

LCD AND MOBILE COLOR CHARACTERIZATION USING SIMPLE AND MASKING MODEL

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Abstract

The characterization of a display is based on defining the transformation from dependent colour space typically RGB and a device independent colour space such as CIE XYZ or LAB. In this project, we evaluated two models for achieving this transformation; the polynomial model and the masking model, implementing them for a LCD monitor and a Samsung galaxy J7 mobile display and we compared the reproduction accuracies of both models. The LCD provided the data to determine the reliability of both models before they were implemented for the mobile display to determine which model better characterizes the mobile display. The spectral radiance measurements of both display devices were taken with a Minolta CS-2000 spectroradiometer for this purpose and the data was processed and analyzed. The colour differences were calculated using the CIELAB formulas for colour difference between each model and a generated set of test colours. Our results showed that the masking model proved a more accurate model for the characterization of the Samsung galaxy J7 mobile display. The masking model was more accurate for predicting the colours than the polynomial model where the highest value of the colour difference of the polynomial model $\Delta E^ = 17.81$ and the colour difference for the masking model $\Delta E^* = 12.75$ for Samsung J7 mobile display.*

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As display technologies rapidly evolved, it was imperative to effectively represent and reproduce images on these display devices. To this end, the International Colour Consortium (ICC) proposed a process that converts input colour values to output colour values via a profile connection space (PCS). The effectiveness of this process however, depends on each device having a device profile that describes the relationship between the device's colour space and the device-independent colour space. This resulted in the problem of the burden of transporting input device's profile with the image and did not account for situations when there is no profile associated with the image. As an alternative, the sRGB colour space was proposed as a result of which the sRGB colour space is assumed as the default colour space for images without profiles [1]. While ICC colour management and sRGB standards have been extremely successful especially to the end users, image reproduction have remained imprecise. This has created the need to understand the characteristics of devices that implement many of these display technologies so as to define some relationship between colour properties peculiar to such devices and colour attributes independent of the devices for consistent and qualitative colour reproduction. This is achieved by defining the relationship between dependent colour space typically RGB and a device independent colour space typically CIE XYZ or LAB that describes the colour perception of an average observer. Finding the transformation from the device dependent colour space to device independent colour space for a display device is what is called display characterization. Characterization of display devices is an important aspect of colour management systems. It gives the ability to be able to predict the colours that will be displayed when a given set of RGB

values are used to drive a display and also the set of RGB values to be entered to a display device to achieve a specific colour representation. For many display devices the procedure for characterization can be summed into two stages of performing a linearisation, often termed gamma correction for the device and then transforming the linearised values into the CIE XYZ tristimulus values [1], [2]. Many models have been proposed for display characterization. Particularly well known for cathode ray tube (CRT) displays is the gain-offset-gamma model (GOG) where the relationship between a device space and a CIE colour space at a series of discrete measured coordinates within the colour space is defined by look-up tables (LUT) [2]. For the purpose of this study, we will evaluate the theory of the Polynomial model [3] and the Masking model [4] for the characterization of a mobile phone display driven by an active matrix organic light emitting diode (AMOLED) technology, discuss the experimental set up for implementing both models as well compare their results and accuracies.

Unlike CRTs whose colour characteristics have been comprehensively studied, LCDs and newer display technologies yet do not have a universally accepted model for characterization as the GOG model for characterizing CRTs has not been adequate for the characterization of modern display technologies mainly because of the non-constancy of primary chromaticities. However, LCDs continue to gain popularity in both consumer and professional markets as they are now offering compactness and low power consumption, combined with higher spatial resolution, dynamic range and better image qualities than traditional CRTs [5]. AMOLEDs have also gain popularity especially in the smartphone market where portability and low power consumption are primary to any display technology employed. In attempting to characterize a LCD, one factor to be consider is the viewing angle. Viewing an LCD screen from different angles causes luminance and chromaticity value shift and this shift is because of leaking light and it varies for different displays [6]. It is also important to consider ambient flare and offset of the display. Offset results in a screen not being completely black when the digital signal count is set to zero. Flare and offset give rise to errors in measurement if not taken into account and thus it is necessary to compensate for flare and offset. Ideally, the environment to obtain characterization data of a display is in a dark room with no external light source of any kind to eliminate flare caused by the reflection of ambient light. This however does not account for the offset of the display. As such, the offset of the display is accounted for when computing the XYZ tristimulus value of the display. Mathematically compensating for the offset of the display means determining the XYZ tristimulus value of black for each of red, green and blue channel. That is when

the input values are set to minimum $(0, 0, 0)$ expressed as:

$$\begin{bmatrix} X_0 \\ Y_0 \\ Z_0 \end{bmatrix}_{k,min} = \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_{r,min} = \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_{g,min} = \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_{b,min} \quad (2.1)$$

