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Parameter Optimized Simple Matrix Color Device Model for Liquid Crystal Display Monitors

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Abstract. *A parameter optimized simple matrix (POSM) model is proposed for characterizing the liquid crystal display (LCD) monitor with variant primary chromaticity and primary crosstalk. This method is the same as the conventional simple matrix (CSM) model except that black point, white point, one-primary measurement data, and two primary measurement data are taken as the training samples for optimizing the signal nonlinear transformations (SNTs) and chromaticity matrix. As the configuration of the POSM model is the same as the CSM model, its backward model is simple and can be implemented for video applications. Polynomial function is taken as the SNT. The optimization process comprises the simulated annealing method for optimizing the coefficients of SNTs and the regression method for calculating the chromaticity matrix. The results show that the average color difference (CIEDE2000) of 224 random test samples for two characterized LCD monitors are 2.02 and 1.33 with a forward POSM model, and are 2.32 and 1.27 with a backward POSM model. The primary crosstalk of the LCD monitor with a higher average color difference is more serious than the other monitor. The performance of the POSM model is much better than the CSM model. For the monitor with lower crosstalk, the POSM model is better than the three-dimensional look-up table (3D-LUT) model with a* $5\times5\times5$ *lattice but is worse than the 3D-LUT model with a* $8\times8\times8$ *lattice.* **©** *2006 Society for Imaging Science and Technology.* [DOI: 10.2352/J.ImagingSci.Technol.(2006)50:1(73)]

INTRODUCTION

Liquid crystal display (LCD) monitors are now popular flat panel displays. To show high fidelity color, it requires accurate color device model describing the relation of input signals and the CIE tristimulus values of output light.[1–7] The tristimulus values can be represented by a vector (X,Y,Z). The device model of a color display is usually represented with a chromaticity matrix and the three tonal transfer curves (TRC) for the red, green, and blue primaries. This model is called the simple matrix model for simplicity. The input signals can be represented by a vector (R,G,B), in which R, G, and B are the red, green, and blue components, respectively. The TRC is used to convert the signals of a primary, e.g., $(R,0,0)$ for red primary, to a value corresponding to its output luminance. The output of the TRC can be called the linear signal because its value is linearly proportional to luminance and is denoted as R_L, G_L, or B_L for red, green, or blue primaries, respectively. The chromaticity matrix is used to transfer the vector (R_L, G_L, or B_L) to its output tristimulus value vector (X,Y,Z). The simple matrix model works when the chromaticity of primaries are invariant to their corresponding signals, i.e., the color coordinates x and y of a primary do not change with signal, and the three primaries are linearly independent, i.e., the output of one primary is independent of the signals of the other two primaries.[1–7] The chromaticity matrix is constructed based on the measurement data of the CIE tristimulus values of each primary. The Y components of the measured tristimulus values of a primary ramp are used to obtain its TRC because it relates to luminance. A TRC can be implemented through interpolation or regression. If the number of measured primary ramp is large enough, the TRC can be represented with a look-up table (LUT) that the luminance of the not measured is calculated through interpolation. A TRC also can be represented with a given function so that its coefficients can be obtained from the primary ramp through regression. The chromaticity matrix can be constructed with the tristimulus values of the three primaries of the respective maximum signals, for example $(R,G,B)=(255,0,0)$ for red primary for an eight-bit system. In this article we take an eight-bit system as an example. Owing to the well developed technologies of cathode ray tube (CRT) monitors, the chromaticity of the primaries are invariant and the primaries are independent. Therefore, the simple matrix model works satisfactory for CRT monitors.[1–7]

Unfortunately, the simple matrix model works worse for LCD monitors. The variant primary chromaticity of LCDs is due to the spectral transmittance of liquid crystal cell changed with applied voltage,[8] which can be observed in Fig. 1 that shows the loci of the color coordinates x and y of the primary ramps of a LCD monitor (ViewSonic VG151), in which the black point has been corrected.[9] The tristimulus values of black point are subtracted from the tristimulus values of the primary ramps when the color coordinates x and y are calculated. As to the primary crosstalk of LCDs, it may come from signal interference. Figure 2(a) shows three primary spectra $S_r(\lambda)$, $S_g(\lambda)$, and $S_b(\lambda)$ for $(R,G,B)=(128,0,0)$, (0, 128, 0), and (0, 0, 128), respectively, for VG151, where λ is wavelength. If the primaries are independent, the sum of the primary spectra should be equal to the spectrum of $(R,G,B)=(128,128,128)$. Figure 2(b) shows the spectrum of the gray light $S_w(\lambda)$ with $(R,G,B)=(128,128,128)$ for the same LCD monitor by a solid line.

