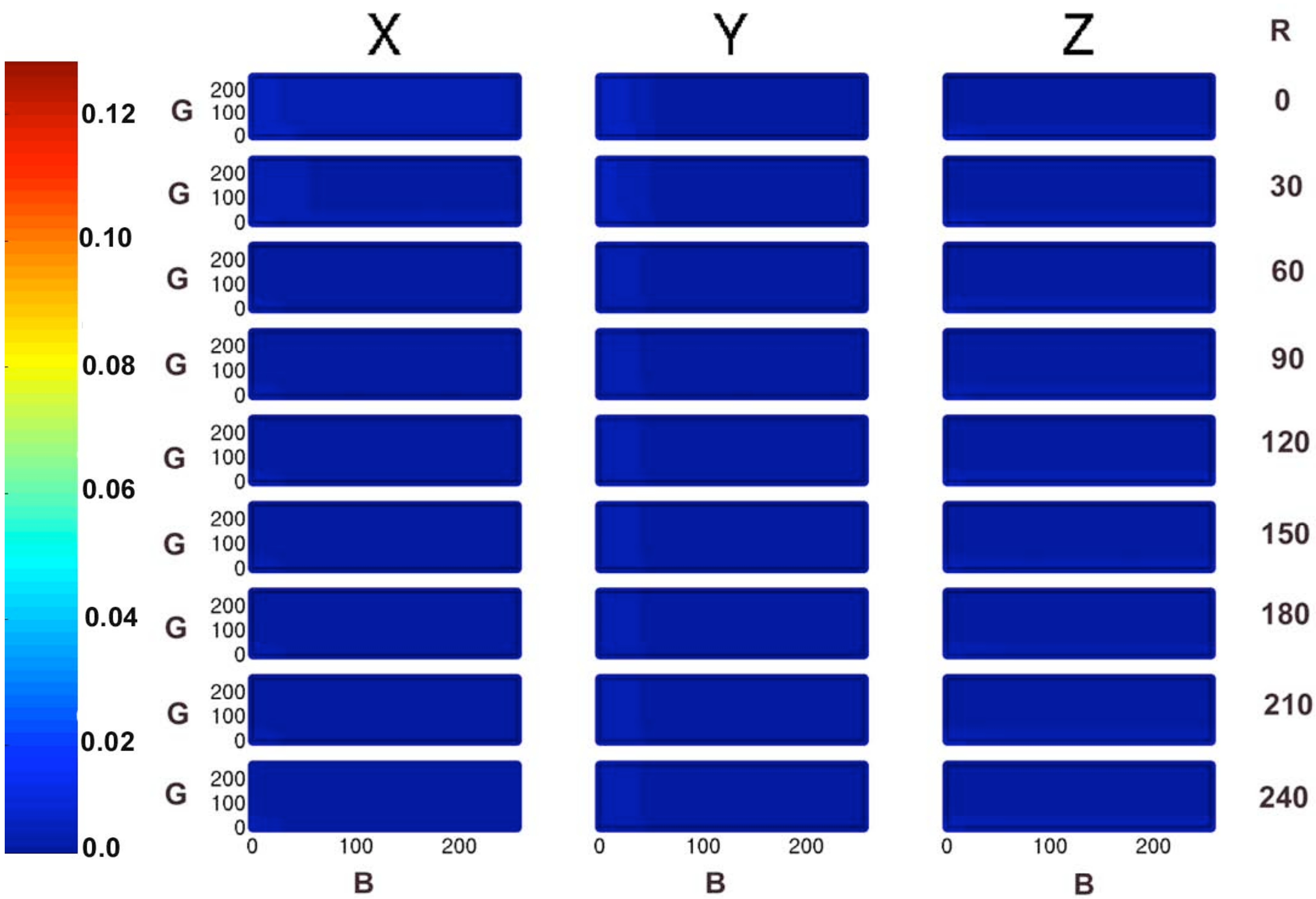


Figure 16. Unsmooothness metric for evaluating LCD CLUT. The intensity scale used is the same as in figure 11.

As seen from Figure 16, the residual between the smoothed and unsmoothed CLUTs is close to or near zero across the plot. The LCD profile CLUT exhibits very few areas of minor deviations from smoothness and in comparison to the camera profile CLUT shows a high degree of smoothness.

4. ICC Profiles for Printers.

Digital printers can be broadly classified as being of the type RGB or CMYK. This means that a printer may accept RGB or CMYK digital counts as it's driving signals even though the final rendering of the image on the substrate is carried out by using CMYK or additional inks. In this context different targets are available for building the printer profiles for RGB and CMYK printers. Usage of CMYK target for an RGB printer and vice-versa will not result in an accurate ICC profile for the printer. The EPSON 7600 printer used in the experiment is an RGB printer. Internally this printer actually uses seven inks. They are Cyan, Magenta, Yellow, Black, Light Cyan, Light Magenta and Light Black.

Printing systems have many non-linearities associated with them. Therefore, the only practical way of relating colorimetry to device digital counts is via empirical or analytical models or by use of CLUTs. In accordance with this, printer ICC profiles necessarily contain three-dimensional CLUTs, which perform this task. The CLUT tags are the same as those encountered in a display ICC profile. The most relevant tags are the BToA tags as the ICC printer profile's primary goal is to predict printer digits required for producing a color requested in PCS coordinates. Gamut mapping is also more relevant for printer ICC profiles due to the inherently small color gamut volumes of printers. To identify the PCS colors that lie outside of the printable color gamut, an additional tag – 'Gamut ' tag- is present within printer ICC profiles. This tag outputs a value zero for all the PCS colors that lie within gamut and a number between zero and one for those colors which lie outside the gamut. Figure 17 outlines the processing chain from CIELAB coordinates to device digits for any given CLUT entry.

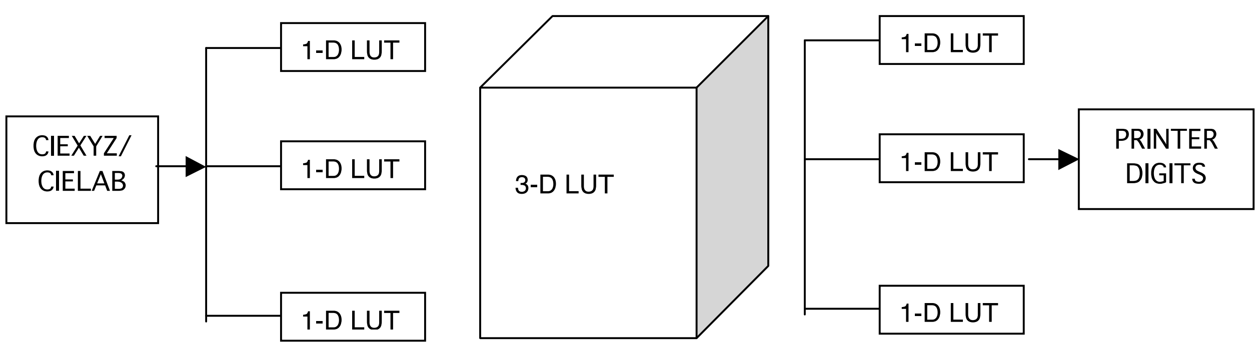


Figure 17. Example structure of a multi-dimensional look up table based transform.