XYZ tristimulus values can be calculated theoretically by the following equations:

$$X = 683 \sum_{380}^{780} L_{\lambda,r} \bar{x}_{\lambda} d\lambda \quad (2.2)$$

$$Y = 683 \sum_{380}^{780} L_{\lambda,g} \bar{y}_{\lambda} d\lambda \quad (2.3)$$

$$Z = 683 \sum_{380}^{780} L_{\lambda,b} \bar{z}_{\lambda} d\lambda \quad (2.4)$$

where $L_{\lambda,r}$, $L_{\lambda,g}$, $L_{\lambda,b}$ are the spectral radiance of the screen and \bar{x}_{λ} , \bar{y}_{λ} , \bar{z}_{λ} are the colour matching functions for red, green, blue respectively.

The tristimulus value of black is then used to determine the maximum tristimulus value for red, green and blue channels as well used to determine the tristimulus values of the display [7]. Taking into consideration this factor, characterization aim is to predict accurately for a given set of digital input values (RGB) to a device, the XYZ that will be displayed and the reverse transform to get back the digital values according to the matrix equation below [3], [7]:

$$\begin{bmatrix} R(d_r) \\ G(d_g) \\ B(d_b) \end{bmatrix} = \begin{bmatrix} X - X_0 \\ Y - Y_0 \\ Z - Z_0 \end{bmatrix} \begin{bmatrix} X_{R,max} & X_{G,max} & X_{B,max} \\ Y_{R,max} & Y_{G,max} & Y_{B,max} \\ Z_{R,max} & Z_{G,max} & Z_{B,max} \end{bmatrix}^{-1} \quad (2.5)$$

Two models of characterization we are evaluating to achieve these are the polynomial model [3] and the Tamura-Tsumura-Miyake masking model [4].

2.1 Polynomial Model

The polynomial model is a linear model that attempts to mathematically model the response of the LCD by assuming the independence of each channel of the display. The polynomial model achieves this by fitting the response of the display

to a quadratic polynomial curve for each channel of the display according to this quadratic equation:

$$R(d_R) = a_r d_r^2 + b_r d_r + c_r \quad (2.6)$$

Where R indicates red and this should be done as well for the green and the blue channels. This curve defines the relationship between the input values of the display and the output luminance of the display. The model can be achieved in three stages. In the first stage, the aim is to determine the 3×3 matrix of maximum tristimulus values of the red, green and blue channel of the display. That is when the input values are $(255, 0, 0)$, $(0, 255, 0)$ and $(0, 0, 255)$. The second stage is to linearise the non-linear relationship between the input values for red, green and blue and the luminance values using the fitted function. This can be achieved by using interpolation or polynomial fitting. The final stage will now be to apply the 3×3 matrix of maximum tristimulus values for RGB to selected linearised values for red, green and blue channels to determine the XYZ tristimulus values of the display [3], [4].

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} X_{R,max} & X_{G,max} & X_{B,max} \\ Y_{R,max} & Y_{G,max} & Y_{B,max} \\ Z_{R,max} & Z_{G,max} & Z_{B,max} \end{bmatrix} \begin{bmatrix} R(d_R) \\ G(d_G) \\ B(d_B) \end{bmatrix} + \begin{bmatrix} X_0 \\ Y_0 \\ Z_0 \end{bmatrix} \quad (2.7)$$

where $X_{R,max}$, $X_{G,max}$, $X_{B,max}$ represents the maximum XYZ of each channel after black correction and X_0 , Y_0 , Z_0 are the tristimulus of the offset of the display.