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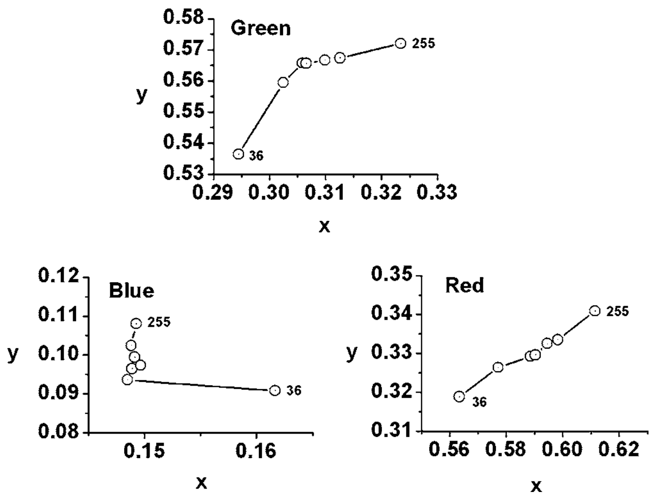


Figure 1. Loci of the color coordinates x and y of the primary gray ramps of the ViewSonic VG151 LCD, in which the black point has been corrected. The data points correspond to the signals $(R,G,B)=(D,0,0)$, $(0,D,0)$, and $(0,0,D)$ for red, green, and blue, respectively, and $D=36$, 72, 109, 145, 182, 218, and 255. The number shown near the symbol is the corresponding value of D.

The dashed line shown in Fig. 2(b) is the spectra $S_s(\lambda)=S_r(\lambda)+S_g(\lambda)+S_b(\lambda)-2S_k(\lambda)$, where $S_k(\lambda)$ is the spectrum of the black point and is an offset spectrum for the output light of any signals. Because the sum of three primary spectra comprises three times of the black point spectrum, we subtract two black point spectra in the formula of $S_s(\lambda)$ so that its offset spectrum is the same as $S_w(\lambda)$. One can see that $S_w(\lambda)$ is apparently larger than $S_s(\lambda)$. This result shows the primaries are not independent and there primary crosstalk exists. In this article, the CIEDE2000 color difference formula is used. The color difference between $S_w(\lambda)$ and $S_s(\lambda)$ is 2.8. The origin of the primary crosstalk of LCDs can be more clearly observed by considering the three-primary and two-primary crosstalk spectra. Figure 3 shows the three-primary crosstalk spectrum $\Delta S_{rgb3}(\lambda)=S_w(\lambda)-S_s(\lambda)$ and the sum of two primary crosstalk spectra $\Delta S_{rgb2}(\lambda)=\Delta S_{rg}(\lambda)+\Delta S_{gb}(\lambda)+\Delta S_{br}(\lambda)$, in which $\Delta S_{rg}(\lambda)$, $S_{gb}(\lambda)$, and $\Delta S_{br}(\lambda)$ are the two-primary crosstalk spectra that are defined as $\Delta S_{ij}(\lambda)=S_{ij}(\lambda)-[S_i(\lambda)+S_j(\lambda)-S_k(\lambda)]$, i, $j=r$, g, and b, and the two primary spectra $S_{rg}(\lambda)$, $S_{gb}(\lambda)$, and $S_{br}(\lambda)$ correspond to the signals $(R,G,B)=(128,128,0)$, (0, 128, 128), and (128, 0, 128), respectively. We subtract one black point spectrum in the formula of the two primary crosstalk spectrum because the sum of two primary spectra comprises two times of the black point spectrum. In Fig. 3, the cases of ViewSonic™ VG151 and VA520 LCDs are shown. One can see that $\Delta S_{rgb3}(\lambda)$ is nearly the same as $\Delta S_{rgb2}(\lambda)$. For the other input digital count, we have examined that $\Delta S_{rgb3}(\lambda)$ is also nearly the same as $\Delta S_{rgb2}(\lambda)$. Since a three primary crosstalk spectrum can be derived from two primary crosstalk spectra, the two primary crosstalk is the origin of the primary crosstalk. From Fig. 3, one can also see that the crosstalk of VG151 is larger than VA520.