4. 1 Printer Stability Tests

The printer's temporal stability in the short term was evaluated by printing a target consisting of 729 colors. The patches were randomly selected and are shown in the appendix. The target was printed ten times in succession. The $CIELAB_{D50}$ coordinates of the 729 colors from all prints obtained were compared to each other using the CIEDE2000 metric. The CIEDE2000 error averaged from comparisons of 45 pairs of prints is listed in Table XI. An additional metric, the MCDM error was also calculated. This metric is a measure of the deviation from the mean CIELAB coordinates of a given dataset and is useful in quantifying precision. Equation 4 shows the calculation of the MCDM metric. Figure 18 shows the histogram distribution of the MCDM metric from calculations of temporal stability.

Table XI. Printer temporal stability CIEDE2000 errors.

	ΔE_{00}	MCDM
Min Error	0.09	0.05
Mean Error	0.33	0.17
Max Error	3.26	1.78

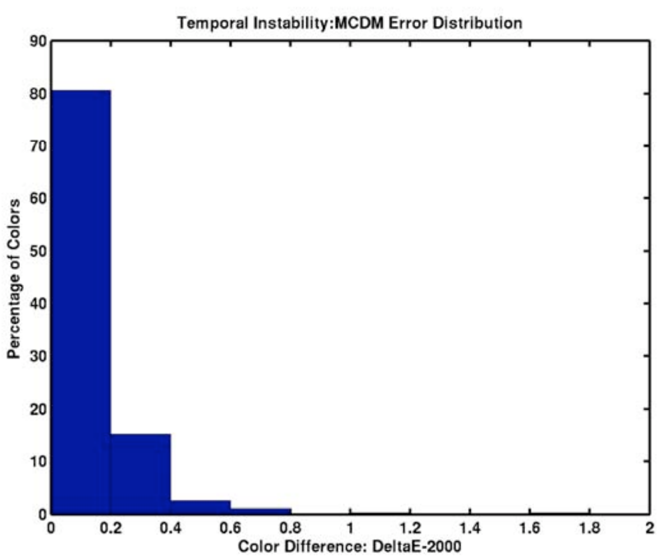


Figure 18. MCDM errors depicting printer's temporal stability.

$$MCDM = \frac{\sum_{i=1,N} [(L^*_i - L^*_{Mean})^2 + (a^*_i - a^*_{Mean})^2 + (b^*_i - b^*_{Mean})^2]^{1/2}}{N} \qquad (4)$$

N-Number of Observations in the dataset.
L, a*, b*-CIELAB coordinates.*

From Table XI the mean MCDM errors are 0.17 and the mean CIEDE2000 is 0.33. This indicates a reasonable short-term temporal precision of the colors delivered by the printer. This is important, as it is more meaningful to use an ICC profile produced for a stable device rather than a device that exhibits high temporal variation.

4.2 Experimental Parameters

There are a variety of test charts offered by the Profilemaker software for creating an ICC profile for printers. These vary by the type of signals the printer accepts (RGB/CMYK), the measuring instrument available and the number of output channels present in the printer. Based upon these considerations for the Epson 7600 printer, the TC 918 RGB chart was utilized for the purposes of building the ICC profile. A second chart, which was custom generated, was also used. This chart corresponded to a 9^3 uniform sampling of RGB digital counts. An sRGB definition was applied to the sampled digital counts and converted to $CIELAB_{D50}$ values. Table XII lists the experimental parameters used for this experiment

Table XII. Experimental equipment and parameters for testing accuracy of the printer ICC profile.

Printer	Epson 7600 Ultrachrome ink
Paper	Epson Premium Luster Photo paper
Characterization Target	TC 918 RGB test chart
Validation Target 1	TC 918 RGB test chart for in-gamut colors
Validation Target 2	Custom sRGB chart for in,out-of-gamut colors.
Measuring Instrument	Gretag Macbeth Spectroscan

The measuring instrument utilized for this segment of the experiment was the Gretag Macbeth Spectroscan which has a flatbed table for measuring charts and a spectrophotometer which can position itself anywhere on the table. Figures 19 and 20 show the printer and the measuring instrument used for the experiment.

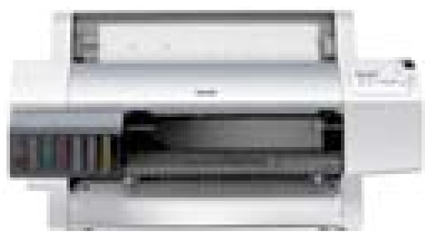


Figure 19. Epson 7600 Ultrachrome Printer. *Figure 20.Gretag Macbeth SpectroScan.*

The measuring instrument is similar to the Gretag Macbeth Eye-One with 45/0 measuring geometry and reports data in the 380-730 nm range with a 10 nm interval. The printer driver used was an Epson 7600 printer driver. As with other devices all possible external sources of color management were turned of to the fullest extent possible. The testcharts mentioned in Table XIII are shown in the appendix.

4.3 Experiment

The characterization target was printed on the Epson 7600 and measured using the Spectroscan, shown in Figure 20. The measurement file was then supplied to the Profilemaker software in order to build the printer ICC profile. Profilemaker then builds an ICC profile containing a CLUT-based transformation structure, which relates printer digital counts to CIELAB coordinates and vice-versa. The CLUT of interest is in the direction from colorimetry to device digits. Table XIII lists additional settings, which were used for the printer profiling. Figure 21 shows a screenshot of the Profilemaker software's printer profiling section and Table XIV lists the important tags within the printer profile delivered by the Profilemaker software.

Table XIII. Profilemaker camera profiling section settings.

Profile size	Large
Viewing Illuminant	D50
Gamut Mapping Intent	Logo Classic
Perceptual Rendering Intent	Neutral Gray

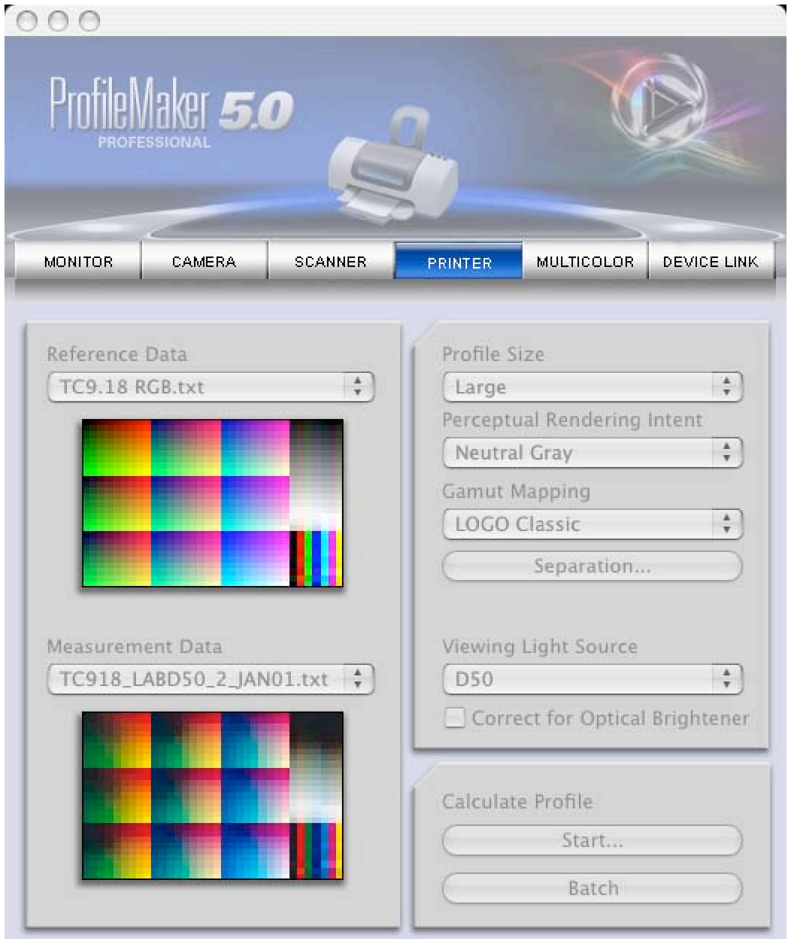


Figure 21. Screenshot of the Profilemaker printer section.