2.2 Masking Model

This model of characterization is credited to Tamura, Tsumura and Miyake. Working together, they proposed a means of accounting for the channel interaction of a display by using secondary and tertiary colours to approximate the effects of the overlap of the red, green and blue channels of the display. It is similar in concept to under colour removal (UCR) in printing. The core idea of this model is to break down colour into 3 colour components. The primary colours composed of red, green and blue, the secondary colours consisting of cyan, magenta, yellow and the tertiary colour of gray. For an arbitrary input of RGB, we consider the relative size of the channel inputs and replace each with the equivalent secondary or tertiary colour according to additive colour theory. The minimum value is replaced by a tertiary

colour, the middle value is replaced by a secondary colour and the maximum value will be a primary colour as illustrated in the figure below [3]:

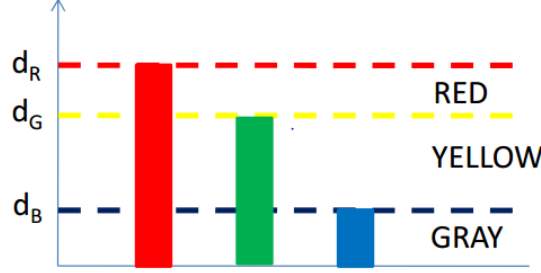


Figure 2.1: Representation of Masking Model.

As an example if we consider a channel input of (250, 180, 60) for red, green and blue channels respectively, since blue is less than green and red, the intensity of blue at 60 is replaced by the intensity of gray at channel input of 60. Next the mixture of the remaining two colours is considered and the intensity of green at 180 is replaced by the intensity of the sum of red and green which is yellow at the intensity of 180 minus 60. That is at the channel intensity of yellow at 180 minus the channel intensity of yellow at 60. Finally the intensity of the maximum channel input is now represented by intensity of the maximum colour after the subtraction of the second maximum channel input from the maximum channel input. In the case of this example, the difference in the intensity of red at 250 and red at 180. Finally, the XYZ tristimulus values of the display is calculated from this approximate representation of a XYZ tristimulus values of primary, secondary and tertiary colour. The whole procedure is summarized according to the equation below [3]:

$$I(d_R, d_G, d_B) = I_k(d_B) + I_y(d_G) - I_y(d_B) + I_R(d_R) - I_R(d_G) \text{ if } d_R < d_G < d_B \quad (2.8)$$

The XYZ of the individual channels taking into consideration the offset black correction discussed above can be calculated as follows [3]:

$$I_i(d_i) = C_i(d_i) \begin{bmatrix} X_i \\ Y_i \\ Z_i \end{bmatrix} + I(0, 0, 0) \quad i = R, G, B, C, M, Y, Gr \quad (2.9)$$

$C_i(d_i)$ for measured input channel d_i can be calculated according to the equation below and any possible value of C_i can be estimated by interpolating measured C_i [3]:

$$C_i(d_i) = I_i(d_i) - I(0, 0, 0)' \begin{bmatrix} X_i \\ Y_i \\ Z_i \end{bmatrix} \quad (2.10)$$

Note that implementing this model requires considering the relative intensities of RGB for the input channel and this intensity relations should determine the equivalent colour representation based on additive colour mixing.

2.3 CIELAB Colour Space

CIE $L^*a^*b^*$ is known by CIELAB Colour Space is used for specification of surface colours. We can calculate a colour difference for two stimuli in CIELAB space by the Euclidean distance in the space defined by two points to represent the stimuli in the space given by the following equations [4]:

$$L^* = 116 \left(\frac{Y}{Y_n} \right)^{\frac{1}{3}} - 16 \quad (2.11)$$

$$a^* = 500 \left[\left(\frac{X}{X_n} \right)^{\frac{1}{3}} - \left(\frac{Y}{Y_n} \right)^{\frac{1}{3}} \right] \quad (2.12)$$

$$b^* = 200 \left[\left(\frac{Y}{Y_n} \right)^{\frac{1}{3}} - \left(\frac{Z}{Z_n} \right)^{\frac{1}{3}} \right] \quad (2.13)$$

where X_n, Y_n, Z_n are the tristimulus values for the appropriately chosen white reference. The values X_n, Y_n, Z_n are sometimes known as neutral point as they look chromatically neutral under certain illumination under certain adaptations. Here, L^* represents the Lightness, a^* represents redness-greenness and finally b^* represents yellowness-blueness. Also, in the expression of a^* , X represents the amount of red light and Y represents amount of green or yellow light. In the similar manner in the expression of b^* , Y represents amount of green or yellow light and Z represents the amount of blue light. Now, if $a^* > 0$ we have reddish colour, $a^* = 0$ neither red nor green and $a^* < 0$ green colour. Again, if $b^* > 0$ we have yellow, $b^* = 0$ neither yellow nor blue and $b^* < 0$ blue colour. If $a^* = b^* = 0$ we have achromatic colours.