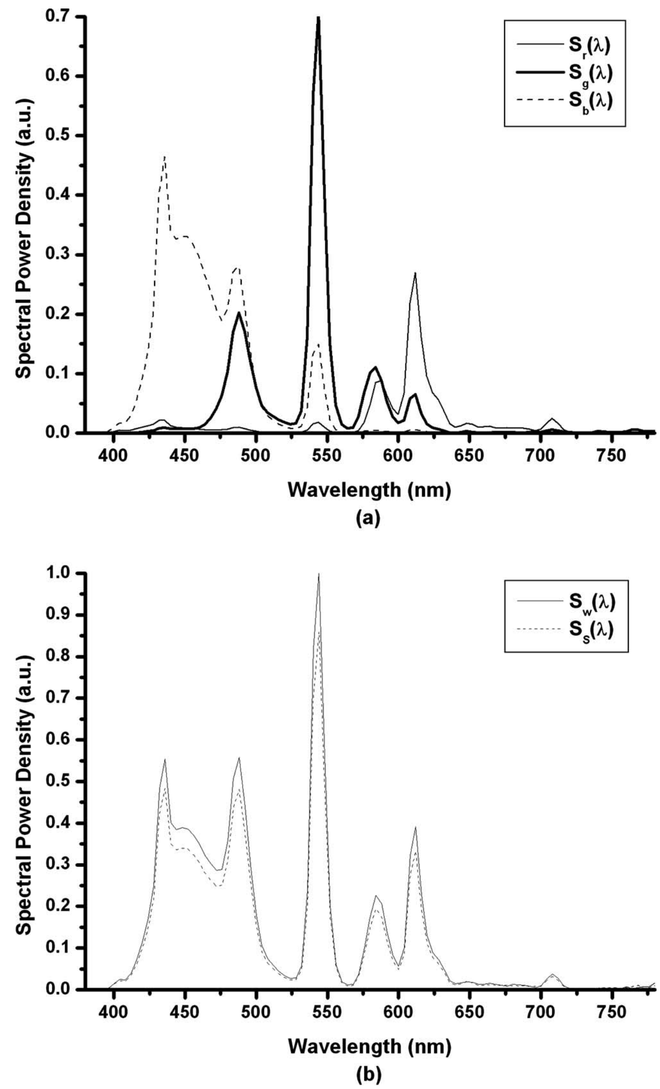


Figure 2. Spectra for showing the primary crosstalk of the ViewSonic VG151 LCD monitor. (a) Spectra of three primary $S_r(\lambda)$, $S_g(\lambda)$, and $S_b(\lambda)$ for the signals $(R,G,B)=(128,0,0)$, (0, 128, 0), and (0, 0, 128), respectively, where λ is wavelength. (b) Spectra of the gray light $S_w(\lambda)$ with $(R,G,B)=(128,128,128)$ and $S_s(\lambda)=S_r(\lambda)+S_g(\lambda)+S_b(\lambda)-2S_k(\lambda)$, where $S_k(\lambda)$ is the spectrum of the black point with $(R,G,B)=(0,0,0)$.

A simple matrix model can be improved by optimizing the chromaticity matrix for a set of measurement data.[10,11] Reference 11 uses an iteration method to optimize chromaticity matrix, in which the TRC of a primary is obtained from transforming the measured tristimulus values of the primary ramp by reverse chromaticity matrix. Reference 11 shows the color difference may vary from below 1.0 to above 3.0 that depends on the LCD. When the impacts of variant primary chromaticity and primary crosstalk are significant so that the simple matrix model is not accurate enough, the other approach to characterize LCDs should be taken. Three-dimensional LUT (3D-LUT) models can be used to characterize the color devices.[12] A 3D-LUT model is usually used to solve highly nonlinear problem, for example the characterization of color printers. If an $8\times8\times8$ lattice is

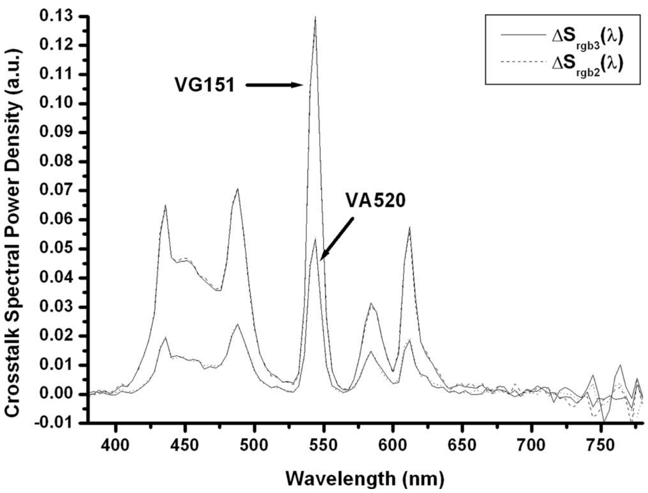


Figure 3. Three primary crosstalk spectra $\Delta S_{rgb3}(\lambda)$ and $\Delta S_{rgb2}(\lambda)$ for the ViewSonic VG151 and VA520 LCDs. The solid and dashed lines almost overlap for each LCD.

used for the 3D-LUT model, it requires 512 measurements in total. The tristimulus values of the signals that are not measured can be interpolated from the measurement data. In addition to the large number of required measurement data, the backward model of the 3D-LUT is also very complicated. A backward model is used to convert (X,Y,Z) to (R,G,B), which is required for device calibration. For video application, a simple backward model is desirable. Therefore, the 3D-LUT method is not realistic for video application.

This article proposes another approach to optimize the chromaticity matrix and TRCs of the simple matrix model for characterizing the LCD monitors. The impacts of variant primary chromaticity and primary crosstalk to the performance of this optimized simple matrix model are investigated. With proper nonlinear transform for each input channel (red, green, or blue), we found that it is possible to approximately linearize the color characteristics. Thus, the nonlinear transforms for the three channels together with an optimized 3×4 chromaticity matrix can also be used to convert signals into tristimulus values. The TRCs of the three primaries can be absorbed into the three nonlinear transforms, respectively. As both the parameters of the three nonlinear transforms and the 3×4 chromaticity matrix are found by an optimization process, we call this method the parameter optimized simple matrix (POSM) model. In Device Models, we will first describe the conventional simple matrix (CSM) model and then the POSM model. Experiments and Results shows the experiments and results for two LCD monitors. The performance with the POSM model is studied and compared to the performances with the CSM model and the 3D-LUT model. The results show this optimized model gives satisfactory results. The conclusions are given in the last section.