The gamut mapping intent corresponding to 'Logo Classic' was chosen as this is the only available option that does not alter the colors being reproduced significantly. This is important to get an accurate estimate of the performance of the ICC profile. The other options 'Logo Chroma Plus' and 'Logo Colorful Plus' alter the colors being reproduced selectively in their saturation and chroma contents, respectively. The choice of the perceptual rendering intent was arbitrarily set, as this does not affect the accuracy of the profile evaluation for in-gamut colors.

Table XIV. Printer ICC profile –important tags and characteristics.

Tag	Data Type	Size (Bytes)	Nodes/Elements
Copyright	Text	42	Copyright by LOGO GmbH
Profile Description	Text	104	User specified file name
Chromatic Adaptation Tag	Signed Fixed 32	44	3x3 Identity Matrix
White Point	XYZ	20	1X3 Matrix
A2B0	mft2	221806	35937 Nodes
A2B1	mft2	221806	35937 Nodes
A2B2	mft2	221806	35937 Nodes
B2A0	mft2	221842	35937 Nodes
B2A1	mft2	221842	35937 Nodes
B2A2	mft2	221842	35937 Nodes
Gamut	mft2	76038	35937 Nodes

For testing the accuracy of the printer profile, two different types of tests were conducted:

(a) The prediction accuracy of the ICC profile for predicting the colors of the characterization target.

(b) The prediction accuracy of the ICC profile for predicting the colors of the sRGB target.

The aim of (a), as with other devices was to test the Profile's accuracy in predicting the colors of the dataset used to create it. An extra feature was that these colors were all within the printer's color gamut. Figure 22 outlines the workflow for determining (a).

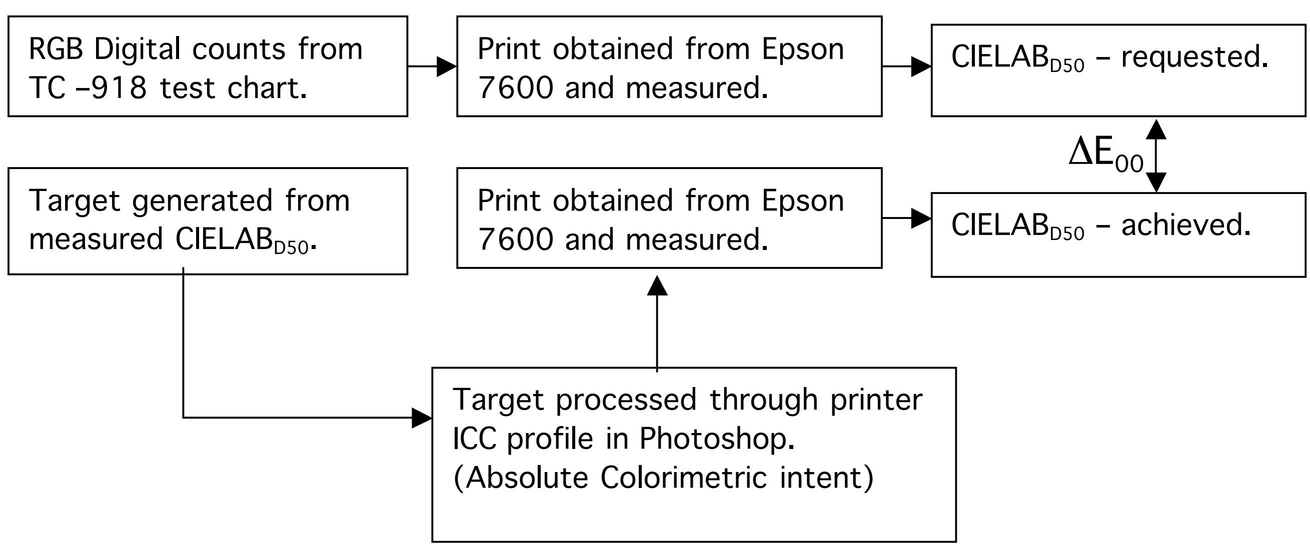


Figure 22. Workflow for evaluating printer ICC profile prediction error-characterization target.

The purpose of (b) was to evaluate the performance of the ICC profile for a combination of in-and out-of-gamut colors. A suitable target needed to be created for this purpose. Since a vast majority of the images captured or synthetically rendered adhere to the sRGB standard, it was decided to create a test chart which would contain a sampling of colors from the sRGB color gamut. More specifically, the interest was more toward testing the prediction accuracy of the ICC profile on colors, which lie on the surface of the sRGB color gamut. In order to process such a target through the printer ICC profile, the target was created in the $CIELAB_{D50}$ color space.

The procedure for target creation is listed below:

(1) Obtain a 9X9X9 uniform sampling of the RGB digital counts corresponding only to surface points on the RGB cube.
(2) The RGB digital counts are rendered to an sRGB definition using equation 1.
(3) The sRGB values are converted to CIEXYZ values for D65 viewing conditions using equation 2.
(4) Convert CIEXYZ D65 values to CIEXYZ D50 values using a Chromatic Adaptation Transform (CAT).
(5) Convert CIEXYZ D50 values to $CIELAB_{D50}$ and create a target.

Steps (1)-(5) above lead to the generation of a target, which was labeled as the 'sRGB target'. The target is shown in the appendix. Equations 5 and 6 give the necessary equation for converting from $CIEXYZ_{D65}$ viewing conditions to $CIEXYZ_{D50}$ viewing conditions. Equation 5 gives the conversion equation, while equation 6 gives the equation needed to obtain pseudo cone responses for any given illuminant or white-point.

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_{D50} = \left(CIECAT_{02}^{-1} * \begin{bmatrix} (\frac{L_d}{L_s}) & 0 & 0 \\ 0 & (\frac{M_d}{M_s}) & 0 \\ 0 & 0 & (\frac{S_d}{S_s}) \end{bmatrix} * CIECAT_{02} \right) * \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_{D65} \qquad (5)$$

$L_d, M_d S_d$=Destination white pseudo cone responses, $L_s, M_s S_s$=Source white pseudo cone responses.

$$\begin{bmatrix} L \\ M \\ S \end{bmatrix} = \begin{bmatrix} 0.7328 & 0.4296 & -0.1624 \\ -0.7036 & 1.6975 & 0.0061 \\ 0.0030 & 0.0136 & 0.9834 \end{bmatrix} * \begin{bmatrix} X \\ Y \\ Z \end{bmatrix} \qquad (6)$$

The 3x3 transformation matrix in equation 6 is the CIECAT02 matrix. This matrix gives the pseudo-cone responses corresponding to supplied tristimulus values. The pseudo-cone responses of the source and destination white points are required to perform a *Chromatic Adaptation Transform (CAT)*.

