Color Management of DLP™ Projectors

David R. Wyble and Mitchell R. Rosen
Munsell Color Science Laboratory, Rochester Institute of Technology
Rochester New York, USA

Introduction

Data projectors are often used in demanding imaging applications requiring accurate color. To properly control the color output of such a device, one needs accurate color control models. This paper will describe a color management algorithm for a four-color DLP projector.

Four-channel color displays have only recently been introduced to the market. The displays being examined in this paper have the traditional red, green and blue channels and also a supplemental white channel. In parallel to the four-color printer problem, a fourth channel in a display creates a color reproduction challenge since one XYZ can potentially be mapped to many RGBW combinations. A further complication of these projectors is that at the computer interface they are treated as RGB displays. The conversion from RGB to RGBW takes place internally making them at once compatible with current RGB display signals and yet unfriendly to simple color management approaches.

The characterization of a display forms the foundation of a mapping from device digital coordinates to colorimetry. This is referred to as the "forward model." A common method for characterizing typical RGB color displays starts with three one-dimensional input look-up tables (LUTs) for linearizing the digital input signals with respect to tristimulus values (XYZ). This is followed by a 3x3 matrix for scalar rotation, completing the transformation to tristimulus space. Extending this model to a four-channel display is straightforward: the fourth channel needs its own linearization LUT and the rotation matrix becomes a 3x4. If the RGBW channels of these projectors were all directly controllable, then this would represent the forward model. Unfortunately, the computer can only present RGB digital coordinates that are internally converted to RGBW. Thus, the forward model must include the conversion from RGB to RGBW.

To complete the color management of a projector, an inverse model is needed to convert from colorimetry back to device digital coordinates. For these displays, such a model will need to solve both the one-to-many problem of XYZ to RGBW as well as the transformation from RGBW back to RGB. For the balance of this paper, a description of the data collection and a review of the forward model are followed by derivation and use of the inverse model.

There are several published efforts regarding the use and characterization of projection displays. Some of these papers have described characterizations of LCD-based projectors.[1,2] Stone[3] has performed studies on the details of implementing multiple-projector systems. Much theoretical research has been done on the design and modeling of DLP systems.[4-6] A forward characterization model was demonstrated.[7] The current paper, describing the derivation and implementation of the inverse model, completes the picture of DLP color management.

Characterization Measurements

An Optoma EzPro 755 was used for the majority of the exercises described in this article. This projector has a 1024x768 pixel DLP imaging array, and has an output of 2000 ANSI lumens. The video signal was generated through a standard Macintosh G4 Powerbook computer XVGA video output. The measurement device was a LMT C1210 colorimeter. We placed the C1210 in the center of the field approximately two meters from the projector. All images were uniform over the entire field, and were displayed for about 5 seconds prior to measurement. This time was sufficient for both the projector and measurement device to stabilize at the given setting.

The brightness and contrast controls of the projector were adjusted to eliminate any clipping at low or high levels. This is required if the forward model LUTs are to be inverted without any additional processing. If, for other reasons, projector settings were desired that imposed clipping, the ramp data need to be adjusted to a monotonic form before inverting.

Characterization results on the primary projector were consistent with those of a second DLP-based projector described below and with projectors characterized in previous work.[7] RGBW configuration is found in DLP projectors produced for office or lecture room use whereas the digital cinema line of DLP projectors are based on an RGB color rendering approach. The latter technology is not covered by this discussion.

The Forward Model

The forward model accepts RGB digital input coordinates and predicts the output color XYZ produced by the projector. The forward model is identical to one previously reported;[7] this model can be summarized in equations 1 and 2:

$$
\begin{aligned}
R' &= rLUT(R),\\
G' &= gLUT(G),\\
B' &= bLUT(B),\\
W' &= wLUT\{\min(R,G,B)\},
\end{aligned}
\tag{1}
$$

$$C_{out} = MC_{in} \tag{2}$$

where C_{out} is the output color XYZ, C_{in} are the linearized scalars, R', G', B, and W'; M is the 3x4 rotation matrix plus a dark correction making it 3x5. M is derived as:

$$
M = \begin{bmatrix} X_R^c & X_G^c & X_B^c & X_W^c & X_K \\ Y_R^c & Y_R^c & Y_R^c & Y_W^c & Y_K \\ Z_R^c & Z_R^c & Z_R^c & Z_W^c & Z_K \end{bmatrix} \tag{3}
$$

where X,Y, and Z are measured tristimulus values and the subscripts R, G, B, W, and K are for full red, full green, full blue, full white, and black (residual light when R=G=B=0), respectively. 'C' superscript indicates that dark correction has been applied; the calculation for dark corrected XYZ values is shown in equation 4 for the red primary.

$$
\begin{bmatrix} X_R^c \\ Y_R^c \\ Z_R^c \end{bmatrix} = \begin{bmatrix} X_R - X_K \\ Y_R - Y_K \\ Z_R - Z_K \end{bmatrix} \tag{4}
$$

Equation 5 shows the calculation of the dark corrected white column. It is the difference between the sum of the dark-corrected tristimulus values of the full red, green, and blue primaries and the dark corrected measured light when all three on are simultaneously on full (R=G=B=255):

$$
\begin{bmatrix} X_W^c \\ Y_W^c \\ Z_W^c \end{bmatrix} = \begin{bmatrix} X_{255,255,255}^c - \left(X_R^c + X_G^c + X_B^c\right) \\ Y_{255,255,255}^c - \left(Y_R^c + Y_G^c + Y_B^c\right) \\ Z_{255,255,255}^c - \left(Z_R^c + Z_G^c + Z_B^c\right) \end{bmatrix} \tag{5}
$$

The four LUTs are shown in Fig. 1. They are derived from the measured XYZ data. R, G, and B LUTs are normalized values of the X, Y, and Z values, respectively, of the R, G, and B ramps. The white LUT must account for that part of the color that exceeds what the combined RGB separations would produce. Therefore, first subtract the Y values of the red, green, and blue ramps from the Y values of the white ramp. The result is clipped at zero to remove negative components and then normalized to create the white LUT. The multiple subtractions may result in a somewhat noisy signal. For our example projector the final white LUT was smoothed with a polynomial to maintain a monotonic relationship. The R, G, and B LUTs were similarly smoothed.

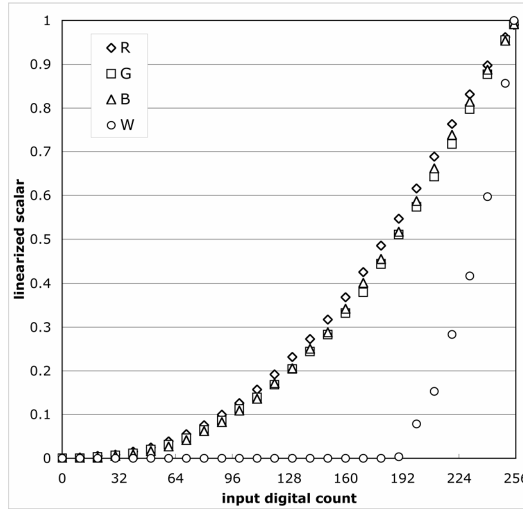

Figure 1. Forward model lookup tables.

As seen in Fig. 1, the RGB to RGBW transformation built into this system results in no White approximately 75% of the range.

The Inverse Model

When color managing a display as an output device, the inverse model is required. The inverse model accepts a color request, here in tristimulus values XYZ, and predicts the input RGB coordinates which, when projected, results in the requested color.