DEVICE MODELS

The color of light can be described with CIE 1931 chromaticity system.[13] The tristimulus values of the CIE chromaticity system are given by

$$X=\int S(\lambda)\bar{x}(\lambda)d\lambda, \tag{1}$$

$$Y=\int S(\lambda)\bar{y}(\lambda)d\lambda, \tag{2}$$

$$Z=\int S(\lambda)\bar{z}(\lambda)d\lambda, \tag{3}$$

where $S(\lambda)$ is power spectral density and $\bar{x}(\lambda)$, $\bar{y}(\lambda)$, and $\bar{z}(\lambda)$ are color matching functions. As $\bar{y}(\lambda)$ is also the luminance efficiency function, Y relates to luminance. The CIE 1931 color coordinates are the Y together with

$$x=\frac{X}{X+Y+Z}, \tag{4}$$

$$y=\frac{Y}{X+Y+Z}. \tag{5}$$

Note that X, Y, and Z can be easily derived from x, y, and Y.

The values of signals R, G, B lies between 0 and MAX, in which $\mathrm{MAX}=2^M-1$ for M-bit system. For simplicity, we normalize the signals as $r(R)=R/\mathrm{MAX}$, $g(G)=G/\mathrm{MAX}$, and $b(B)=B/\mathrm{MAX}$ so that the normalized signals $0\leqq r$, g, b $\leqq 1$. The TRCs of the CRT display can be described by the so called gamma function. Taking red primary as an example

$$R_L(r)=\alpha_r r^{\gamma_r}, \tag{6}$$

where the coefficients α_r and γ_r are constants for the red primary. The gamma function usually fits the TRCs of LCD less well. In general, by a Taylor series expansion, we can describe TRCs by the polynomials

$$R_L(r)=\sum_{j=0}^{P} a_{rj}r^j, \tag{7}$$

$$G_L(r)=\sum_{j=0}^{P} a_{gj}g^j, \tag{8}$$

$$B_L(r)=\sum_{j=0}^{P} a_{bj}b^j, \tag{9}$$

where $R_L(r)$, $G_L(g)$, and $B_L(b)$ are the normalized TRC of red, green, and blue primaries, respectively; P is the order of the polynomials; a_{ij} $(i=r,g,b;\ j=0,1,2\ldots P)$ coefficients are constants. With the normalization condition that $R_L(1)=G_L(1)=B_L(1)=1$, we have

$$a_{iP}=1-\sum_{j=0}^{P-1} a_{ij}, \quad i=r,g,b. \tag{10}$$

When the black level is not negligible, the output tristimulus values of the given signals (R,G,B) can be calculated by

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} X_r - X_k & X_g - X_k & X_b - X_k & X_k \\ Y_r - Y_k & Y_g - Y_k & Y_b - Y_k & Y_k \\ Z_r - Z_k & Z_g - Z_k & Z_b - Z_k & Z_k \end{bmatrix} \begin{bmatrix} R_L(r) \\ G_L(g) \\ B_L(b) \\ 1 \end{bmatrix}, \tag{11}$$

where the 3×4 matrix is chromaticity matrix and is denoted as $\boldsymbol{M}$. In Eq. (11), X_r, Y_r, and Z_r are the tristimulus values of the red primary with the signals $(R,G,B)=(\mathrm{MAX},0,0)$; X_g, Y_g, and Z_g are the tristimulus values of the green primary with the signals $(R,G,B)=(0,\mathrm{MAX},0)$; X_b, Y_b, and Z_b are the tristimulus values of the blue primary with the signals $(R,G,B)=(0,0,\mathrm{MAX})$. Since black point is considered in the chromaticity matrix, $a_{r0}=a_{g0}=a_{b0}=0$ in Eqs. (7)–(9). Equations (7)–(11) describe the CSM model. Obviously, the linear nature of Eq. (11) shows it is valid when the chromaticity of primaries are invariant and the three primaries are linearly independent. As is mentioned earlier, this assumption is usually valid for CRT monitors but not for LCD monitors.

Two strategies are taken for the optimized model for LCDs. One is the proper choice of the measurement data. The other is the optimization method. The measurement data for the CSM model are the tristimulus values of primary ramps. The measurement data of a primary is used to obtain the coefficients of its TRC through regression. The measurement data of the black point and the three primaries of the maximum signal are used to calculate the matrix elements of Eq. (10). For the LCDs with primary crosstalk, the output of a primary is influenced by the signals of the other two primaries. It requires a new set of measurement data for modeling LCDs. In addition to taking the conventional black point and three one-primary data sets, we also take the white point and three two-primary data sets because the dominant crosstalk comes from two-primary crosstalk as is shown in introduction section. The one-primary data set is

$$(R,G,B) = (I[i],0,0), \tag{12}$$

$$(R,G,B) = (0,I[i],0), \quad i = 1,2,\ldots,N_s. \tag{13}$$

$$(R,G,B) = (0,0,I[i]), \tag{14}$$

where $I[i]$ is an integer set and N_s is the number of the integer set. The two-primary data set is

$$(R,G,B) = (J[i],\ K[j],0), \tag{15}$$

$$(R,G,B) = (0,J[i],K[j]), \quad i,j = 1,2,3,\ldots,M_s, \tag{16}$$

$$(R,G,B) = (K[i],0,J[j]), \tag{17}$$

where $J[i]$ and $K[i]$ are two integer sets and M_s is the number of the two integer set. Including the black point and white point data, we need $N=2+3\times(N_s+M_s^2)$ measurement data in total. The black point, white point, one-primary and two-primary data sets are called the training samples for optimization process.