2.4 CIELAB Colour Difference

The associated colour difference metric of CIELAB has become widely accepted and it can be interpreted as the Euclidean distance between two points in CIELAB space. This colour difference equation is given by:

$$\Delta E_{ab}^* = \sqrt{(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2} \quad (2.14)$$

where

$$\Delta L^* = L_T^* - L_S^* \quad (2.15)$$

$$\Delta a^* = a_T^* - a_S^* \quad (2.16)$$

$$\Delta b^* = b_T^* - b_S^* \quad (2.17)$$

In the above equations the subscripts refer to the standard S and the Trial T. Industrial applications utilises this colour difference as we can have a visual match between the standard sample and the trial sample [4].

Experimental Setup and Procedure

This chapter includes the equipments, the preparation steps prior to taking the measurement and the collection of data obtain from each of the measurement.

3.1 The principle of the Minolta CS2000

The operation of the Minolta CS2000 is as shown in Fig. 3.1. The light beam pass through the objective lens and the light from the measurement area pass through the center of the aperture mirror to the optical fiber. The remaining light is guided to finder optics by aperture mirror. Thus, the measurement area appears like a black circle when it is viewed through the finder. When the light enters the optical fiber, it is reflected several times so that it is mixed equally in a uniform manner. The light then passes through the collimator lens and is incident on plane diffraction grating where it is dispersed and focused by condenser lens in accordance with wavelengths. An array sensor is placed at the focus point of this condenser lens. The A/D convertor converts the amount of detected light into digital values based on the spectral luminance and chromaticity is calculated by the processing section of the CS-2000 spectroradiometer [8].

3.2 The equipments used

Konica-Minolta CS2000 spectroradiometer was used for the radiometric measurements in the all parts of the experiments. A LCD was measured in the first part of the experiment while for second and third part of the experiment Samsung J7 mobile display was measured. A Laptop running CS-S10w program connected with

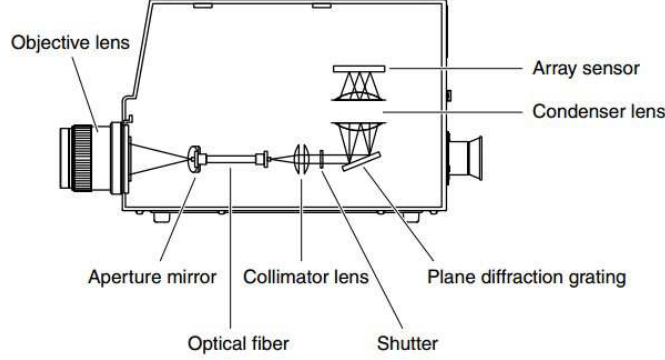


Figure 3.1: Sensor section view of the spectroradiometer CS-2000

the spectroradiometer as shown in Fig. 3.2.

3.3 Equipments setup preparation

The first part of the experiment aimed to measure the spectral radiance of the LCD display as the test data. The spectroradiometer was positioned directly horizontal with its lens facing the screen of the display at about one meter as shown in Fig.3.3. The focus of the lens in the spectroradiometer was adjusted for the maximum accuracy. The monitor was left to warm up 60 minutes before the measurement were taken to ensure stability. A (5 cm x 5 cm) coloured square was the imaged area on the screen of the monitor and measured by the spectroradiometer. The Konica-Minolta CS2000 was positioned in such a way that the center of the square was measured with 1° aperture. In the second measurement we measured the spectral radiance of the Samsung J7 mobile display. The third measurement was to obtain the radiometric measurements of random colours on the mobile display. In both parts of the experiment, the spectroradiometer was positioned directly perpendicular to the screen of mobile in about half meter away as shown in Fig.3.4. The mobile phone was set at maximum illuminance (outdoor illuminance) and the automatic setting such as the automatic brightness and the automatic lock screen were switched off in the second and third spectral radiance measurements. A coloured