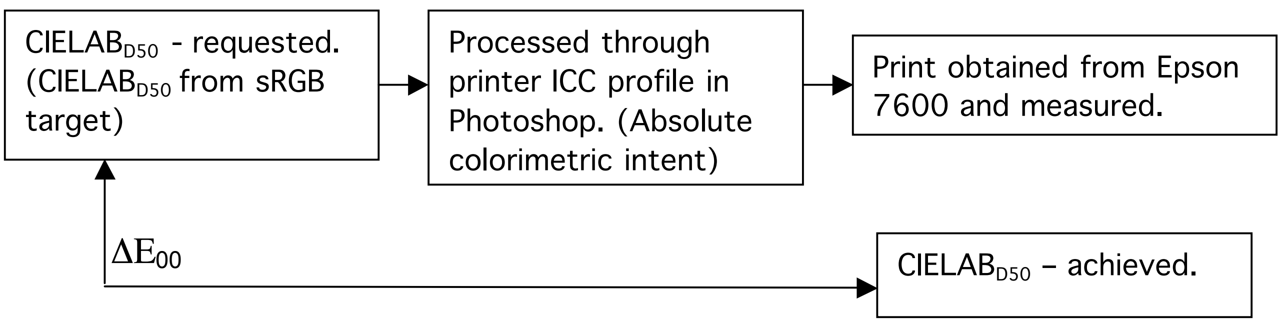


Figure 23. Workflow for evaluating printer ICC profile prediction error-sRGB target.

4. 4 Results

The results from evaluation of the printer ICC profile prediction accuracy as illustrated by Figure 22 are listed in Table XV. Figure 24 shows a histogram of the errors. From Table XV the mean error is 1.62 and the maximum error is 6.27. This result is for colors already determined to be within the printer's gamut. It should also be noted that unlike the camera and the display, the direction of the ICC profile CLUT being tested for accuracy is reversed here, i.e., BToA CLUT as opposed to AToB CLUT. The BToA CLUT is constructed by inversion of AToB CLUT, which inherently introduces errors due to the inversion process. Additionally, the effects of gamut mapping are also introduced. Therefore, a mean error of 1.63 CIEDE2000 is an indication of a good degree of CLUT accuracy.

Table XV. Printer ICC profile prediction errors -characterization target.

ΔE_{00}	
MEAN	1.62
MAX	6.27
MIN	0

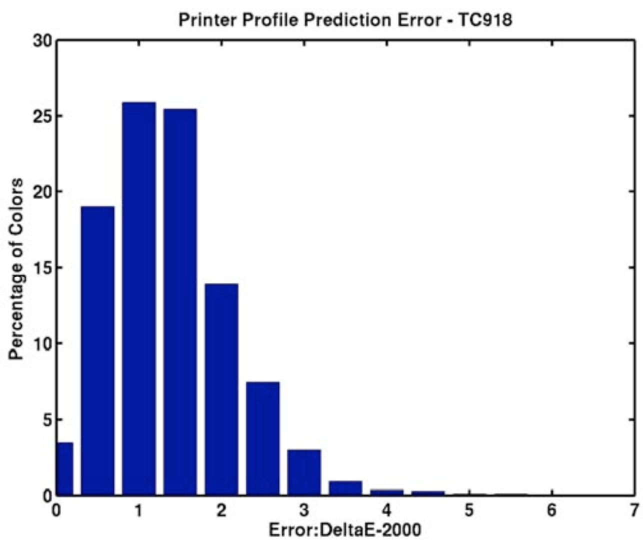


Figure 24. Printer ICC profile prediction error –characterization target.

Results for the prediction accuracy of the printer ICC profile for the colors corresponding to the sRGB test chart are listed in Table XVI. Figure 25 shows the error distribution histogram. The results are divided in to the performance of the ICC profile for predicting in-gamut colors and out-of-gamut colors. The classification of colors was done by the use of the gamut tag contained within the ICC profile. The tag outputs a value of 0 for colors within the printer's gamut and between 0-1 for colors outside of the printer's gamut

Table XVI. Printer ICC profile prediction errors sRGB test chart.

ΔE_{00}	In Gamut	Out of Gamut	Combined
COLORS	477	249	726
MEAN	5.05	11.13	7.14
MAX	11.94	16.26	16.26
MIN	0.42	4.38	0.42

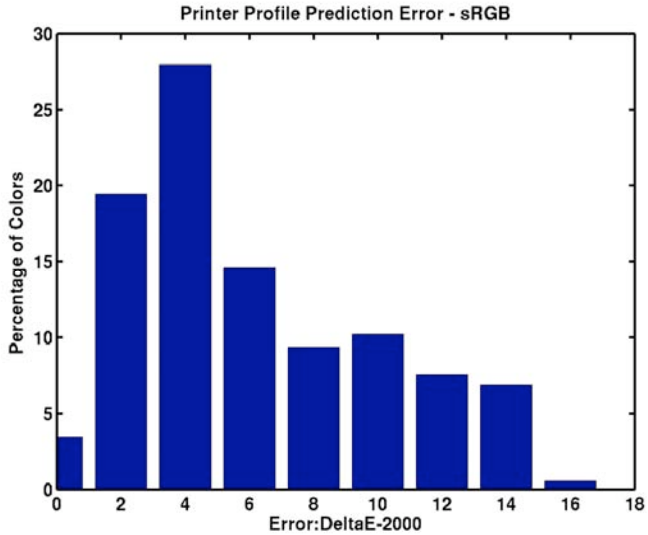


Figure 25. Printer ICC profiles prediction error –sRGB target.

The first column of Table XVI indicates that approximately 66% of the sRGB surface colors being predicted are within the printer's gamut. But despite this the mean and the maximum prediction errors are quite high when compared to values in Table XV. The reason is that in contrast to the dataset predicted in Table XV the dataset in Table XVI has all of its colors near or on the printer's gamut surface. The prediction error value for out-of-gamut colors from column 2 of Table XVI are expected and is a function of the distance of the predicted color from the printer's gamut surface.

In order for the out-of-gamut prediction errors to be small, the dissimilarity between the printer gamut and the sRGB gamut needs to be small. Figure 26 illustrates this dissimilarity from two different angles in CIELAB space. Clearly, the sRGB gamut has a larger spread along much of the lightness axis (L^*) as well as the chromatic axes (a^*-b^*). Therefore many of the larger out-of-gamut prediction errors can be expected from these differences. There are also regions along the chromatic axes, which are a part of the printer's gamut but not the sRGB gamut. Higher prediction errors can be expected from these regions as well.