We also take Eqs. (7)–(9) as the nonlinear transformations from (R,G,B) to (R_L,G_L,B_L). In the following section, the results show that the TRC with the optimized coefficients for the training samples differs from the conventional TRC obtained with only one-primary data set. We call the optimized TRC as a signal nonlinear transformation (SNT) to tell from the conventional TRC. The coefficients of the SNT can be found by optimization methods, such as multidimensional search,[14] that minimize the average color difference $\overline{\Delta E_{00,\mathrm{Train}}}$ of training samples. As there are many local optima around the global optimum, we use the simulated annealing method (SAM)[15] to avoid freezing at some local optima. For a given set of the coefficients of the three SNTs, one can search the local minimum of $\overline{\Delta E_{00,\mathrm{Train}}}$ for example with the gradient method.[14] The required 3×4 chromaticity matrix for calculating $\overline{\Delta E_{00,\mathrm{Train}}}$ is solved by regression method. Taking the measured tri-stimulus values as a $3\times N$ matrix $\boldsymbol{T}$, we have

$$\boldsymbol{T} = \begin{bmatrix} X_1 & X_2 & \cdots & X_N \\ Y_1 & Y_2 & \cdots & Y_N \\ Z_1 & Z_2 & \cdots & Z_N \end{bmatrix}. \tag{18}$$

For a given set of SNTs in the routines of the SAM computer code, we have the signals transformed by SNTs and take the results as a $4\times N$ matrix $\boldsymbol{S}$, in which

$$\boldsymbol{S} = \begin{bmatrix} R_{L1} & R_{L2} & \cdots & R_{LN} \\ G_{L1} & G_{L2} & \cdots & G_{LN} \\ B_{L1} & B_{L2} & \cdots & B_{LN} \\ 1 & 1 & \cdots & 1 \end{bmatrix}. \tag{19}$$

By regression, the chromaticity matrix can be written as

$$\boldsymbol{M} = \boldsymbol{T}\boldsymbol{S}^T[\boldsymbol{S}\boldsymbol{S}^T]^{-1}. \tag{20}$$

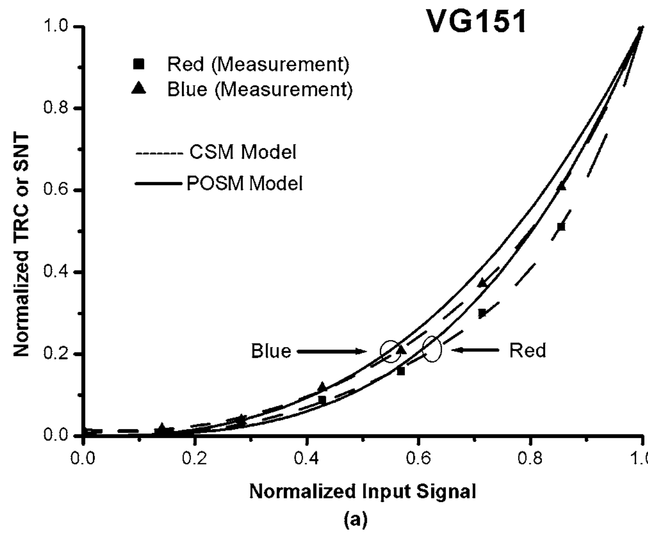
Note that this regression method has the least square fitting sense.[12] Thus we have a temporary 3×4 matrix model and $\overline{\Delta E_{00,\mathrm{Train}}}$ can be calculated. The optimization process of the SAM is a loop of basic step. For a basic step, the coefficients corresponding to the local minimum of previous step are displaced according to Gaussian probability

$$f(a_{ij}) = \frac{1}{\tau_{ij}\sqrt{2\pi}} \exp\left[-\frac{(a_{ij}-\mu_{ij})^2}{2\tau_{ij}^2}\right], \quad i = r,g,b, \quad \text{and} \quad j = 1,2,\ldots,P-1, \tag{21}$$

where a_{ij} and μ_{ij} are the SNT coefficients of current step, and previous step, respectively; τ_{ij} is the variance of the corresponding coefficient. Note that there are only P-1 independent coefficients for a TRC because of the black point correction and normalization condition. Then the displaced coefficients are taken as a starting point to search the local minimum of $\overline{\Delta E_{00,\mathrm{Train}}}$. The variances τ_{ij} are decreased for every step so that the final coefficients converge. The rule for decreasing the variance and the initial SNT coefficients and variances should be properly chosen so that the loop could converge to the desirable solution as fast as possible. We take the coefficients of the TRC for the CSM model as the initial SNT coefficients. The initial variances are set to be 1.0 and they are decreased by one tenth of their values for each step. With the SAM and regression, we can find a set of the SNTs together with a 3×4 chromaticity matrix that minimizes the average color difference.