The following steps describe use of the inverse model. First, transform the XYZ request into theoretical RGB values. These are theoretical because they sometimes exceed unity. Since we are not yet considering any white addition, the predicted R, G, and B scalars may be greater than one to account for the fact that many of the measured patches are made up of red, green, blue and white primaries. This transformation is through a new rotation matrix M_2, the inverse of the leftmost three columns of the matrix M:

$$
\begin{bmatrix} R \\ G \\ B \end{bmatrix}_{theo} = M_2 \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_{request} \tag{6}
$$

$$
M_2 = \begin{bmatrix} X_R^c & X_G^c & X_B^c \\ Y_R^c & Y_G^c & Y_B^c \\ Z_R^c & Z_G^c & Z_B^c \end{bmatrix}^{-1} \tag{7}
$$

We now choose the white scalar W' as the minimum of the theoretical RGB values. This scalar is shaped by $wLUT_j$ ("*w*hite LUT"), described below, resulting in a new scalar W applied to the XYZ values of the white separation. This estimates the amount of the requested XYZ values that can be accounted for using a W amount of white. This white contribution is subtracted from the requested XYZ values. If the prediction of W is accurate, the residual XYZ after removing the white component can be produced using only RGB separations. Therefore we predict RGB coordinates by applying M_2 to the remaining XYZ values. Mathematically, these steps are summarized as:

$$W' = \min\left\{\begin{bmatrix} R \\ G \\ B \end{bmatrix}_{theo}\right\} \quad (8)$$

$$W = wLUT_j\left(W'\right) \quad (9)$$

$$\begin{bmatrix} R \\ G \\ B \end{bmatrix}_{pre-LUT} = M_2\left(\begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_{request} - W\begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_{white}\right) \quad (10)$$

$$\begin{bmatrix} R \\ G \\ B \end{bmatrix}_{final} = iLUT_j\left(\begin{bmatrix} R \\ G \\ B \end{bmatrix}_{pre-LUT}\right) \quad (11)$$

There are three instances of $wLUT_j$, j=R,G,B. The instance is selected according to which of R,G,B is the minimum. The three LUTs $iLUT_j$ (j=R,G,B) are the inverses of the LUTs used in the forward model.

Determining $wLUT_j$

The most interesting part of the inverse model process is the creation of the set of LUTs to predict the white contribution, which depends on the minimum of the theoretical RGB values. The three forms, for R,G, and B, are created identically. What follows is the method for creating the red instance.

1. Select *r* from 0...255
2. Run the RGB triplet (*r*,255,255) through the forward model, yielding XYZ_{pred}
3. Rotate the predicted color through M_2 to yield theoretical RGB values.
4. Repeat steps 1-3 until r=255.
5. Construct $wLUT_r$ using R_{theo} as the input and *r* as the output.

The input to $wLUT_r$ is the theoretical red scalar value, assuming red is the minimum of the RGB theoretical values. This value will be floating point, and must therefore be interpolated. The three $wLUT_j$ are shown in Figure 2. These look as we would expect; the white scalar is zero until the minimum of red, green, and blue exceeds a threshold level.

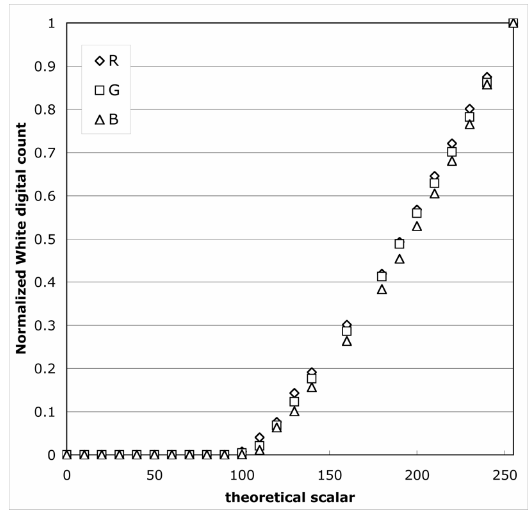

Figure 2. Inverse LUTs

Experimental Results

Testing the Forward Model

A matrix of 10x10x10 RGB coordinates was projected and measured as test data. These RGB coordinates were then processed through the forward model and the color differences between the measured tristimulus values and those predicted by the model were calculated using ΔE^*_{94}. The CIELAB values were calculated using the whitepoint of the projector. Colorimetric statistics for this and all subsequent experiments are listed in Table 1. The histogram of the complete results is shown in Figure 3. We believe this performance to be sufficient for most applications where a reasonable level of color control is necessary.

