Spectral simulation of the color-stimuli of the LCD displays without spectrophotometrical measuring

K. Samu and A. Szakaly-Molnar
Budapest University of Technology and Economics; Department of Mechatronics, Optics and Engineering Informatics;
Budapest, Hungary
samuk@mogi.bme.hu; maniko@mogi.bme.hu

Abstract—**Liquid crystal display technology requires the spectral power distribution measurement of the displayed RGB colors. Such measurement tasks are typically resolved by means of spectrophotometers and the measured data is used in several applications. The costs of color management methods have been decreasing recently mainly because of the reduced costs of spectrophotometric equipment. However the hardware costs are still the limit for a general use. Our intention was to develop a method to enable the determination of spectral power distribution with basic photometry without the use of costly spectrophotometers.**

Keywords — LCD display SPD, color management, ICC profile, Calibration

I. INTRODUCTION

In order to determine spectral power distributions based on RGB values the spectral curve characteristics and the location of principal points have to be similar. In the case of CRT displays the similarity of the spectral characteristics between different monitors is well established as in the preceding years the same kinds of phosphors have been used in their manufacturing [1]. In the case of LCD displays there are several technological parameters that can modify the spectral power distributions [2]. The most important ones are the effects of the primary light sources and the color filters.

During the initial phase of our research we have aimed to discover the relations between the different spectral characteristics of commercially available LCD displays [3]. The question was if there could be similarities such as the ones found in the case of CRT monitors [4].

In the last couple of years approximately 60 different monitor types of five manufacturers (Asus, Apple, Fujitsu-Siemens, LG, NEC) [5] have been spectrally and photometrically investigated. We have concluded that the monitors measured have related spectral power distributions (Fig.1.) [6].

The differences found between the displays are primarily related to the altered color temperatures and gamma curves. Therefore we can assume that the technologies applied at the different LCD manufacturing sites might be very similar.

The LCD displays that had different spectral characteristics can be taken as few extremities only meaning that the similarity of LCD monitors as well as CRTs in terms of spectral power distribution can be considered significant [7,8].

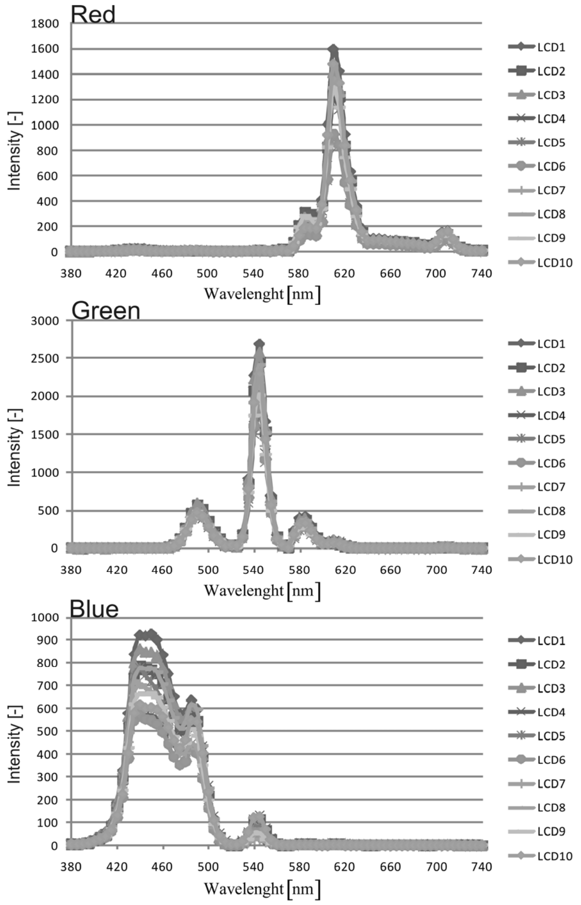

Figure 1. Ten different types of LCD monitor R-G-B primers similarity for the spectral output-distribution

The other experiment necessary for the calculation of the spectral power distribution is the examination of the effect on the overall intensity when changing the DAC values of the three primaries (RGB) [9].

A digital-to-analog converter (DAC) [10] is configured to convert a digital signal into an analog voltage. DAC values are scaled numerical values (0-255) corresponding to the electron gun control levels required to drive the associated phosphor set at various luminous intensities.

