The PLVC Display Color Characterization Model Revisited

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Abstract: This work proposes a study of the Piecewise Linear assuming Variation in Chromaticity (PLVC) display color characterization model. This model has not been widely used as the improved accuracy compared with the more common PLCC (Piecewise Linear assuming Chromaticity Constancy) model is not significant for CRT (Cathode Ray Tube) display technology, and it requires more computing power than this model. With today's computers, computational complexity is less of a problem, and today's display technologies show a different colorimetric behavior than CRTs. The main contribution of this work is to generalize the PLVC model to multiprimary displays and to provide extensive experimental results and analysis for today's display technologies. We confirm and extend the results found in the literature and compare this model with classical PLCC and Gain-Offset-Gamma-Offset models. We show that using this model is highly beneficial for Liquid Crystal Displays, reducing the average error about a third for the two tested LCD projectors compared with a black corrected PLCC model, from 3.93 and 1.78 to respectively 1.41 and 0.54 ΔE^*_{ab} units. © 2008 Wiley Periodicals, Inc. Col Res Appl, 33, 449–460, 2008; Published online in Wiley InterScience (www.interscience.wiley.com). DOI 10.1002/col.20447

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INTRODUCTION

Color characterization of a display color device is a major issue for the accurate color rendering of a scene on a display device. It aims to define the transformation between the device color space, typically RGB, and an independent color space, describing the perceived color, based on the CIE standard observer, typically CIEXYZ or CIELAB.[1] This transformation has two directions. The forward transformation aims to predict the displayed color for any set of digital values input to the device, i.e., a triplet (d_r,d_g,d_b). The inverse transformation provides the set of digital values to input to the display in order to display a desired color. Note that a calibration process precedes the characterization. This step aims to establish the settings (contrast, brightness, correlated color temperature . . .) of the display.

For some applications the color characterization model has to be as precise as possible. However, a compromise between the amount of experimental data needed to build a model and the accuracy needed by the application typically has to be found. Indeed, for some uses, the number of measurements has to be limited either because of the conditions of use or because of the number of transformations that has to be set up. The latter is particularly true for projectors and for multidisplay systems, where one may have to perform an accurate characterization for each display and at several positions of the display to compensate for spatial nonuniformity.[2]

Many color characterization methods or models exist, here we can classify them in three groups. In a first one, we find the models that tend to model physically the color response of the device. They are often based on the assumption of independence between channels and of chromaticity constancy of primaries. Then, a combination of the primary chromaticities weighted by the luminance response of the display relative to a digital input can be used to perform the colorimetric transform. The second group can be called numerical models. They are based on a training data set which permits optimization of the parameters of a polynomial function to establish the transform. The last category consists of 3D Look Up Table (LUT) based models.

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The models in the last group are based on the measurement of a defined number of color patches, i.e., we know the transformation between RGB and CIELAB in a small number of color space locations. Then this transformation is generalized to the whole space by interpolation. Studies assess that these methods achieve good results,[3,4] depending on the combination of the interpolation method used,[5–9] the number of patches measured, and on their distribution[4] (some of the interpolation methods cited above cannot be used with a nonregular distribution). However, to be precise enough, a lot of measurements are typically required, i.e., a 10 × 10 × 10 grid of patches measured in Bastani's article.[3] Note that such a model is technology independent as no assumptions are made about the device but that the display will always have the same response at the measurement location. Such a model needs high storage capacity and computational power to handle the 3D data. The computational power is usually not a problem because Graphic Processor Units (GPU) can perform this kind of task easily today. The high number of measurement needed is a greater challenge.

The numerical models suppose that the transform can be approximated by a set of equations, usually an *n*-order polynomial function. The parameters are retrieved using an *n*-order polynomial regression process based on measurements. The number of parameters required involve a significant number of measurements, depending on the order of the polynomial function.[10] The advantage of these models is that they take into account channel interdependence by applying cross components factors in the establishment of the function.[11–13] More recently, good results for an alternative method have been reached by Wen and Wu[14] who removed the three-channel crosstalk, considering that the interchannel dependence is only due to two-channel crosstalk from the model, thus reducing the required number of measurements.

Physical models are historically the most used for displays, as the CRT technology follows well the assumptions cited above.[15,16] Such a model typically first aims to linearize the intensity response of the device. This can be done by establishing of a model that assumes that the response curve follows a mathematical function, such as a gamma law for CRT,[16–19] or a S-shaped curve for LCD.[20–22] Another way to linearize the intensity response curve is to generalize measurements by interpolation along the luminance for each primary.[23] The measurement of the luminance can be done using a photometer. Some approaches propose as well a visual reponse curve estimation, where the 50% luminance point for each channel is determined by the user to estimate the gamma value.[17] This method can be generalized to the retrieval of more luminance levels in using halftoned patches.[24,25] Recently, a method to retrieve the response curve of a projection device using an uncalibrated camera has been proposed by Bala *et al.*[26,27] and extended by Mikalsen *et al.*[25]

The second step of these models is commonly the use of a 3 × 3 matrix containing primary chromaticities to build the colorimetric transform from luminance to an additive independent color space. The primary chromaticities can be estimated by measurement of the device primaries at full intensity, using a colorimeter or a spectroradiometer, assuming their chromaticity constancy. In practice this assumption does not hold perfectly, and the model accuracy suffers from that. The major part of the nonconstancy of primaries can be corrected by applying a black offset correction.[28] Some authors tried to minimize the chromaticity nonconstancy in finding the best chromaticity values of primaries (optimizing the components of the 3 × 3 matrix).[29] Depending of the accuracy required, it is also possible to use generic primaries such as sRGB for some applications[26,27] or data supplied by the manufacturer.[17]

However, the use of a simple 3 × 3 matrix for the colorimetric transform leads to inaccuracy because of the lack of channel independence and of chromaticity constancy of primaries. An alternative approach has been derived in the masking model and modified masking model which take into account the cross-talk between channels.[13]

Furthermore, the lack of chromaticity constancy can be critical, particularly for LCD technology, which has been shown to fail this assumption.[21,30] Then a model that is not subject to this effect should be used. In 1989, Post and Calhoun[23] demonstrated that among the models they tested in that article, the Piecewise Linear assuming Variation in Chromaticity (PLVC) and the Piecewise Linear assuming Chromaticity Constancy (PLCC) models were the most accurate. The former one takes into account the chromaticity shift of primaries.

From a study of recent display characterization litterature, it appears that the PLVC model is not well known. It has been studied only for CRT technology (as far as we know) and as the chromaticity shift of primaries is not critical for this technology, it was not necessary to use it,[23,31] especially after flare correction.[28] For today's display technologies such as LCD or DLP, we found no studies involving the PLVC model. A previous work[32] we have done has suggested that this model can give better results in color prediction on liquid crystal technology, for the same amount of measurements, than some classical matrix based methods.