EXPERIMENTS AND RESULTS

Two 15 in. LCD monitors were tested, which are ViewSonic VG151 and VA520 and their crosstalk spectra have been shown in Fig. 3. From their specifications, the vertical viewing angles are 100° and 110° for VG151 and VA520, respectively. The horizontal viewing angles of the two monitors are the same and is 120°. Typical contrast ratios are 350:1 and 300:1 for VG151 and VA520, respectively. Typical brightness are 210 and 250 cd/m^2 for VG151 and VA520, respectively. The monitors are warmed up for an hour before they are measured so that the measurement data do not drift with time. Tristimulus values are measured with Photo Research PR650 spectroradiometer. We take $N_s=7$ for the one-primary data set and $M_s=3$ for the two-primary data set, where $I[i]=\{36,72,109,145,182,218,255\}$, $J[i]$, $K[i]=\{36,127,218\}$ in Eqs. (15)–(17). The number of training samples is 50 for the POSM model. The two-primary data set is chosen so that the cases of low, medium, and high luminance are included. The digit count of 255 is not used in the two primary data set because of the reduced two primary crosstalk at the maximum input signal.[16] The light modulation of the liquid crystal cell of the LCD is that its transmittance is maximal when its applied voltage is zero. Therefore, the primary crosstalk due to signal interference is the minimum at the maximum input signal. The same $I[i]$ is used in Eqs. (12)–(14) for the CSM model. Two 3D-LUT models are used for comparison: $5\times 5\times 5$ and $8\times 8\times 8$ equally spaced lattices, which are denoted as 3D-LUT(125) and 3D-LUT(512) because the required number of measurement data are 125 and 512, respectively. The tetrahedral interpolation is used for the 3D-LUT models.[17] 224 random samples are measured to test the performance of these models, which are chosen by randomly selecting R, G, and B values for the input signals. For a TRC or SNT represented with a polynomial, the use of the higher polynomial order may improve the fitting accuracy of the training samples but, on the other hand, may deteriorate the prediction accuracies of the test samples because of the oscillating nature of higher order polynomial. Therefore, there exists an optimal order. We use Eqs. (7)–(9) with the optimized order of polynomial



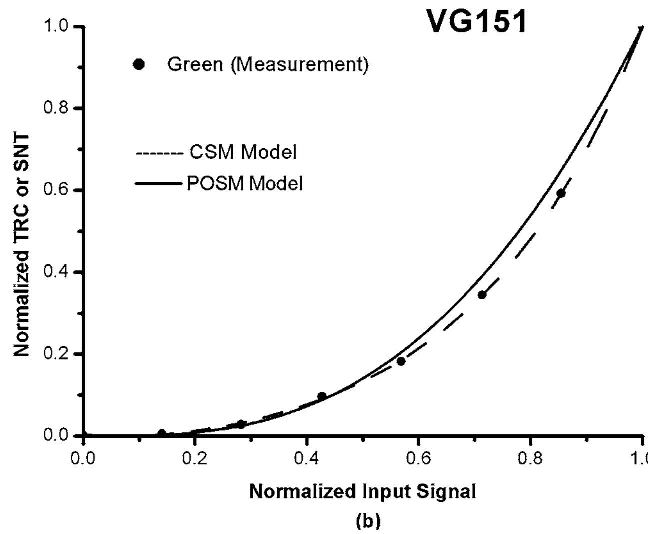


Figure 4. The TRCs of the CSM model and the SNTs of the POSM model for the ViewSonic VG 151, where red and blue primaries are shown in Fig. 4(a) and green primary is shown in Fig. 4(b).

$P=4$ for the TRC of the CSM model and the SNT of the POSM model, respectively.

With the black point and one primary data set, the TRCs of the CSM models are shown in Figs. 4 and 5 for the VG151 and VA520, respectively, by dashed lines. The measurement data are shown by symbols. One can see that the fittings are well with the polynomials. With the POSM model, we have the SNTs that are shown in Figs. 4 and 5 by solid lines. One can see that the SNTs of the POSM model differ from the TRCs of the CSM model, except that the STN and the TRC of the green channel of VA520 are almost the same. From the chromaticity matrixes of the CSM model and the POSM model, we can derive the color coordinates of the primaries and white point. Figures 6(a) and 6(b) show the chromaticity triangles of the CSM and POSM models for VG151 and VA520, respectively. The black points are corrected in Fig. 6 as in Fig. 1. The three apices of the chromaticity triangle of the CSM model are the measured x and y