Our specific tests have given the conclusion that the change in DAC values generates a constantly proportional change in the spectral power distribution of each primary (Fig.2.).

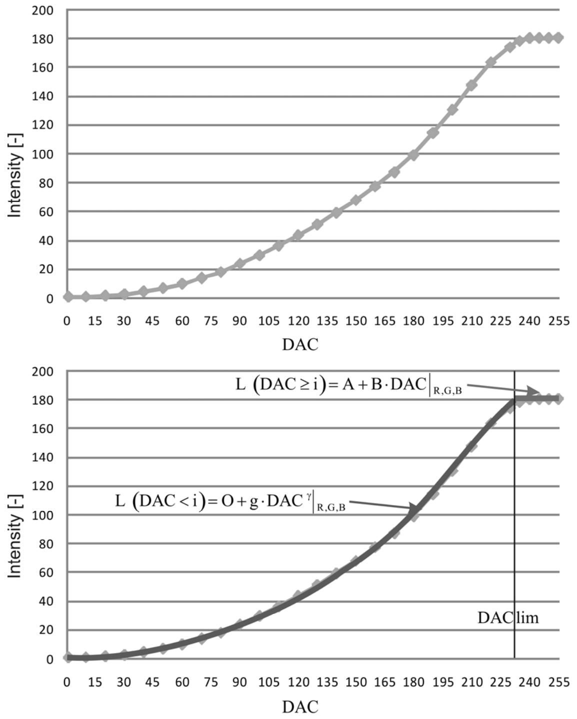

Figure 2. G primary output-distribution belong to different DAC values

Therefore from any primary R, G or B spectral power distributions the LCD display characteristics corresponding to the specific DAC value can be calculated with multiplying by a given constant value (1).

$$\Phi(\lambda) = k \cdot \Phi_0(\lambda)\big|_{R,G,B} \tag{1}$$

Equation (1), "$\Phi(\lambda)$" is the calculated spectral power distribution, "$\Phi_0(\lambda)$" is the normalized reference primary spectral power distribution and "k" is the constant value.

II. METHODS

The determination of the spectral power distribution is carried out by specific software using the algorithm described above. The only input data to the software is the specific LCD monitors' gamma characteristics.

The LCD's gamma characteristics can be displayed changing with luminance and DAC values. In this case we can observe that after a specific DAC_{lim} value the gamma curve of the monitor begins to flatten. As in our software we wanted a simple a fast gamma curve fitting, we have separated the gamma curve into two sections. Between the DAC values 0 and 170…240 we have applied the fast and simply calculated power fitting method used also at the CRT monitors (2) [11].

$$\mathrm{L}\left(\mathrm{DAC} < \mathrm{DAC}_{\mathrm{lim}}\right) = \mathrm{O} + g \cdot \mathrm{DAC}^{\gamma}\big|_{R,G,B} \tag{2}$$

Equation (2), the "L[cd/m^2]" is the luminance, "O" is the offset luminance at 0 DAC, "g" is the gain, "γ" is the display's gamma value.

At higher DAC values (above 170…240) we have applied a linear regression for the flattened gamma characteristics (3).

$$\mathrm{L}\left(\mathrm{DAC} \geq \mathrm{DAC}_{\mathrm{lim}}\right) = A + B \cdot \mathrm{DAC}\big|_{R,G,B} \tag{3}$$

Equation (3), the "A" and "B" are the linear fit's coefficients.

The gamma characteristics can also be determined via visual photometry. In such case there is absolutely no need for instruments [12] to measure the gamma characteristics along with the spectral power distribution of any $DAC_{R,G,B}$ value. We are currently conducting research on this issue as well.

In the previous methods we have shown that the ratio between the spectral power distributions at each wavelength at two given DAC values can be considered as constant (4).

$$\frac{\Phi_{DAC\,1}(\lambda_i)}{\Phi_{DAC\,2}(\lambda_i)}\bigg|_{R,G,B} \approx const\,. \tag{4}$$

Equation (4), the "i"=350…700 nm and "$\Phi_{DAC1}(\lambda_i)$" and "$\Phi_{DAC2}(\lambda_i)$" are two arbitrary red, green and blue spectral power distributions at the given DAC values.