We revisit the PLVC model through this article, providing full history and citations, detailed results, and analysis on several display technologies, and we show that it could be beneficial to use this model particularly for LC technology. In the next sections, we first review and discuss some major issues of classical 3 × 3 matrix-based models such as the Gain-Offset-Gamma-Offset (GOGO) and PLCC models, related to device properties. We then give a detailed presentation of the PLVC model, and show how it could yield a better compromise between the accuracy, the assumptions made and its computational complexity. Our study is sustained by experimental results on six displays that are presented thereafter and compared with classical models for the same amount of measurements. The results analysis is based on visualizations and statistics.

DISPLAY COLOR CHARACTERIZATION

Historically and for practical reasons, physical models have been widely used for display color characterization, especially the gamma-based models and the PLCC model. They are easily invertible, do not require a lot of measurements, require a little computer memory, and do not require high computing power, and so they can be used in real time. Moreover, the assumptions of channel independence and chromaticity constancy are appropriate for the CRT technology. However, these assumptions and the others made, such as spatial uniformity, both in luminance and in chromaticity, angle view independence, etc., do not fit so well with some of today's display technologies. Making such assumptions can reduce drastically the accuracy of the characterization. For instance, a review of problems faced in LC displays has been done by Yoshida and Yamamoto.[20]

In the same time the computing power has become less and less a problem. Some models not used in practice because of their complexity can now be highly beneficial for display color characterization. This section provides definition, analysis, and discussion about popular physical models and shift toward the definition of the PLVC which permits to compensate for the lack of chromaticity constancy.

Classical Physical Models

In 1983, Cowen[17] wrote what is considered to be the pioneer article in the area of physical models for display characterization. In this work, the author stated that a power function can be used, but is not the best to fit with the luminance response curve of a CRT device. Nevertheless, the well known "gamma" model, which considers a power function to approximate the luminance response curve of a CRT display is currently widely used.

Whichever shape the model takes, the principle remains the same. First, it estimates the luminance response of the device for each channel, using a set of functions such as Eq. (1). This step is followed by a colorimetric transform.

We review here two types of models, the first are based on the power function for CRT devices, which are still the most used, even if it has been shown that they do not fit well LC technology,[33] and the PLCC model, as its good accuracy has been demonstrated.[23] We do not try to ignore that for other technologies than CRT, there is no reason to try to fit the device response with a gamma curve, especially for LCD technology which shows a S-shape response curve in most cases (Fig. 1), but it is still the model which is often used, mainly because it is easy to estimate the response curve with a few number of measurements, or in using a visual matching pattern.

The response in luminance for a set of digital values input to the device can be expressed as follows:

$$\begin{aligned} R &= f_r(D_r) \\ G &= f_g(D_g) \\ B &= f_b(D_b), \end{aligned} \tag{1}$$

where f_r, f_g, and f_b are functions which gives the R, G, and B contribution in luminance of each primary independently for a digital input D_r, D_g, D_b. Note that for CRT devices, after normalization of the luminance and digital value, the function can be the same for each channel. This assumption is not valid for LCD technology[34] and only a rough approximation for DLP based projection systems, as seen for instance in the work of Seime and Hardeberg.[35]

For a CRT this function can be expressed as:

$$H = (a_h \cdot d_h + b_h)^{\gamma_h}, \tag{2}$$

where $H \in \{R, G, B\}$ is the equivalent luminance from a channel $h \in \{r, g, b\}$ for a normalized digital input d_h, with $d_h = \frac{D_h}{2^n - 1}$. D_h is the digital value input to a channel h and n is the number of bits to encode the information for this channel. a_h is the gain and b_h is the internal offset for this channel. These parameters are estimated empirically using a regression process.

This model is called Gain-Offset-Gamma (GOG).[12,36,37] If we make the assumption that there is no internal offset and no gain, $a = 1$ and $b = 0$, it becomes the simple "gamma" model.

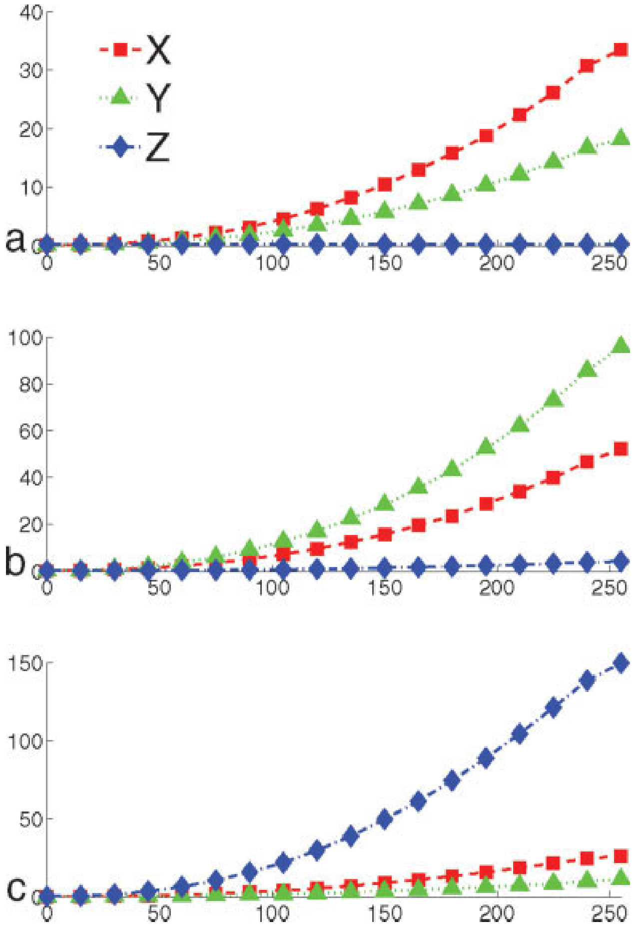

FIG. 1. Response curve in X, Y, and Z for display PLCD1 for respectively the red (a), green (b), and blue (c) channel. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

Note that for gamma-based models, it has been shown that a second order function with two parameters such as $Log(H) = b_h \times Log(d_h) + c_h \times (Log(d_h))^2$ gives better results[17] and that two gamma curves should be combined for a better accuracy in low luminances.[38]

For the PLCC model, the function f is approximated by a piecewise linear interpolation between the measurements. The approximation is valid for a large enough amount of measurements (16 measurements per channel in the Post and Calhoun article[23]). This model is particularly useful when no information is available about the shape of the display luminance response curve.

Then a colorimetric transform is performed from the (R,G,B) "linearized" luminances to the XYZ color tristimulus.

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} X_{r,\max} & X_{g,\max} & X_{b,\max} \\ Y_{r,\max} & Y_{g,\max} & Y_{b,\max} \\ Z_{r,\max} & Z_{g,\max} & Z_{b,\max} \end{bmatrix} \times \begin{bmatrix} R \\ G \\ B \end{bmatrix} \tag{3}$$

where the matrix components are the chromaticities of each primary, measured at their maximum intensity.