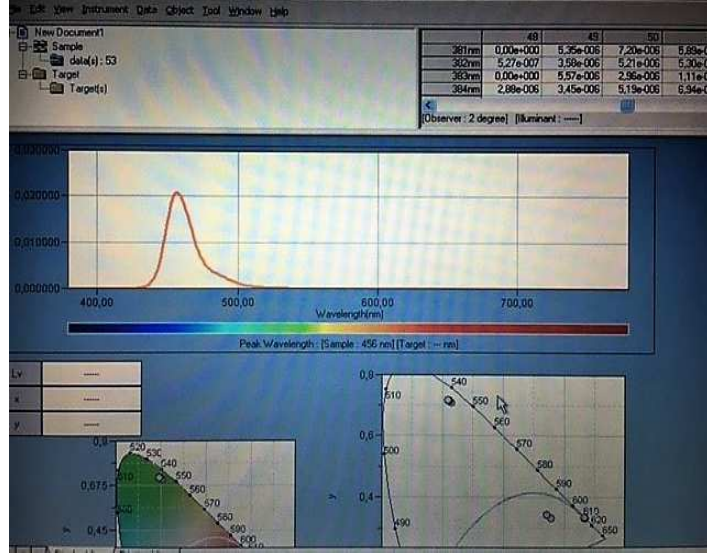


Figure 3.2: The CS-S10w program used for the measurements

square was the imaged area on the screen of the mobile phone and measured by the spectroradiometer as shown in Fig.3.5 and Fig.3.6. All the measurements were performed in a dark laboratory with a fixed distance between the LCD monitor and the spectroradiometer in the first part of the experiment and between the mobile phone and the spectroradiometer in the second and third part of the experiment to ensure accuracy of the measurements and minimize ambient flare.

3.4 Collected data from the measurements

Three set of spectral radiance measurement data were taken. The first measurement was done to obtain the spectral radiance of the LCD monitor of seven colours (Red, Green, Blue, Yellow, Cyan, Magenta and Gray) for each channel a scale of fifteen equal step from 0-255 were taken to obtain the data. The colour changed for each colour from black to the brightest colour and resulted in 126 data columns of data over the wavelength range from 380nm to 780 nm. In second measurement 126 coloured patches were created on a computer using MATLAB. Eighteen pictures were design for each of the seven colours (Red, Green, Blue, Yellow, Cyan, Magenta

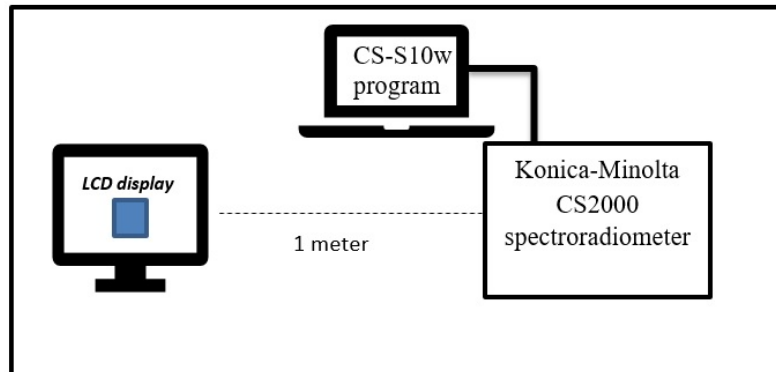


Figure 3.3: The first setup for the radiometric measurement of the LCD display using the sepctroraiameter



Figure 3.4: The experimental set up of the second part of the measurement using Samsung J7 mobile phone

and Gray) and then transferred to the mobile phone. The last measurement was done by measuring 50 different coloured patched and the white of the mobile phone which were created in MATLAB using random matrix as shown in Fig. ??.