This enables us to determine spectral power distributions at any DAC values based on the measurement of several LCD monitors' $\Phi_{0\ R,G,B}(\lambda)$ average spectral power distributions at $DAC_{R,G,B}$=255 intensity using calculated proportionality factors. As our gamma characteristics are defined with photometric dimensions, we need to calculate the proportional conversion based on the V_λ function.

The software based on our method has the initial data on the V_λ function and on the $\Phi_{0\ R,G,B}(\lambda)$ primary spectral characteristics normalized to unity photometrical units with the $k_{R,G,B}$ factor. Such spectral power distributions calculated with the $k_{R,G,B}$ factors and the V_λ function have equally unit areas (5).

$$\int_{350}^{750} k \cdot \Phi_0(\lambda) \cdot V_\lambda(\lambda) = \int_{350}^{750} \Phi_{norm}(\lambda) = 1\big|_{R,G,B} \tag{5}$$

Equation (5), the 1 is a relative photometrical unit.

The correction with V_λ is necessary because of the photometrical-style of the gamma-measuring. Before V_λ multiplication, the shape of the functions is equal with the average of the LCD monitor's spectral output-distribution characteristics by reason of our numerous previous measurements.

If these $\Phi_{norm\ R,G,B}(\lambda)$ photometric spectral power distributions are multiplied by the LCD monitor's photometric (luminance) value at the given DAC value (calculated from the gamma) we get the spectral power distribution comprising the V_λ correction (6).

$$\Phi_{DAC}(\lambda) = L(DAC)\cdot\Phi_{norm}(\lambda)\cdot\frac{1}{V(\lambda)}\Big|_{R,G,B} \qquad (6)$$

After an inverse V_λ calculation we can determine the $\Phi_{DAC\ R,G,B}(\lambda)$ spectral power distribution at any given DAC value (Fig.3.).

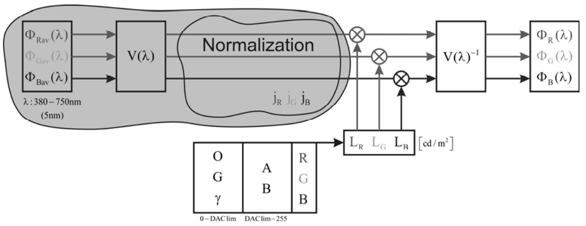

Figure 3. Calculation of the *$\Phi_{R,G,B}(\lambda)$* spectral-output characteristics from the reproduced $DAC_{R,G,B}$ values on optional LCD monitors

III. RESULTS

We have tested our method on a commercially available Samsung SyncMaster 2043BW LCD monitor. We have measured the primary luminances between 0 and 255 DAC values with 10 DAC steps. During the tests the monitor's contrast and luminance was 100% and the measuring instrument (Spectrocam 75 RE spectrophotometer) was calibrated after every measurement. All three primaries were measured separately, remeasuring each value five times. The results of our gamma measurements are displayed in Table 1.

TABLE I.
THE GAMMA-PARAMETERS OF THE SAMSUNG SYNCMASTER 2043BW MONITOR.

	O [cd/m2]	**G [cd/m2]**	**γ [-]**	**A [cd/m2]**	**B [cd/m2]**
R	0,460	0,0002	2,315	63,77	0,0098
G	0,460	0,0012	2,191	174,24	0,0248
B	0,460	0,00003	2,488	20,22	0,0054

The determination of the DAC_{lim} value is automatic in the software. In our test this was 230 for all three primaries.

We have generated nine different color stimuli on the monitor using the DAC values in column 3 of Table2. The color stimuli displayed on the monitor were also measured spectrally. We have compared the real measurement results with those of the simulation software. We have created the simulated spectral power distribution from the parameters of Table1 using the average $\Phi_{0\ R,G,B}(\lambda)$ of 10 LCD monitors.

Figure 4 shows the comparison of the measured and simulated results.

It is important to state that while the calculated spectral power distributions should be handled as relative values, the measured values are absolute. Therefore in each case there is need for a multiplying factor to enable the comparison.