Using such a matrix for the colorimetric transform supposes perfect additivity and chromaticity constancy of primaries. These assumptions have been shown to be acceptable for CRT technology.[15,39]

The channel interdependence can happen in CRT technology due to an insufficient power supply and an inaccuracy of the laser beams which meet inaccurately the phosphors.[11] In LC technology, it comes from the overlapping of the spectral distribution of primaries (the color filters), and from the interferences between the capacities of two neighboring subpixels.[20,35] In DLP-DMD projection devices, there is still some overlapping between primaries and inaccuracy at the level of the DMD mirrors.

Considering the assumption of chromaticity constancy, it appears that when there is a flare,[11] either a black offset (internal flare) or an ambient flare (external flare), added to the signal, the assumption of chromaticity constancy is not valid anymore. Indeed, the flare is added to the output signal and the lower the luminance level of the primaries; the more the flare is a significant fraction of the resulting stimulus. This leads to a hue shift toward the black offset chromaticity. Often the flare has a "gray" (nearly achromatic) chromaticity, thus the chromaticities of the primaries shift to a "gray" chromaticity (Fig. 2, left part). Note that the flare "gray" chromaticity does not necessarily correspond to the achromatic point of the device (Fig. 2). In fact, in the tested LCD devices [Figs. 2(a),2(b),2(e), and 2(f)] we can notice the same effect as in the work of Marcu *et al*.,[40] the black level chromaticity is bluish because of the poor filtering power of the blue filter in the low wavelength.

In this study, the flare is taken all at once as the measured light for an input $(d_{r,k},d_{g,k},d_{b,k}) = (0,0,0)$ to the device. Then it includes ambient and internal flare.

The ambient flare comes from any light source reflecting on the display screen. If the viewing conditions do not change it remains constant, can be measured and

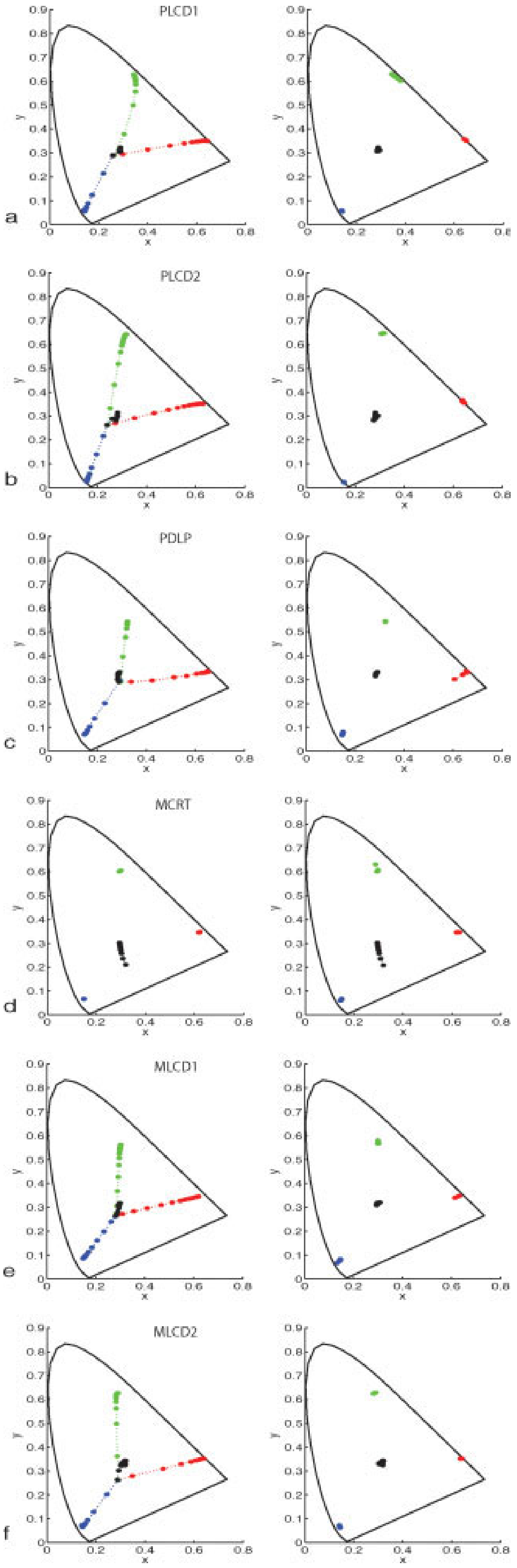

FIG. 2. Chromaticity tracking of primaries with variation of intensity. The left part of the figure show it without black correction; on the right, one can see the result, with a black correction performed. All tested devices are shown. (a) PLCD1, (b) PLCD2, (c) PDLP, (d) MCRT, (e) MLCD1, and (f) MLCD2. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

taken into account, or can be simply removed in setting up a dark surrounding (note that for a projection device, there is always an amount of light which lights the room, coming from the bulb through the ventilation hole).

The internal flare, which is the major part of chromaticity inconstancy at least in CRT technology,[11] is coming from the black level. In CRT technology, it has been shown that in setting the brightness to a high level, the black level increases to a non-negligible value.[11] For LC technology, the panel let an amount of light passing through due to a leakage of the crystal to stop all the light. In DLP technology, an amount of light can be not absorbed by the "black absorption box" and is focalized on the screen via the lens.

On Fig. 2, one can see the chromaticity shift to the flare chromaticity with the decreasing of the input level. We have performed these measurements in a dark room, then the ambient flare is minimized, and only the black level remains. After black level subtraction, the chromaticity is more constant (Fig. 2), and a new model can be setup in taking that into account.[2,11,12,28]

The models reviewed above have been extended in adding an offset term. Then the GOG can become a Gain-Offset-Gamma-Offset (GOGO) model.[11,12,41]

The previous Eq. (1) becomes:

$$H = (a_h \cdot d_h + b_h)^{\gamma_h} + c, \tag{4}$$

where c is a term containing all the different flares in presence. If we consider the internal offset b_h as null, the model becomes Gain-Gamma-Offset (GGO).[41]

A similar approach can be used for the PLCC model. When the black correction[28] is performed, we name it PLCC* in the following. The colorimetric transform used then is the Eq. (5), which permits to add the flare back after the colorimetric transformation.

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} X_{r,max} - X_k & X_{g,max} - X_k & X_{b,max} - X_k & X_k \\ Y_{r,max} - Y_k & Y_{g,max} - Y_k & Y_{b,max} - Y_k & Y_k \\ Z_{r,max} - Z_k & Z_{g,max} - Z_k & Z_{b,max} - Z_k & Z_k \end{bmatrix} \times \begin{bmatrix} R \\ G \\ B \\ 1 \end{bmatrix} \tag{5}$$

The A_ks, $A \in \{X, Y, Z\}$, come from a black level estimation.

Such a correction permits to achieve better results. However, on the right part of Fig. 2, one can see that even with the black subtraction, the primary chomaticities do not remain perfectly constant. On the Fig. 2, right-(a), it remains a critical shift especially for the green channel.