Testing the Inverse Model

The inverse model was verified in three steps. The first step is theoretical only. We predicted RGB coordinates for the 1000 measured test data points by processing the measured XYZ values through the inverse model. These predicted RGB coordinates were then processed through the forward model. The resulting XYZ values were compared to the measured data. A histogram of the results is in Figure 4. The color differences are very low, as one would expect if the inverse model were in fact a working inverse of the forward model.

The second step is also theoretical. We created a set of random XYZ values. These were processed identically as the measured values in the preceding paragraph. Color difference was calculated between predicted XYZ values and the input random XYZ values. A histogram of these results is shown in Figure 5. The input data were mostly in-gamut, but a few of the larger errors are likely due to out of gamut colors.

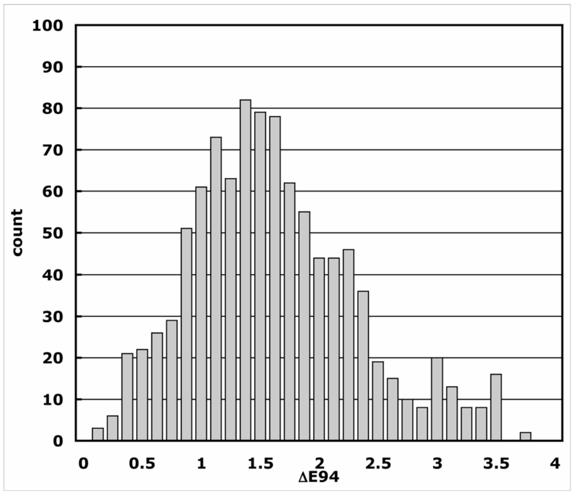

Figure 3. Forward model colorimetric performance.

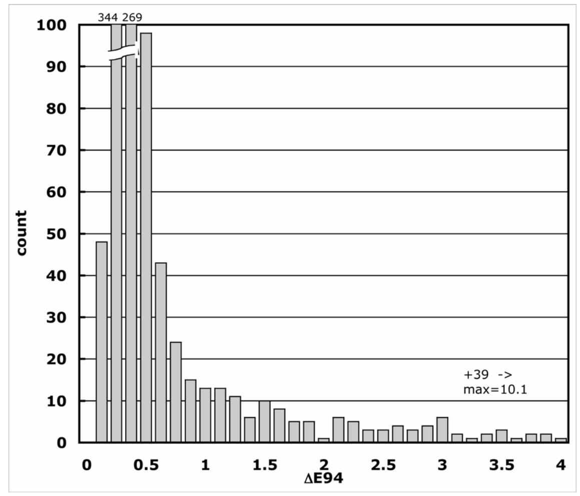

Figure 5. Color difference results for inverse model, step 2.

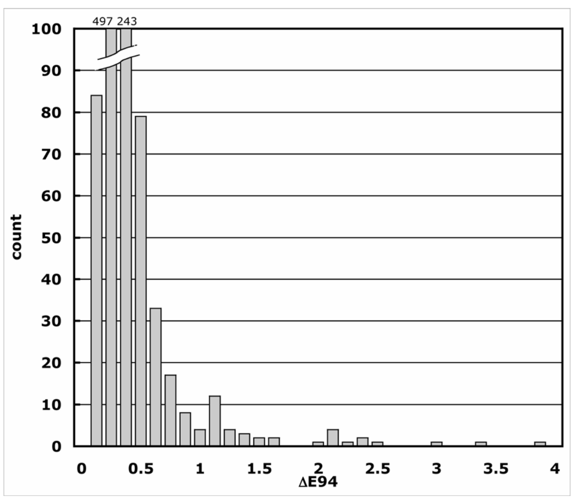

Figure 4. Color difference results for inverse model, step 1.