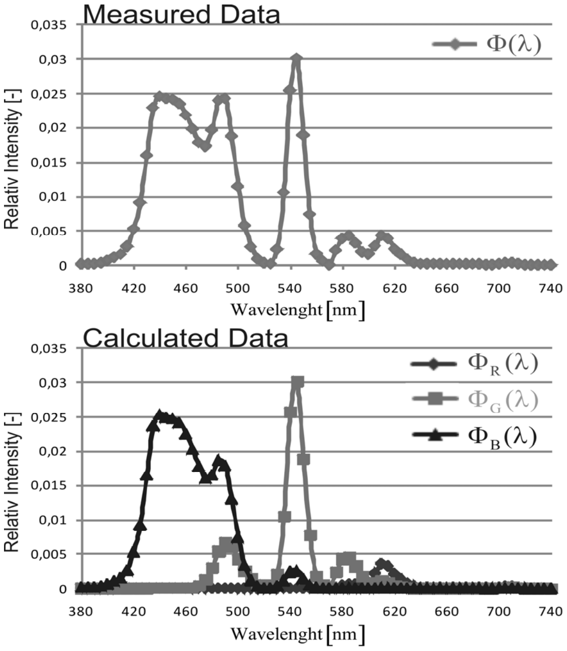

Figure 4. The $\Phi_{Measured}(\lambda)$ and the $\Phi_{Calculated}(\lambda)$ spectral-output characteristics from the color of the R(70)-G(140)-B(210) values

For the better understanding of our method's accuracy we have carried out the colorimetric analysis both for the simulated and the measured results. Table 2 shows the ΔE^*_{ab} color differences between the stimulus and simulation at $DAC_{R,G,B}$ based on their CIE Lab coordinates [13,14].

The measurement results show that at any given stimulus with a specific DAC intensity (Table 2) the average color differences are below 1.5 (ΔE^*_{ab} =1,46). This value verifies the success of the simulation because it can be considered as only slightly perceivable.

Color stimuli containing 0 or other low DAC values the ΔE^*_{ab} appears to be higher. However these color differences can also be considered as adequate from our simulation process.

For the increase in the color differences we can state the following reasons:

1) Errors related to gamma fitting. Increasing the accuracy of the regression method should reduce this error.
2) At low DAC levels the measurement error of photometric instruments is relatively high. Using more sophisticated equipment this error also can be reduced.

For a method using only calculations the results can be considered as acceptable.

TABLE II.
ΔE^*_{AB} COLOR-STIMULI DIFFERENCE BETWEEN THE MEASURED AND THE SIMULATED COLOR-STIMULI.

DAC_R	**DAC_G**	**DAC_B**	**ΔE^*_{ab}**	**STD**
70	140	210	1,07	0,1099
70	210	140	1,56	0,0076
140	70	210	1,61	0,0082
140	210	70	1,82	0,0227
210	70	140	1,31	0,0087
210	140	70	1,42	0,0130
0	0	150	7,48	0,0133
0	150	0	1,91	0,0137
150	0	0	6,30	0,1208
90	245	90	2,34	0,0270
245	90	90	1,78	0,0318
90	90	245	1,27	0,0128
0	200	250	3,47	0,0129
0	250	200	0,61	0,0232
200	0	250	10,03	0,0160
200	250	0	1,87	0,0158
250	0	200	6,22	0,0862
250	200	0	1,27	0,0086
0	50	240	3,45	0,0070
0	240	50	1,93	0,0086
50	0	240	9,35	0,0173
50	240	0	1,42	0,0050
240	0	50	2,65	0,3758
240	50	0	5,31	0,1990

IV. CONCLUSION

Our measurement and calculations certify that our goal has been achieved in determining the LCD monitor's spectral power distribution at any given RGB combination while avoiding spectrophotometrical techniques and only knowing the gamma characteristics. The measurement of the gamma characteristics can be realized with a light meter using photodetector or even with visual estimation.

Thus a cost effective method has been described for the calculation of CIE color coordinates from spectral data calculated from RGB values. A transformation with similar accuracy could be realized only with a color management method using much more sophisticated instruments and softwares.

Our method also enables us to use it in color management applications. We can apply the photometric gamma measurements in order to determine the ICC profiles of LCD displays. This means that the majority of commercially available LCD monitors could be calibrated using a simple photometer and software.

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