Several explanations are involved. First, there is a technology contribution. For LC technology, the transmittance of the cells of the panel changes within the input voltage.[30,42] This leads to a chromaticity shift with the changing of input digital value. For different LC displays, we notice a different shift in chromaticity, this is due to the combination Backlight/LC with the color filters. Because the filters transmittances are optimized taking into account the transmittance shift of the LC cells, the display can achieve good chromaticity constancy. For CRT, there are less problems due to the same phosphors properties, as well for DLP as the light and the filters remain the same.

However, even with the best device, there is still a small amount of nonconstancy. This lead to a discussion about the accuracy of the measured black offset. Indeed, the measurement devices are less accurate in the low luminances and Berns *et al*.[43] proposed a way to estimate the best black offset value. In our study, we did not use their method because we considered that our measurement device (a spectroradiometer Minolta CS-1000) was precise enough, especially for projectors and LCD monitors that show a consequent amount of black level. However, we have averaged three measurements of the black level and increased the acquisition time of the spectroradiometer, to be sure that we have a good estimation of it. A way to overcome the problems linked with remaining inaccuracy for LCD devices has been presented by Day *et al*.[29] It consists in the replacement of the full intensity measurement of primary chromaticities by the optimum chromaticity values in the colorimetric transformation matrix.

It appears that the chromaticity shift is a major issue for LCD. Sharma[34] stated that for LCD devices the assumption of chromaticity constancy was weaker than the channel interdependence. This is a justification for investigating the PLVC in the next section.

Piecewise Linear Model Assumming Variation in Chromaticity

According to Post and Calhoun,[23] the first persons who have introduced the PLVC were Farley and Gutmann[44] in 1980. Note that it preceded the well known article from Cowan.[17] Further studies have been performed afterward on CRT,[23,28,31] and a preliminary study has been done on LC technology.[32] This model does not consider the channel interdependence, but does model the chromaticity shift of the primaries. In this section, we recall the principles of this model and some features that characterize it.

Knowing the tristimulus values of X, Y, and Z for each primary as a function of the digital input, assuming additivity, the resulting color tristimulus values can be expressed as the sum of tristimulus values for each component (i.e., primary) at the given input level. Note that in order not to add several times the black level, we remove it from all measurements used to define the model. Then, it's added to the result, to return to a correct standard observer color space.[28,31] The model is summarized and generalized in Eq. (6) for N primaries, and illustrated in Eq. (7) for a three primaries RGB device, following an equivalent formulation as the one given by Jimenez del Barco *et al*.[28]

For an N primaries device, we consider the digital input to the i^{th} primary, $d_i(m_i)$, with i an integer $\in [0,N]$, and m_i

an integer limited by the resolution of the device (i.e. $m_i \in [0, 255]$ for a channel coded on 8 bits). Then, a color $XYZ(\ldots, d_i(m_i), \ldots)$ can be expressed by:

$$
\begin{aligned}
X(\ldots, d_i(m_i), \ldots) &= \sum\nolimits_{i=0, j=m_i}^{i=N-1} [X(d_i(j)) - X_k] + X_k \\
Y(\ldots, d_i(m_i), \ldots) &= \sum\nolimits_{i=0, j=m_i}^{i=N-1} [Y(d_i(j)) - Y_k] + Y_k \qquad (6) \\
Z(\ldots, d_i(m_i), \ldots) &= \sum\nolimits_{i=0, j=m_i}^{i=N-1} [Z(d_i(j)) - Z_k] + Z_k
\end{aligned}
$$

with X_k, Y_k, Z_k the color tristimulus coming out from a $(0, \ldots, 0)$ input.

We illustrate this for a three primaries RGB device, with each channel coded on 8 bits. The digital input are $d_r(i)$, $d_g(j)$, $d_b(l)$, with i, j, l integers $\in [0, 255]$. In this case, a $XYZ(d_r(i), d_g(j), d_b(l))$ can be expressed by:

$$
\begin{aligned}
X(d_r(i), d_g(j), d_b(l)) &= [X(d_r(i)) - X_k] \\
&\quad + [X(d_g(j)) - X_k] + [X(d_b(l)) - X_k] + X_k \\
Y(d_r(i), d_g(j), d_b(l)) &= [Y(d_r(i)) - Y_k] \\
&\quad + [Y(d_g(j)) - Y_k] + [Y(d_b(l)) - Y_k] + Y_k \\
Z(d_r(i), d_g(j), d_b(l)) &= [Z(d_r(i)) - Z_k] \\
&\quad + [Z(d_g(j)) - Z_k] + [Z(d_b(l)) - Z_k] + Z_k \qquad (7)
\end{aligned}
$$

All experimental devices considered in this study were RGB primaries devices, thus the transformation between digital RGB values and RGB device's primaries is as direct as possible. The A_k, $A \in \{X, Y, Z\}$ are obtained by accurate measurement of the black level. The $[A(d_i(j)) - A_k]$, are obtained by one dimensional linear interpolation with the measurement of a ramp along each primary. Note that any 1-D interpolation method can be used. We have followed the previous authors and used a piecewise linear interpolation.

Previous studies of this model have shown good results, especially on dark and mid-luminance colors. When the colors reach higher luminances, the additivity assumption is less true for CRT technology. Then the accuracy decreases (depending on the device properties). More precisely, Post and Calhoun[23,31] stated that chromaticity error is lower for the PLVC than for the PLCC in low luminances. This is due to the setting of primary chromaticities at maximum intensity in the PLCC. Both models lack accuracy for high luminance colors due to channel interdependence. Jimenez del Barco *et al.*[28] found that for CRT technology, the higher level of brightness in the settings leads to a nonnegligible amount of light for a (0,0,0) input. This light should not be added three times, and they proposed a correction for that.* They found that the PLVC model was more accurate in medium to high luminance colors, however, they stated that in low and high luminances the inaccuracy is more important. In low luminances it is due to inaccuracy of measurements, however in high luminances, the interaction between channels can make the model inaccurate.

The inversion of a display color characterization model is of major importance for color reproduction. The PLVC model inversion is not straightforward as the matrix based models previously defined. For a three primaries display, according to Post and Calhoun,[23] it can be performed, defining all subspaces defined by the matrices of each combinations of measured data (the intercepts have to be subtracted, and once all the contributions are known, they have to be added). One can perform an optimization process for each color[28] or can define a grid in RGB which will allow us to perform the inversion using 3D interpolation. Note that Post and Calhoun have proposed to define a full LUT considering all colors. They said themselves that it is inefficient. Defining a reduced regular grid in RGB leads to inaccuracy in interpolation, and we addressed this problem in another communication.[45] We built an optimized Look Up Table, based on a customized RGB grid. This method shows quite good results, at least better than the PLCC* for LCD technology. Moreover the computation required is not a problem as it can be done fast enough in the graphic pipeline.

Results for the forward direction are presented in next section and compared with the PLCC, PLCC*, and GOGO models previously defined.