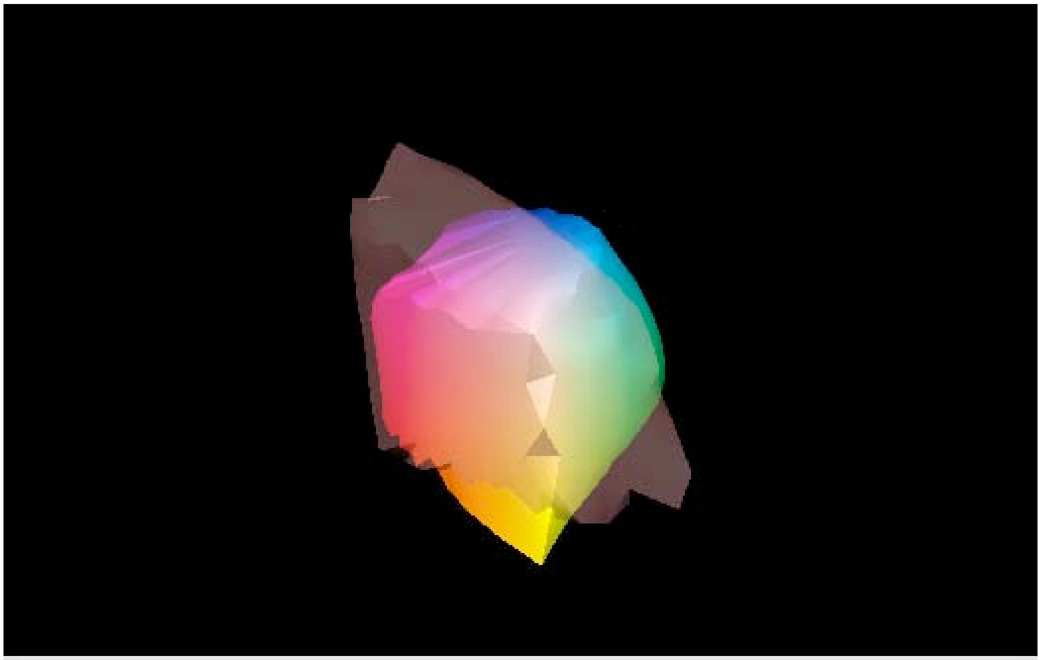
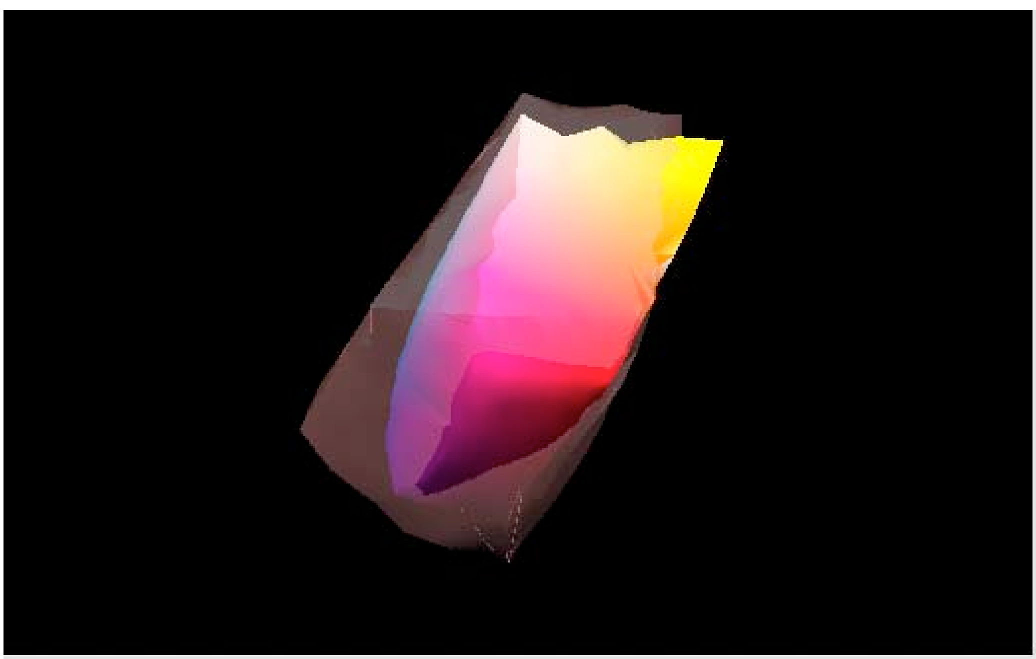


Figure 26 (a) Dissimilarity between the sRGB and printer CIELAB gamuts as viewed from top of the L axis. Printer color gamut is represented in true color and the sRGB gamut is represented by the transparent pink surface.*



(b) Dissimilarity between the sRGB and printer CIELAB gamuts as viewed from positive end of a axis. Printer color gamut is represented in true color and the sRGB gamut is represented by the transparent pink surface.*

4.5 Color Look Up Table Smoothness

As with the camera and the display ICC profiles the CLUT smoothness was investigated. A visual smoothness metric plot is shown in Figure 27. As indicated before, the CLUT being investigated in this case was in the direction from colorimetry to device digits or a BToA1 CLUT. Figure 27 shows regions of unsmooth lookup, most of these occurring at the printer's the gamut boundary. As indicated earlier in the report deviation smoothness can be a contributor to prediction errors.

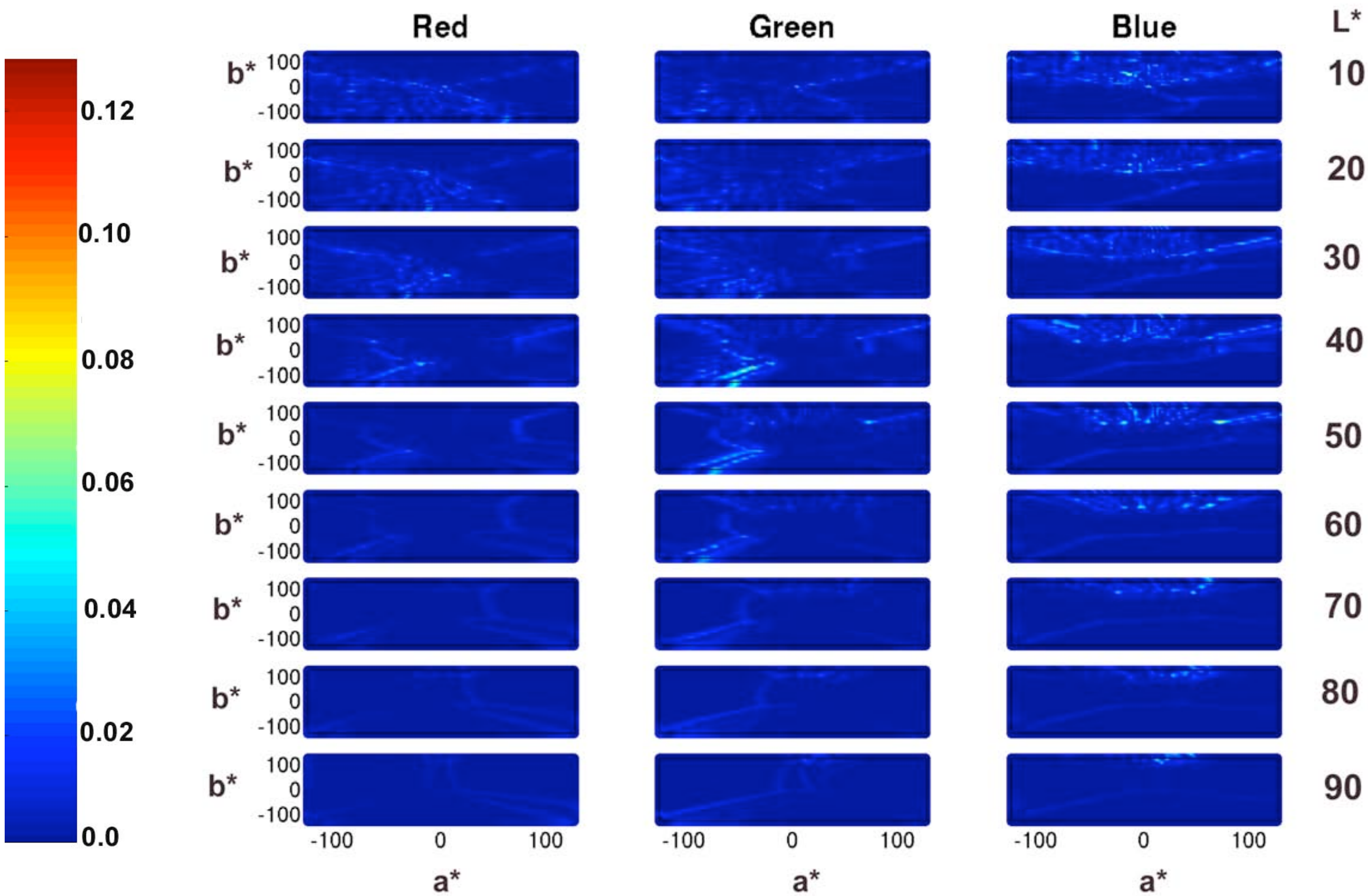


Figure 27. Unsmooothness metric for evaluating Printer CLUT. The intensity scale used is the same as in figures 11 and 16.