Figure 3.5: The colored picture for the display on the mobile phone

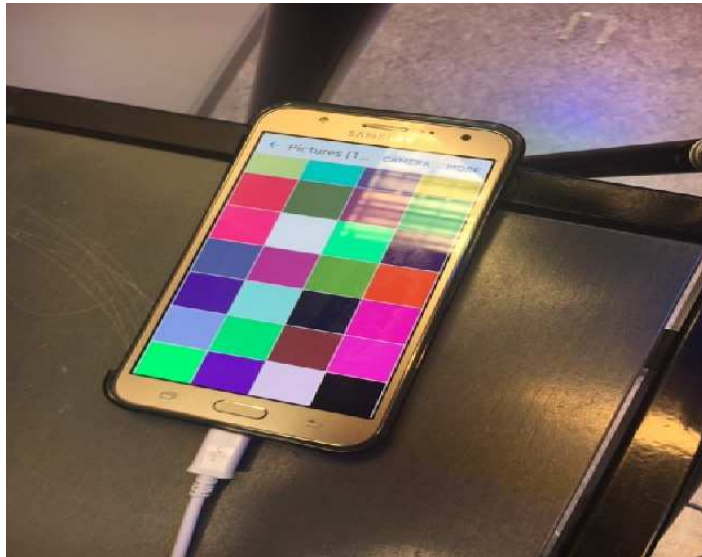


Figure 3.6: The random color picture for test in the third part of the measurement of the mobile display

3.5 Obtain colour characteristics data

Nonlinear relationship between the RGB and the digital counts for LCD are given by the figure below:

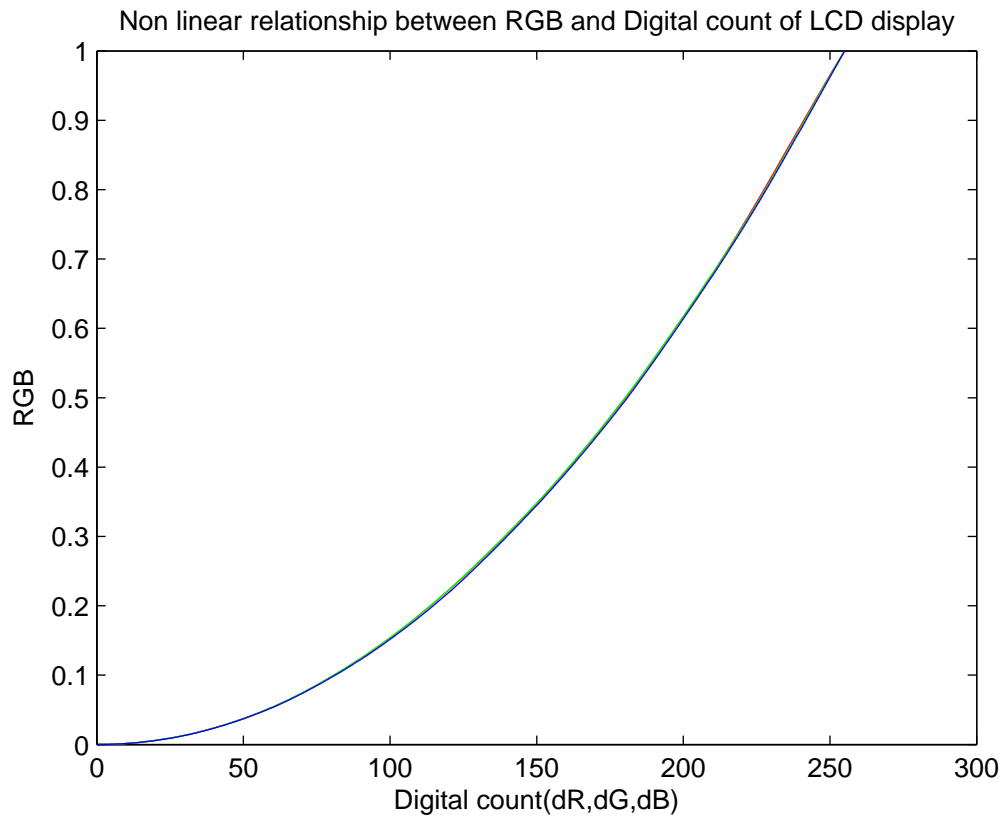


Figure 3.7: Non linear curve for lcd from Polynomial model.

Nonlinear relationship between the RGB and the digital counts for Samsung Galaxy-J7 Display are given by the figure below:

Non-linear relationship between RGB AND Digital count of Samsung Galaxy J7 mobile displa