EXPERIMENTAL SETUP AND RESULTS

To demonstrate and analyze the accuracy of the PLVC model, we tested it on several displays, and we compared it with several well known and commonly used models. This section concerns the results obtained for six display devices listed in Table I. The device set contains two LCD and one DLP projectors, one CRT and two LCD monitors. We compare the precision of the PLVC model with that of the PLCC, the GOGO, and the black corrected PLCC*. In general, the PLVC gives better results than the other methods tested for the same amount of measurements except for the technologies where the chromaticity shift of primaries is low (CRT and DLP after black correction), where the results are similar. The improvement depends significantly on how the chromaticity of primaries is shifting, and on the channel interdependence, following the definition of the model.

Experimental Setup

We measured 18 color patches for each primary (each 15 digital values from 0 to 255) to build the models, thus

TABLE I. References of the tested devices.

Related in the text as	Device reference
PLCD1	Panasonic PT-AX100E
PLCD2	3M-X50
PDLP	ProjectionDesign Action One
MCRT	Philips 107S monitor
MLCD1	Acer AL1721 monitor
MLCD2	DELL 1905FP monitor

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*Eqs. (6) and (7) are based on the equation proposed by Jimenez del Barco *et al.*,[28] and take that into account.

TABLE II. Results for tested displays.

Results for each display and each tested model for 100 random colors equiprobably distributed in RGB		ΔE^*_{ab} mean	ΔE^*_{ab} max	ΔE^*_{ab} std. dev.	ΔE^*_{ab} 95 ptl	ΔL^* mean	ΔC^*_{ab} mean	ΔH^*_{ab} mean
PLCD1	PLCC	6.42	19.06	4.28	18.01	−0.51	−5.27	−0.56
	PLCC*	3.93	8.28	2.15	7.27	−0.86	−2.45	−0.47
	GOGO	3.96	14.61	2.62	9.26	−**0.39**	**0.20**	−0.44
	PLVC	**1.41**	**3.56**	**0.63**	**2.58**	−0.86	−0.64	−**0.09**
PLCD2	PLCC	15.19	55.62	14.94	46.42	1.20	−7.63	−1.08
	PLCC*	1.78	2.96	0.51	2.55	**0.25**	−0.30	−0.29
	GOGO	2.86	11.41	2.30	8.67	0.32	−0.44	−0.28
	PLVC	**0.54**	**1.64**	**0.28**	**1.13**	**0.25**	−**0.03**	−**0.05**
PDLP	PLCC	1.81	8.87	1.80	7.15	0.81	−0.78	−0.41
	PLCC*	0.99	2.17	0.34	1.62	**0.61**	**0.11**	−0.14
	GOGO	5.42	21.17	3.75	12.75	−1.13	1.35	**0.07**
	PLVC	**0.85**	**2.02**	**0.33**	**1.38**	**0.61**	0.21	−0.11
MCRT	PLCC	0.92	1.91	0.39	1.62	0.52	−0.27	−0.03
	PLCC*	**0.88**	**1.87**	**0.40**	**1.59**	0.51	−0.20	−**0.02**
	GOGO	1.41	4.45	0.91	3.31	**0.06**	−0.95	−0.05
	PLVC	0.94	2.06	0.42	1.77	0.51	−**0.12**	−0.11
MLCD1	PLCC	7.26	23.90	5.80	21.12	**0.53**	−5.32	−**0.13**
	PLCC*	1.81	4.10	0.86	3.06	−0.95	−0.70	0.46
	GOGO	4.22	24.45	3.28	8.80	−0.56	0.70	0.17
	PLVC	**1.50**	**3.32**	**0.64**	**2.67**	−0.95	−**0.57**	0.52
MLCD2	PLCC	4.66	12.08	2.30	9.45	−**0.58**	−1.44	0.46
	PLCC*	4.88	9.36	2.16	7.76	−0.84	**0.41**	0.43
	GOGO	6.89	45.54	6.09	16.38	−1.39	1.01	−**0.29**
	PLVC	**2.04**	**4.55**	**0.91**	**3.78**	−0.84	1.03	0.81

Errors and statistics for 100 random colors equiprobably distributed in RGB. We applied the PLCC, PLCC with black correction (PLCC*), GOGO, and PLVC models. We computed ΔE^*_{ab}, ΔL^*, ΔC^*_{ab}, and ΔH^*_{ab} following[46] between the estimated and the measured colors.

including three measurements of the black level which were averaged to limit the low luminance measurement inaccuracy. Hundred random patches equiprobably distributed in RGB color space were measured for the evaluation. We used the spectroradiometer CS-1000 from Minolta (Accuracy: luminance: ±2%, x: ±0.0015, y: ±0.001, Repeatability: Luminance: ±0.1%, xy: 0.0002 for illuminant A). The devices were warmed up for at least one hour before any measurement, and the random patches were measured just after the ramp patches to limit the influence of the display nonrepeatability. Experiments were performed in a dark room. We used the 2° CIE observer and the white point of the display for any color space transform.

Global Results

A comparison of models is provided in Table II for the models tested (PLCC, PLCC*, GOGO, and PLVC) and each display. We provide the ΔE^*_{ab} error in average (mean), maximum (max), its standard deviation (std. dev.), and the 95 percentile (95 ptl) between the measured and the predicted color for our random data test set. We give also the average ΔL^*, ΔC^*_{ab}, and ΔH^*_{ab} errors.[†] The values ΔE^*_{ab}, ΔL^*, ΔC^*_{ab}, and ΔH^*_{ab} have been computed following the CIE 015.2004 colorimetry, technical report.[46]

The PLCC without black correction does not perform well when there is a major chromaticity shift of primaries. Results can be found not acceptable for most applications. Major errors in average and impressive maximum error occurs for these devices [Figs. 2(a), 2(b), 2(e), and 2(f)]. One can see that it is the ΔC^*_{ab} which is the main weakness. However, for the MCRT display it can be judged acceptable with an average error of $\Delta E^*_{ab} = 0.92$ as the primary chromaticities does not shift with the lightness [Fig. 2(d)]. For the display PDLP, it could be judged satisfactory with an average error of $\Delta E^*_{ab} = 1.81$ as the chromaticities are remaining quite constant except for really low luminances [Figs. 2(c) and 3].

Applying a black correction, we reduce drastically the error for almost all devices except MLCD2, even for this device the error in chroma is better distributed. On the right part of Fig. 2, one can see that the major part of chromaticity inconstancy has been removed. For most applications such a model can be used, we found averaged error from 0.88 to 4.88 ΔE^*_{ab} units for our set of displays. The major improvement is in chroma. We see an increase in the systematic error for lightness for devices PLCD1, MLCD1, and MLCD2, whereas it is decreasing in PLCD2. For displays PDLP and MCRT, it remains more or less the same (the error in lightness decreases not significantly, a bit more for PDLP).

The GOGO model gives possibly acceptable results for some displays especially for MCRT, but for some it

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[†] Please note that when we say that any of ΔL^*, ΔC^*_{ab}, or ΔH^*_{ab} is better, we are evaluating a systematic error. These indicators are signed. A 0 average only shows that the error is distributed perfectly randomly around the 0 error, and not that there is no error.