As compared to the camera profile CLUT smoothness, the intensity of the regions where maximum deviations from smoothness occur are less. Therefore the contribution of the CLUT lack of smoothness in prediction error of the ICC profile is relatively small compared to the camera profile but larger than that of the display profile.

5.0 Conclusions

Among the different modules evaluated from the Profilemaker software the camera profile prediction errors were the worst. This could be be improved with the use of a target containing a larger number of colors to build the profile or using a chart with a slightly larger number of colors but optimally determined colors or using a better shaping technique before input of data to the CLUT. The condition for optimality is although hard to define and needs to be built from a collection of a large number of scenes and images. The LCD module produced the best results with the mean prediction errors below 1.0 CIEDE2000, inspite of the CLUT built from a very small number of physical measurements. The prediction error of the printer ICC profile was intermediate to that of the camera and LCD.

Tests of smoothness revealed that the LCD profile showed the highest degree of smoothness followed by the printer profile. The camera profile exhibited a very high degree of lack of smoothness.

6.0 References

(1) MATLAB version 7.0. *http://www.mathworks.com*

(2) Gretag Macbeth Profilemaker Professional version 5.0
http://www.gretagmacbeth.com

(3) Digital Color Imaging Handbook, Gaurav Sharma. CRC Press 2003. (Chapter 5)

(4) ICC profile format specification, version 4.1. *http://www.color.org*

7.0 Acknowledgments

The authors would like to thank GretagMacbeth AG for their generous donation of an Eye-One spectrophotometer and ProfileMaker 5.0.

Appendix I.

1. Computation of CIELAB from CIEXYZ

$$L^* = 116 f(\frac{Y}{Y_n})$$

$$a^* = 500(f(\frac{X}{X_n}) - f(\frac{Y}{Y_n}))$$

$$b^* = 200(f(\frac{Y}{Y_n}) - f(\frac{Z}{Z_n}))$$

$$f(x) = \begin{cases} x^{1/3} & x > 0.008856 \\ 7.787x + \frac{16}{116} & x \le 0.008856 \end{cases}$$

X_n, Y_n, Z_n – CIEXYZ values of a perfectly reflecting diffuser under the illuminant space desired. For ICC purposes, this illuminant is D50.

2. Computation of Absolute CIELAB ($CIELAB_{D50}$) coordinates from Media-relative CIELAB coordinates ($CIELAB_{Media\text{-}Relative}$)

2.1 Conversion from $CIELAB_{Media\text{-}Relative}$ to $CIEXYZ_{Media\text{-}Relative}$.

Procedure is similar to inversion of (1) except that the normalizing values are derived from CIEXYZ values of media-white rather than the perfect reflecting diffuser.

$$X_{Media-Relative} = X_{Media-White} f^{-1}(fx)$$

$$Y_{Media-Relative} = Y_{Media-White} f^{-1}(fx)$$

$$Z_{Media-Relative} = Z_{Media-White} f^{-1}(fz)$$

$$f_x = \frac{a^*_{Media-Relative}}{500} + f_y$$

$$f_y = \frac{L^*_{Media-Relative} + 16}{116}$$

$$f_z = f_y - \frac{b^*}{200}$$

$$f^{-1}(t) = \begin{cases} t^3 & t > 0.206893 \\ 1/7.787(t - \frac{16}{116}) & 0 \le t \le 0.206893 \end{cases}$$

2. 2 Conversion from CIEXYZ $_{Media\text{-}Relative}$. to CIEXYZ $_{Absolute}$

$$X_{Absolute} = (\frac{X_{Media-White}}{X_{D50}})X_{Media-Relative}$$

$$Y_{Absolute} = (\frac{Y_{Media-White}}{Y_{D50}})Y_{Media-Relative}$$

$$Z_{Absolute} = (\frac{Z_{Media-White}}{Z_{D50}})Z_{Media-Relative}$$

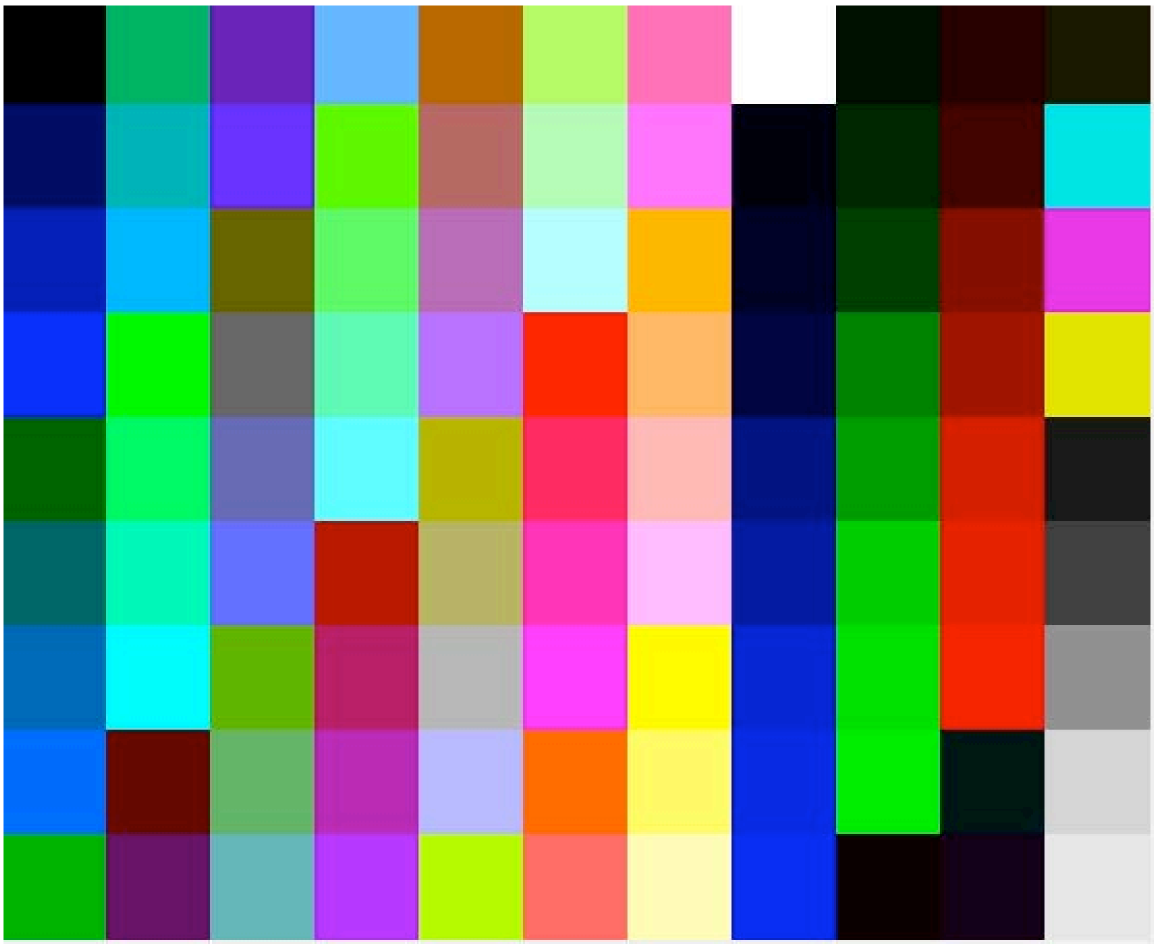
2.3 Conversion from CIEXYZ $_{Absolute}$ to CIELAB $_{Absolute}$