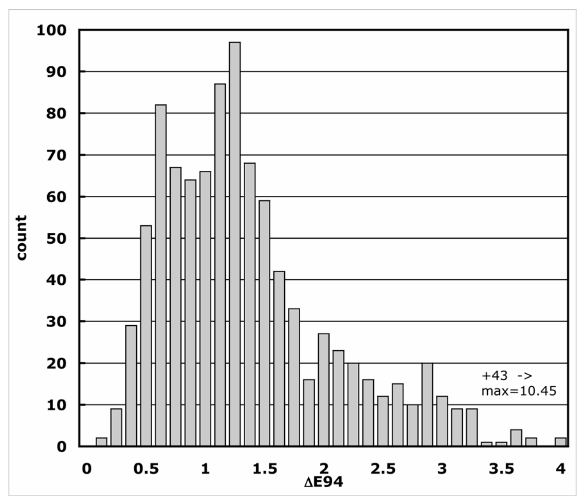

Figure 6. Color difference results for inverse model, step 3.

The third step is the most rigorous. Here same set of random XYZ values were processed through the inverse model, and these predicted RGB values were displayed and measured. Color difference was calculated between measured XYZ values and the input random XYZ values. A histogram is shown in Figure 6.

Two additional tests were performed to help determine the general usefulness of this model. First, the measurements for the Optoma projector from two sessions taken seven months apart were compared. The results show that a single projector can perform reasonably well over time. Second, a second DLP projector, an InFocus LP650, was similarly characterized. The model predicted LP650 performance as well as the Optoma. Table 1 summarizes the complete set of experiments described above.

Table 1. Colorimetric Testing Results

Test	Mean ΔE_{94}	Max ΔE_{94}
Forward model	1.56	3.71
Inverse step 1	0.30	3.75
Inverse step 2	0.71	10.09
Inverse step 3	1.49	10.45
Forward model (February ‘04)	1.0	3.7
InFocus LP650	0.51	4.17

Discussion

One known problem with the forward model is the handling of white addition in the midtones. The subtraction used to create the white LUT results in non-negligible negative values in the range of 100-190 digital counts, shown in Figure 7. The behavior implies that some white is being added at lower digital counts, perhaps in place of some quantity of one or more other separations. Clearly the engineers of this projector designed a more complex, possibly three-dimensional, white addition strategy that is not fully accounted for using the simple model implemented here.

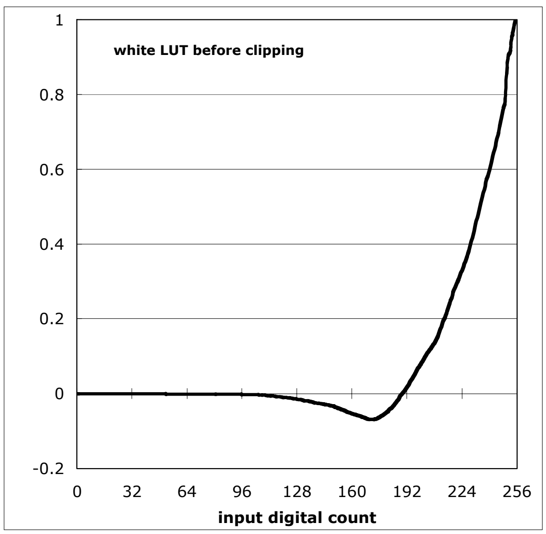

Figure 7. White forward lookup table before clipping.

Conclusion

We have presented working forward and inverse color management models for DLP-based data projectors. The inversion of a previously reported forward model has been shown to work well. The inverse model demonstrates that complete color control can be accomplished accurately enough for many applications. The inverse model is not difficult to derive, and requires no additional measurements over the forward model.

In the future, we hope to address the known shortfall in the white scalar calculation. This will likely create a more complex model, possibly with three-dimensional relationships between input RGB values and RGBW scalars. Even with the presumed increased accuracy of an improved model, users may find the current simpler form satisfactory for their needs.

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Biography

David Wyble received his B.S. degree in Computer Science from the SUNY Brockport in 1992 and M.S. in Color Science from Rochester Institute of Technology in 1998. Since 1997 he has worked as a staff scientist in the Munsell Color Science Laboratory at RIT. His research interests are in color measurement and device characterization. He is a member of the IS&T and active in the Inter-Society Color Council and the Council of Optical Radiation Measurements.