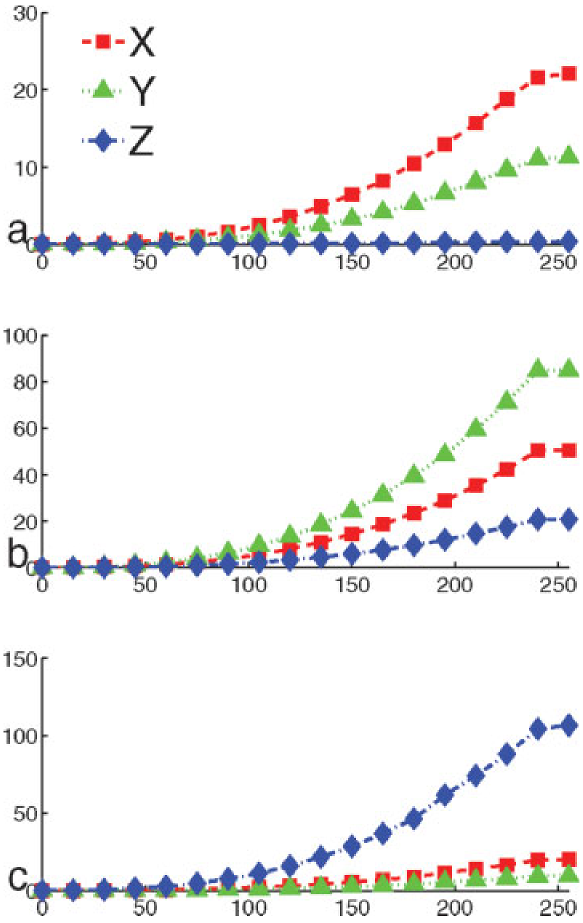

FIG. 3. Response curve in X, Y, and Z for display PDLP for, respectively, the red (a), green (b), and blue (c) channel. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

seriously fails, especially for MLCD1, MLCD2, and PDLP with average error from around 4 to around 7 ΔE^*_{ab} units. These displays are showing a really different response curve in luminance than a gamma shape (Fig. 3).

The PLVC model yields significantly improved model precision, compared with the previous discussed models, for most of the tested displays. Especially for the two LCD projectors and the monitor MLCD2 where the averaged accuracy is more than doubled (Table II). One can see in Fig. 2, that for PLCD1 the chromaticity shift is still significant after black correction. This is not so obvious for the other ones. For MCRT, we reduced the systematic error in chroma, but increased it in hue. For PDLP, the improvement compared with the PLCC* is not major but exists, probably due to the shift in chromaticity on the red channel (see Fig. 2). Display MLCD1 shows only a small improvement comparing with the PLCC*.

Detailed Analysis

The PLCC* and the PLVC give the best results among the tested models, and in the following, we have compared these two models in more detail. Considering that the retrieved response curves in luminance are the same for both models, and considering the behavior of each model, it is obvious that the ΔL^* are the same for these two models.

If we look at Fig. 4, where the histogram of the error distribution can be observed and at the standard deviation in Table II, we notice that in using the PLVC model, we reduced the spreading of the error (except for the display MCRT where it remains the same).

The following deals with the results in deeper details concerning the location of errors in the device gamut. For this purpose, we used visualization of errors in CIELAB. For 2D and place constraints, we present the projection in a^*b^* and L^*a^* planes, respectively Figs. 5 and 6 for the display PLCD1, and the projection in L^*a^* plane for MCRT (Fig. 7) and MLCD2 (Fig. 8), to illustrate our analysis and because they can be considered representative of the general results found, under some restrictions (The other visualizations for the other displays are directly available by request to the authors).

One can see on the a^*b^* plane in Fig. 5 that the main improvement obtained with the PLVC model follows roughly the direction of the line from $(-a^*,+b^*)$ to

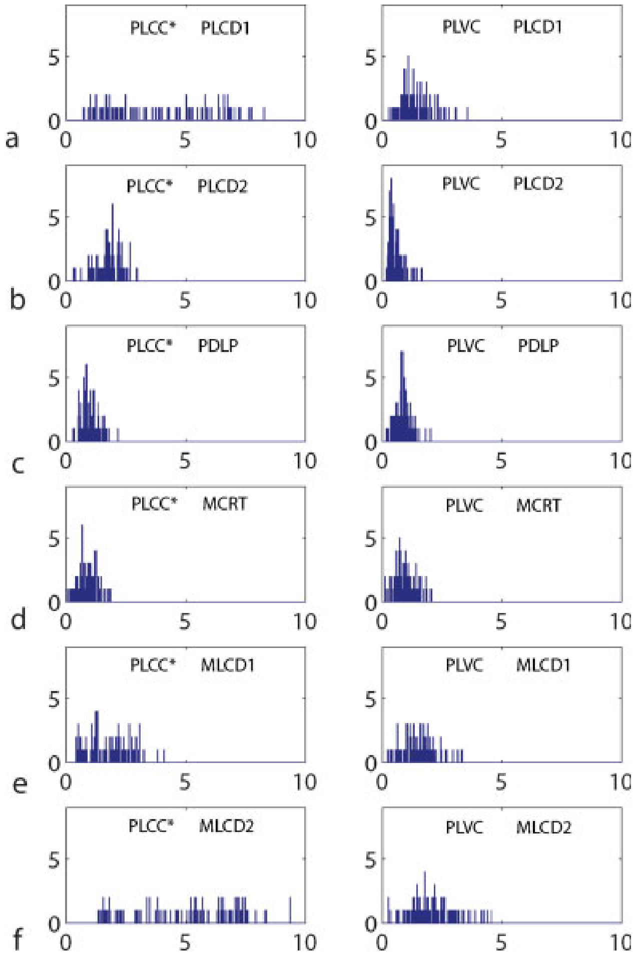

FIG. 4. Comparison of the model prediction error distribution in ΔE^*_{ab} between PLCC* (left) and PLVC (right). [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