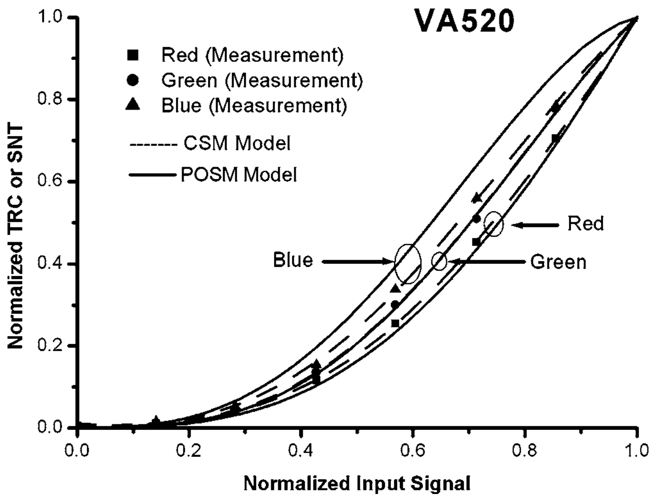


Figure 5. The TRCs of the CSM model and the SNTs of the POSM model for the ViewSonic VA520.

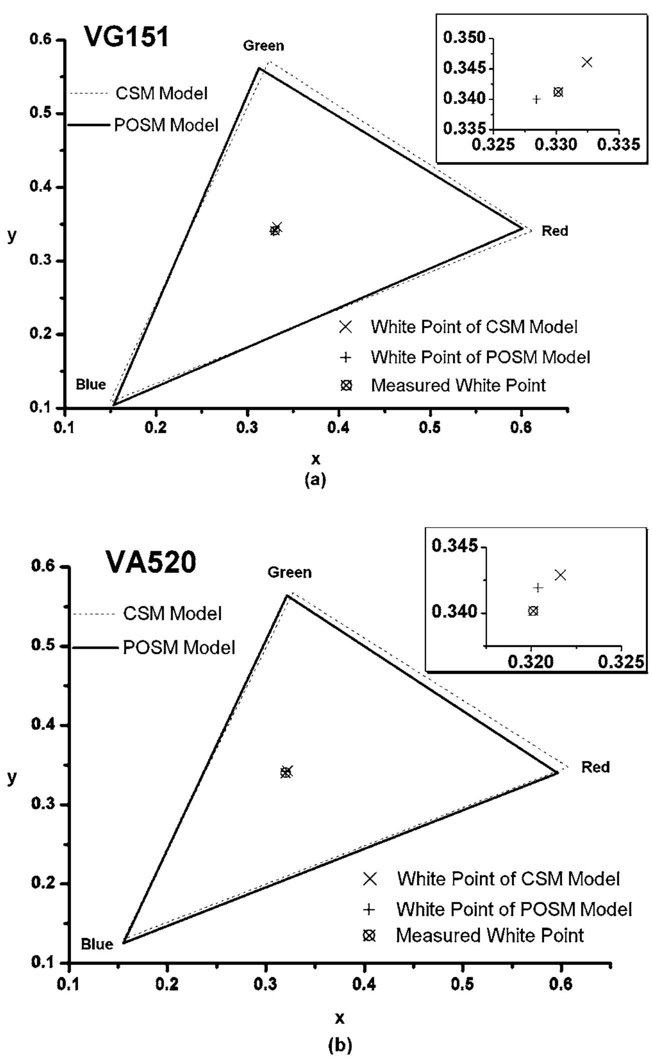


Figure 6. Chromaticity triangles and white points for the (a) ViewSonic VG 151 and (b) ViewSonic VA520. The cases with the CSM and the POSM are shown for comparison. The inset shows the enlarged area around the white points.