Same as 1, replace X, Y, Z, by $X_{Absolute}$, $Y_{Absolute}$, $Z_{Absolute}$
X_n, Y_n, Z_n by X_{D50}, Y_{D50},, Z_{D50}

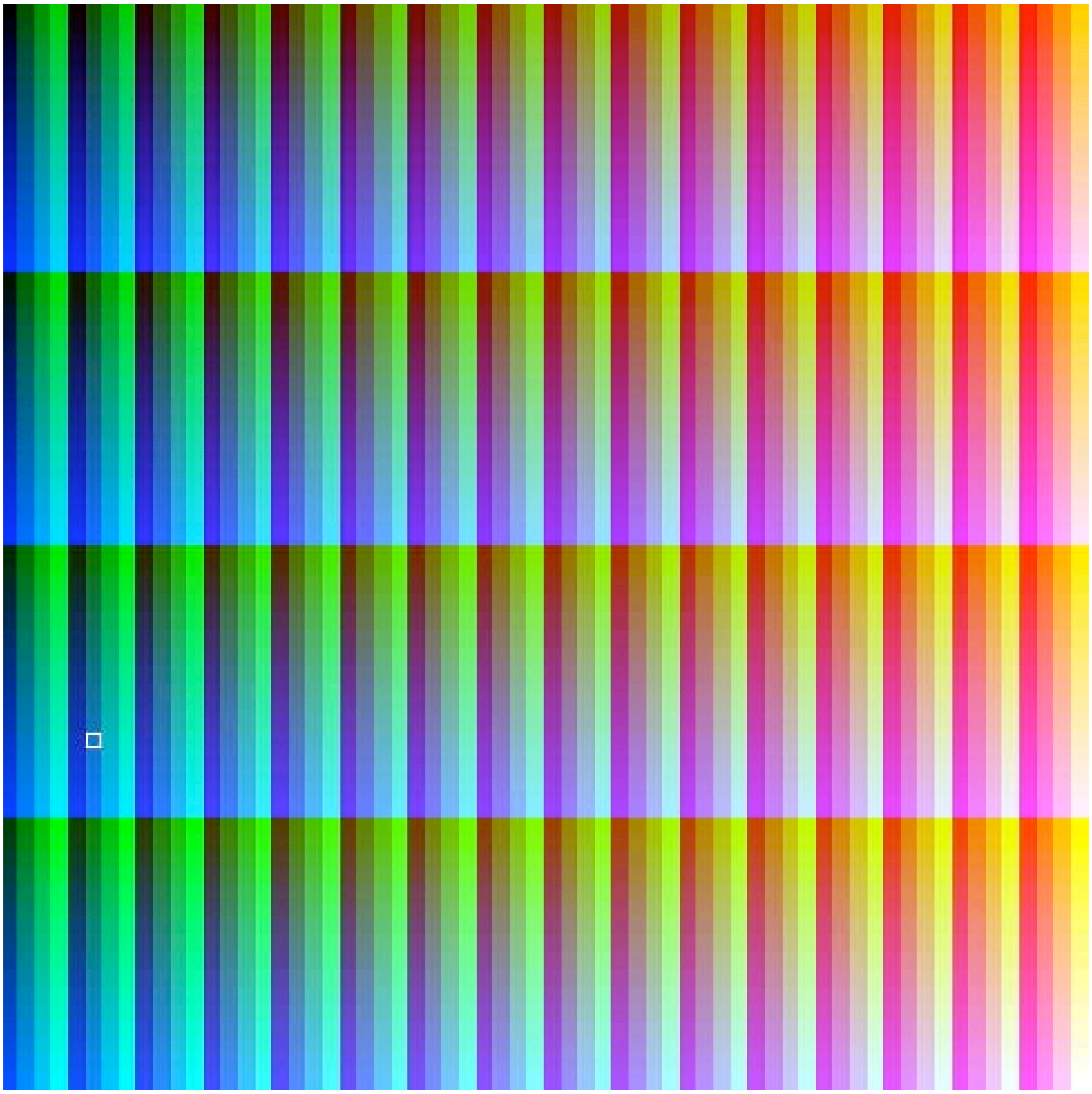
Appendix II.

LCD Test Charts:

LCD 99 colors chart.

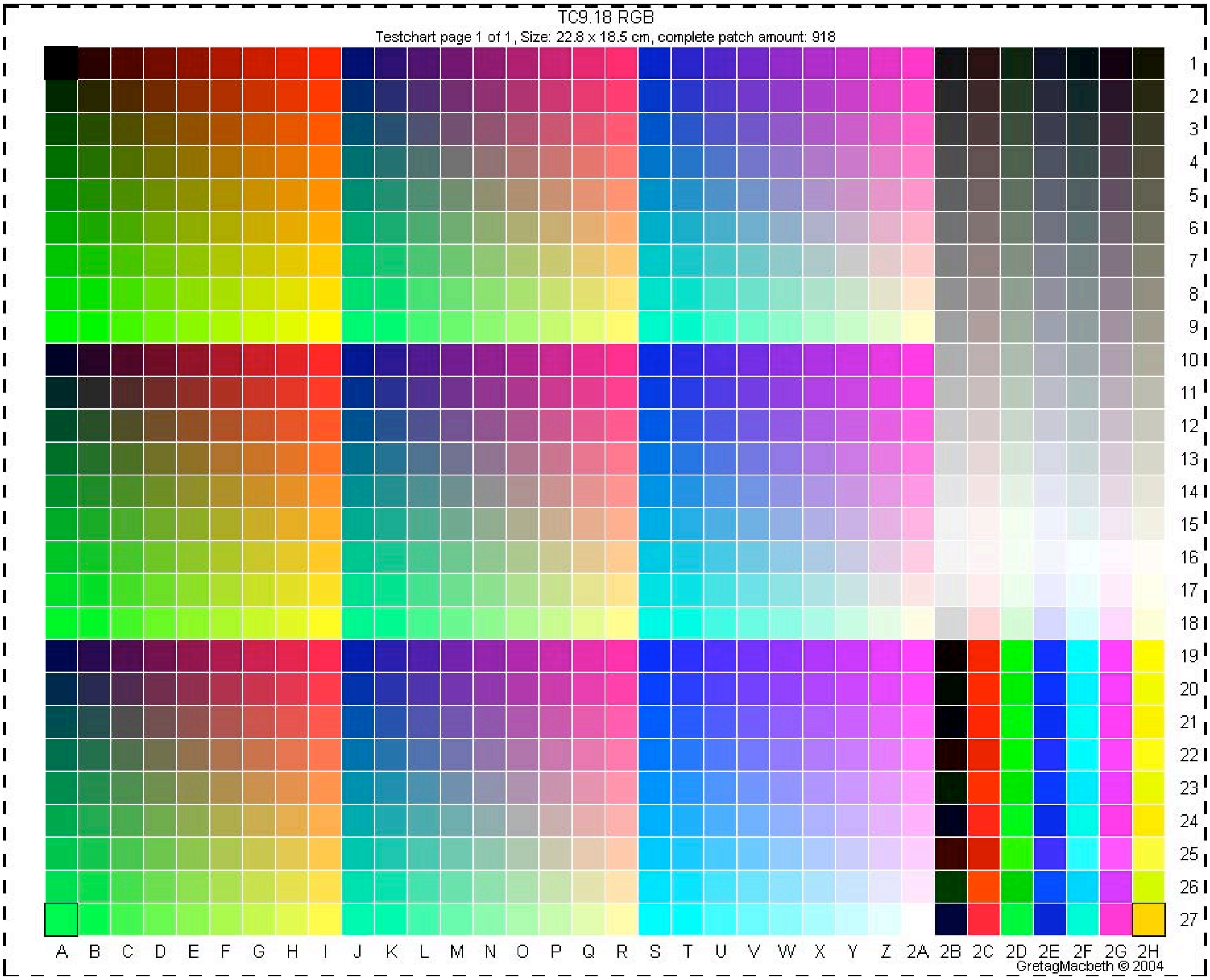


LCD 4096 colors chart.