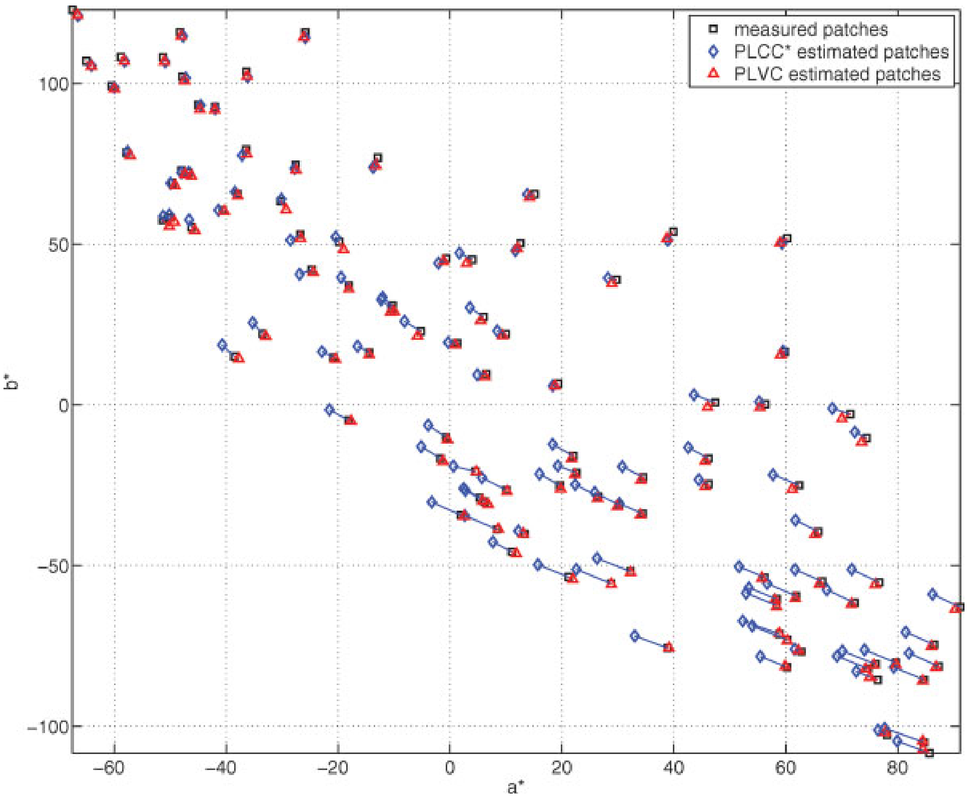

FIG. 5. PLCD1: visualization of errors for the testing data set projected on the *a*b** plane.

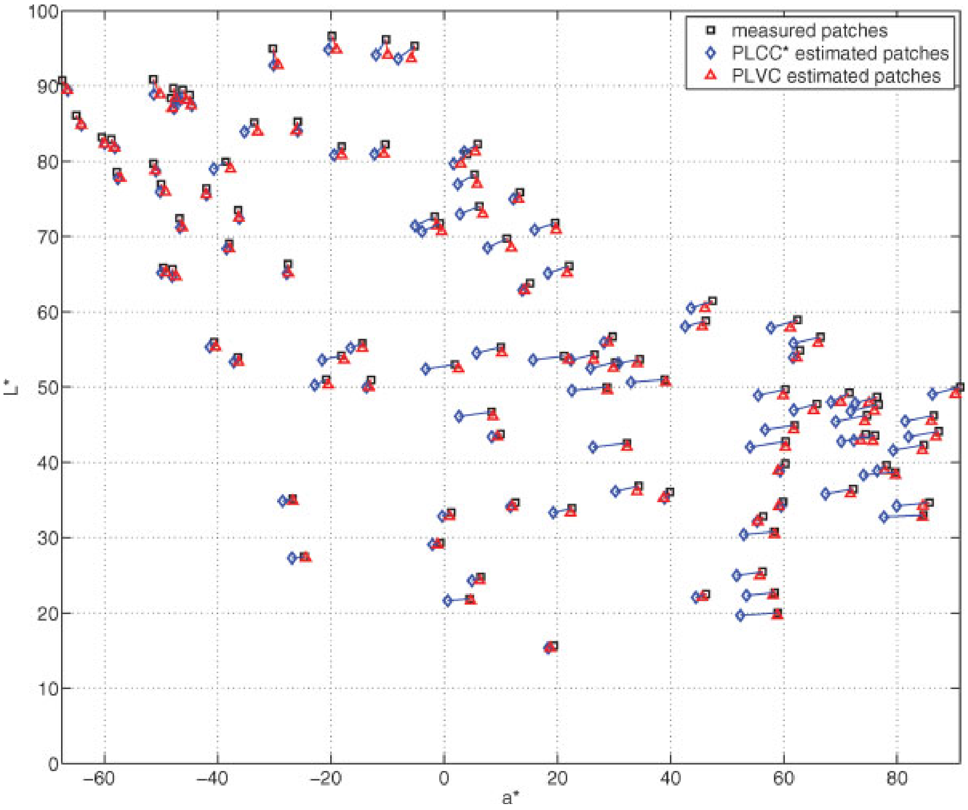

FIG. 6. PLCD1: visualization of errors for the testing data set projected on the *a*L** plan.

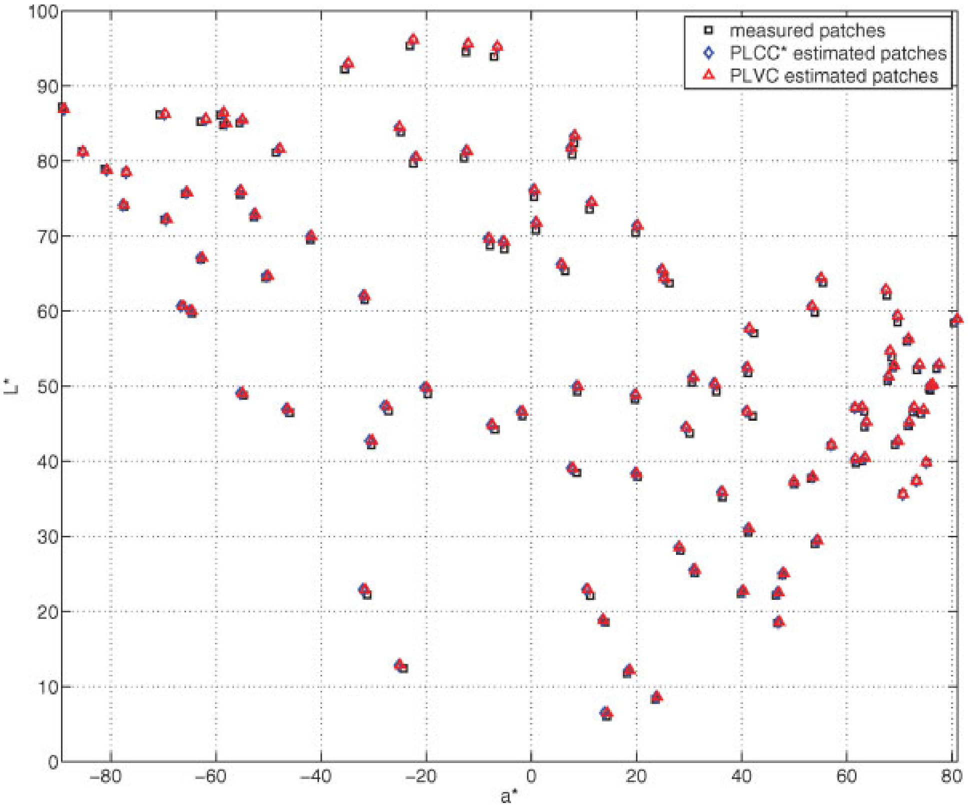

FIG. 7. MCRT: visualization of errors for the testing data set projected on the *a*L** plan.