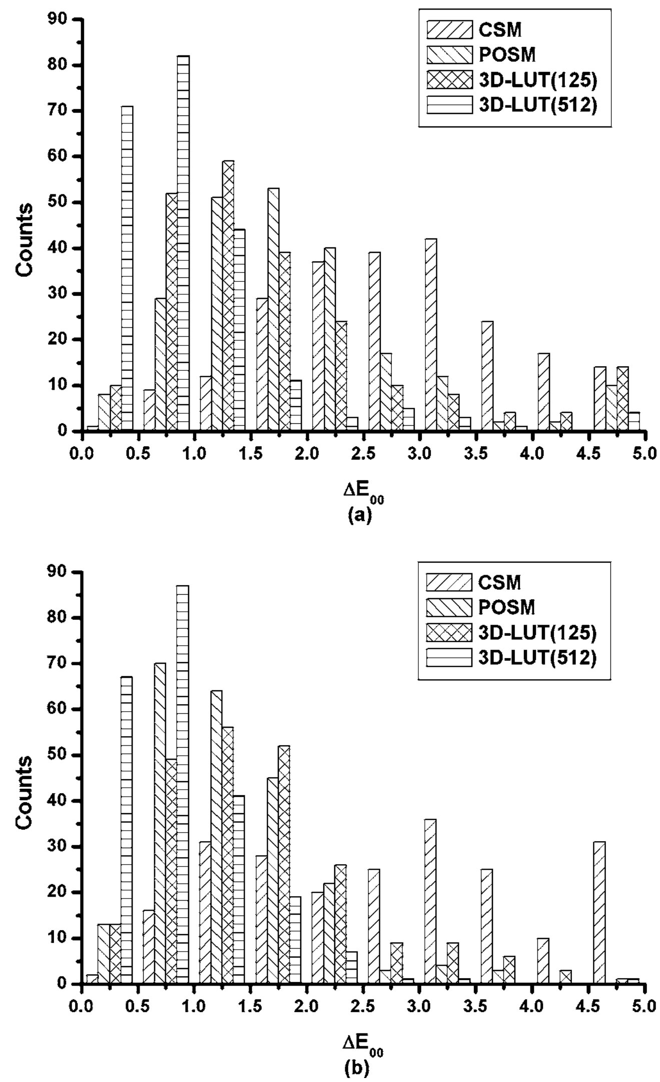


Figure 7. Color difference statistics of 224 test samples for the (a) ViewSonic VG151 and (b) ViewSonic VA520 with the CSM model, the POSM model, the 3D-LUT(125) model, and the 3D-LUT(512) model. The data with ΔE_{00} larger than 5.0 is counted in the slot from 4.5 to 5.0.

color coordinates of the primaries with maximum luminance. The three apexes of the chromaticity triangle of the POSM model are the optimized x and y color coordinates of the primaries. Since the x and y color coordinates of primaries in fact change with signal as is shown in Fig. 1, the apices of the chromaticity triangles of the POSM and CSM models are not the same. The color coordinates of the white points of the CSM and POSM models are also shown in Fig. 6, where the measured white points are shown for comparison. One can see that the three white points are different. The x and y color coordinates of the white point of the POSM model are closer to the measured white point than VG151 but the color difference is larger than VG151 because the error of the predicted stimulus Y is larger. The color differences of the measured white point and the predicted white point with the POSM model are 0.92 and 1.2 for VG151 and VA520, respectively. For comparison, the color differences of the measured white point and the predicted white point with the CSM model are 2.8 and 1.55 for VG151 and VA520, respectively.

Figures 7(a) and 7(b) show the color difference statistics of the 224 random test samples for VG151 and VA520, respectively, by using the CSM model, the POSM model, the 3D-LUT(125) model, and the 3D-LUT(512) model. The data with ΔE_{00} larger than 5.0 is counted in the slot from 4.5 to 5.0. The average color differences $\overline{\Delta E_{00,\mathrm{Test}}}$ of the test samples of VG151 are 2.93, 2.02, 1.89, and 1.04 for the CSM model, the POSM model, the 3D-LUT(125) model, and the 3D-LUT(512) model, respectively. For VA520, $\overline{\Delta E_{00,\mathrm{Test}}}$ $=2.88$, 1.33, 1.61, and 0.89 for the CSM model, the POSM model, the 3D-LUT(125), and the 3D-LUT(512) model, respectively. One can see the significant improvement with the POSM model comparing to the CSM model. For VA520, the POSM model is even better than the 3D-LUT(125) model while only 50 measurement data are used. The performance of the VA520 POSM model is better than the VG151 POSM model because of the lower primary crosstalk for VA520. If we remove the two primary measurement data from the training samples for the optimization of the POSM model, $\overline{\Delta E_{00,\mathrm{Test}}}=2.64$ and 1.45 for VG151 and VA520, respectively. One can see that the increase of the color difference without the two primary measurement data is more significant for VG151 also because of more serious two primary crosstalk.

The accuracy of the backward POSM model is also checked. For the 224 random test samples, the backward POSM model is used to convert their measured tristimulus values to output signals, then the tristimulus values of the output signals are interpolated from the 3D-LUT(512) model. The average color differences of the backward models are 2.32 and 1.27 for VG151 and VA520, respectively, which are about the same as the corresponding forward models.

CONCLUSIONS

The device model of a display is usually characterized with the CSM model. Black point and one primary measurement data are used to derive the parameters of the the CSM model. However, when there are variant primary chromaticity and primary crosstalk, the CSM model works less well. We propose the POSM model for characterizing the LCD monitors with variant primary chromaticity and primary crosstalk. This method is the same as the CSM model except that black point, white point, one primary measurement data, and two primary measurement data are taken as the training samples for optimizing the SNTs and chromaticity matrix. As the configuration of the POSM model is the same as the CSM model, its backward model is simple and can be implemented for video applications. The polynomial function is taken as the SNT. The optimization process comprises the SAM for optimizing the coefficients of the SNTs and the regression method for calculating the chromaticity matrix. Two LCD monitors are characterized. The required number of measurement data are 22, 50, 125, and 512 for the CSM model, the POSM model, the 3D-LUT(125) model, and the 3D-LUT(512) model, respectively. The results show the average color differences of 224 test samples for the two tested LCD monitors are 2.02 and 1.33 with the forward POSM model, and are 2.32 and 1.27 with the backward POSM model. The primary crosstalk of the LCD monitor with a higher average color difference is more serious than the monitor with a lower average color difference. The performance of the POSM model for the LCD monitor with lower primary crosstalk is better than the CSM model and the 3D-LUT(125) model but is worse than the 3D-LUT(512) model. The performance of the POSM model for the LCD monitor with higher primary crosstalk is better than the CSM model but is slightly worse than the 3D-LUT(512) model. Further studies are required for the choice of training samples and the method for further reducing the color difference.

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