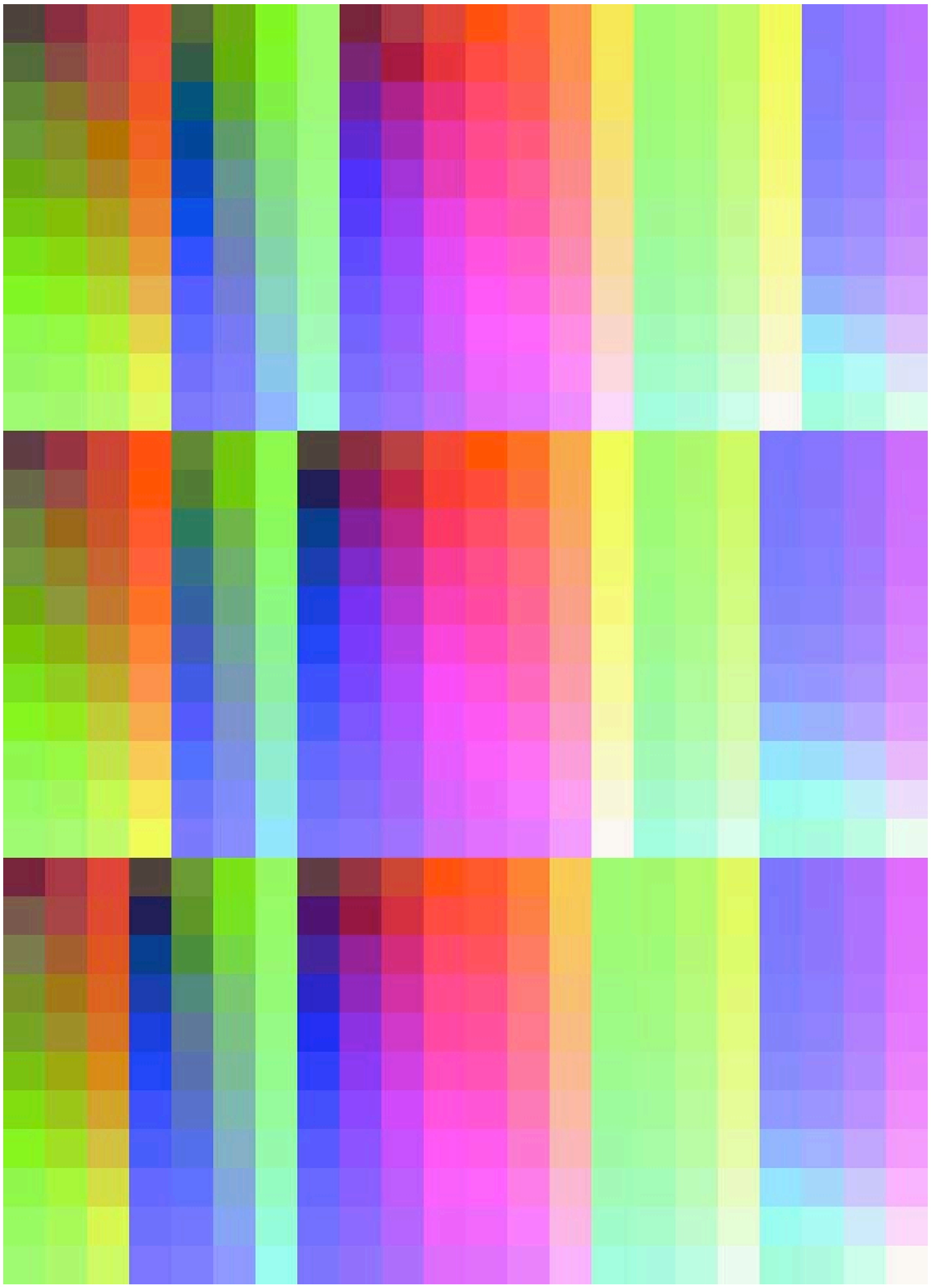


Printer Test Charts:

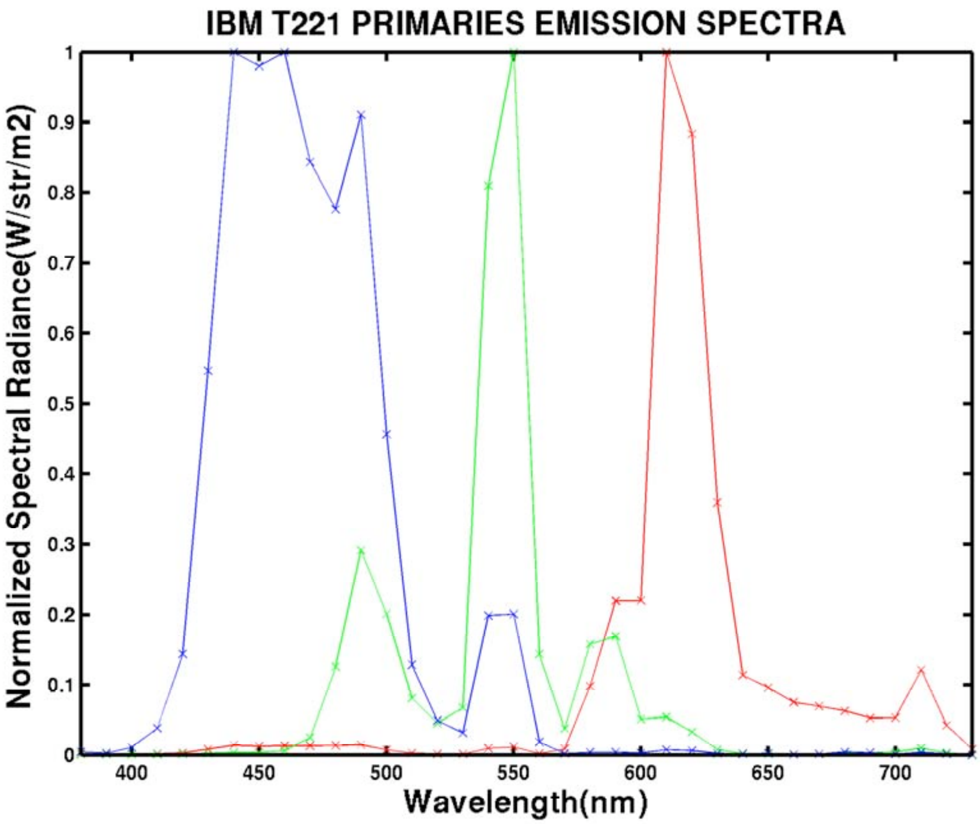
TC-918 RGB Characterization Chart.



The sRGB Test Chart. (Also used to verify the temporal stability of the printer)



Appendix III.
IBM T221 Primaries Emission Spectra.



IBM T221 LCD display primaries normalized radiance spectra. The spectra were measured using the Gretag Macbeth Eye-One instrument in radiometric mode.