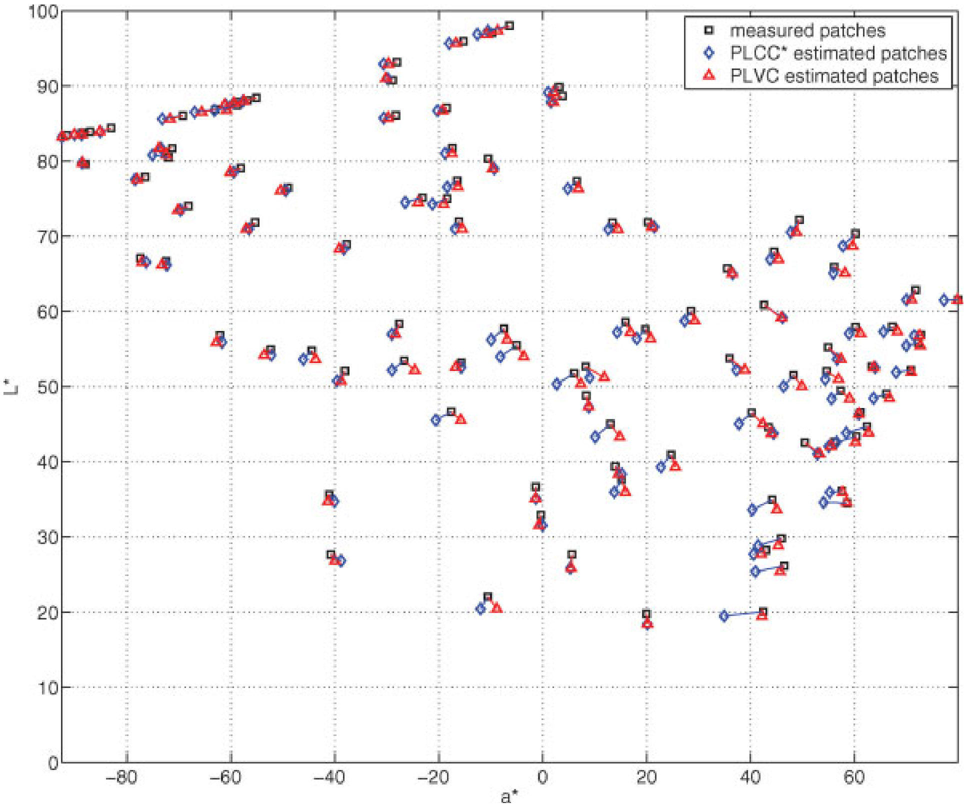

FIG. 8. MLCD2: visualization of errors for the testing data set projected on the *a*L** plan.

($+a^*, -b^*$). this effect can be seen more or less strong on every tested LCD devices especially in the bluish area. That means that a correction in chroma has been performed for the bluish area, and a correction mainly in hue for the reddish and cyan area. A small similar effect can be seen in the not saturated blue of PDLP. Nothing is noticeable for MCRT in a^*b^* plane, as the chromaticity of primaries is constant.

About the error location in a^*b^* plane of the PLVC model, it is difficult to find a systematic type of error as they are really small in the a^*b^* plane. Examining Fig. 5, one could say that the remaining error is localized in the red area. However, nothing similar has been noticed for the other displays, and it is not representative.

For the display PLCD2, no noticeable error remains in a^*b^* plane, for PDLP we can notice some errors in the purple and in the desaturated greenish/yellowish area. For MCRT, some errors remain in the half plane defined by positive b^* values. For MLCD1, they are located in the bluish to reddish area (and a little bit in the yellow). For MLCD2, an amount of error remains everywhere. The location of errors appears to be different for different displays, and to conclude we can say that the results in chroma/hue depend on the display.

If we now look at the luminance factor, in display PLCD1 (see Fig. 6), PDLP, MLCD1, and MCRT we can notice the same thing as in the previous studies, from low to medium luminances, the accuracy is good. The results are worse when the luminance is high. PLCD2 shows really small luminance shift. MLCD2 shows a stronger luminance shift in the medium level (Fig. 8). Note that for PDLP and MCRT displays, the measured luminance is lower than the estimated one when there is a difference (Fig. 7), while the opposite occurs for the other devices.

These differences in behavior could be explained by the interdependence between channels. MLCD2 luminance shift follows the shape of the derivative of an S-shape curve, as shown by Yoshida and Yamamoto.[20] The LCD projectors tested were 3-LCD ones, therefore the interaction between channels due to coupling capacitive should not appear, at least for uniform color patches, since they are physically independent. The over-estimation of the luminances in MCRT is probably due to a lack of power supply when the maximum intensity is required. For pure colors, we did not notice any non-monotonicity in the response curve, but the grey response curve is below the sum of the pure color response curve. The same remark can be done for PDLP, but we can observe the saturation of the response curves at the higher input values (see Fig. 3).

In summary, the error in luminance is strongly dependent of the interaction between channels, which is indeed the weakness of the PLVC model. This seems to be not critical for the display tested, as we achieve good results in using the PLVC or PLCC models. Looking at the a^*b^* plane, the PLVC model increases significantly the accuracy in chroma and hue for LCD technology.

CONCLUSION AND PERSPECTIVES

In this work, we have revisited the PLVC display color characterization model. We achieved the same conclusion on CRT technology as the previous published studies of this model, and we extend this conclusion to the DLP tested projector: the PLCC is performing well, as long as a black correction is carried out, with equivalent results. For our DLP projector, the averaged ΔE^*_{ab} is of 0.99 using the PLCC* against 0.85 using the PLVC. For our CRT monitor, the averaged error is of 0.88 using the PLCC* against 0.94 using the PLVC. Furthermore we have shown, through our experiments, the efficiency of the PLVC model for LCD technology. On three out of six of the tested displays we reduced significantly the error by using PLVC compared to using PLCC*. On these devices, we obtained average ΔE^*_{ab} of 3.93, 1.78, and 4.88 with the PLCC* model compared to 1.41, 0.54, and 2.04 with the PLVC model.

A straightforward further experiment, to follow this work, could be to evaluate results on multiprimary displays using Eq. 6. Indeed, in order to increase the size of the display's gamut, one could use N primaries. Several systems have been defined for this purpose, see for example the work of Ajito *et al.*[47] The problem is that one needs to isolate each channel to measure their response curves. As we usually do not know the transformation used by the manufacturer, this can be a tough task. A solution has been proposed for 4 primaries DLP (R,G,B and white segments) by Wyble.[48,49] In their model, the characteristics of the luminance of the white channel is retrieved with regard to additive property of the display, given the four-tuplet (R,G,B,W) from an input (d_r, d_g, d_b). An idea could be to retrieve as well the X and Z components of the white channel using the same method. We would be able then to apply the PLVC model. For more primaries, this can be less obvious. In such cases, major problems can arise to perform the inversion which becomes far more difficult than the problems addressed in previous studies,[23,28,45] as it is a projection from a three-dimensional space into a N-dimensional one. However one could use some work which has been done in this direction.[50]

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