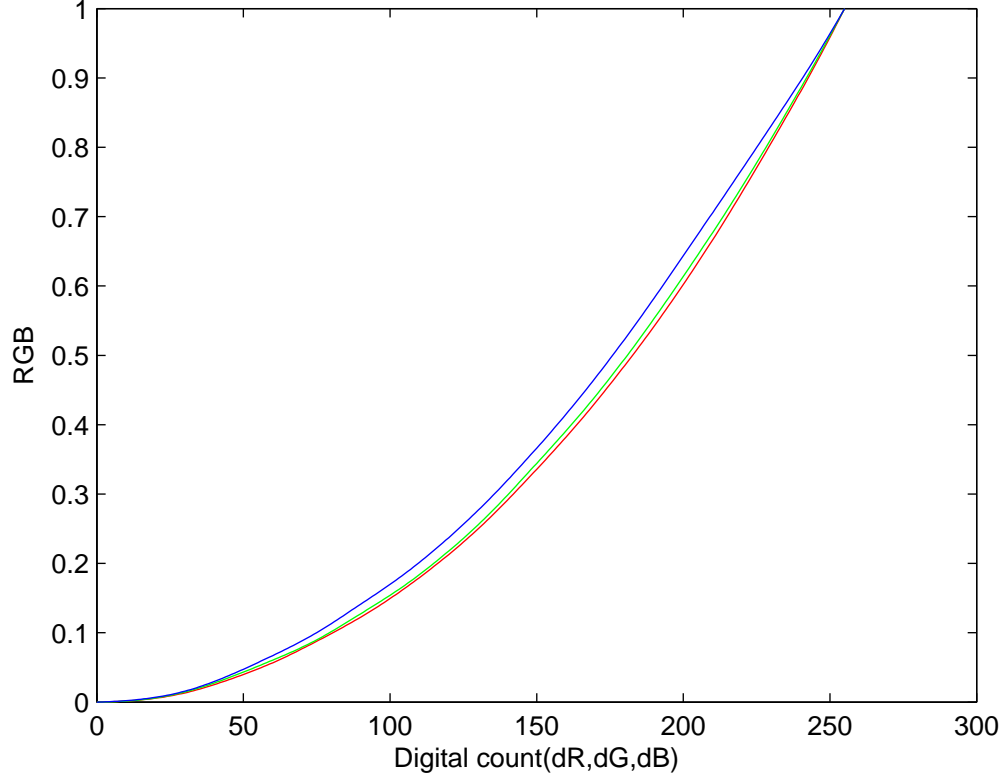


Figure 3.8: Non linear curve for Samsung Galaxy-J7 Display from Polynomial model.

3.6 Analysis

Obtain colour characteristics data In order to properly characterize the display, the measured spectral radiance data had to be converted to XYZ tristimulus values. This process for the two models included several steps. In the polynomial model, the maximum measured spectral radiance of each of the three primaries (Red,Green,Blue) were used to calculate the XYZ maximum tristimulus values of the primaries colours, but the black correction was performed on the measured spectral radiance data of the three primaries prior to the calculation of the XYZ tristimulus as explained in the theory part by subtracting the black colour from all measurements. Then all the negative values of measured spectral radiance data after the black correction

were replaced with zeros. The measured spectral radiance for each channel were normalized by dividing the spectral radiance of each colour by the sum of its maximum over all wavelengths. After that normalized spectral radiance was interpolated using the spline method to get the look-up (LUT) table for each of the primaries for converting from the digital count (dr, dg, db) to its corresponding normalized power measurement. Finally, the XYZ tristimulus values of any digital input (dr,dg, db) were obtained using the matrix equation mentioned in the theory.

For the masking model, the black correction was performed on the measured spectral radiance of the colours in the same way as explain previously in the polynomial model. After black correction was done, negative values in the spectral power measurements were set to zero. In the case of the masking model, this process was done for all seven measured colours compared to being done for only three colours in the polynomial. Then, XYZ tristimulus values for each colour was calculated from the corrected data to get the XYZ values for the measured colours. This XYZ values ranged for channel intensities of 0 to 255 with a step of 15. To get all possible XYZ values within this range, the calculated XYZ values were interpolated with the spline method as well and this was done for all seven colours. For any digital input of RGB, the relative sizes of the channel inputs are considered and the equivalent XYZ value were selected from this interpolated data as explained in the theory.

Fifty colours and the white of the display were measured with the spectroradiometer and used to test the accuracy of both characterization models described in the theory section above. All analysis of the measured data were done with MATLAB (see appendix for the codes). The fifty colours were randomly generated and their RGB values recorded (see appendix). The RGB values were then used in both models to estimate the XYZ tristimulus values of the colours and these were compared with tristimulus values calculated directly from the measured spectral radiance of the display according to (equation of tristimulus). Below are the primaries of the Samsung galaxy J7 display:

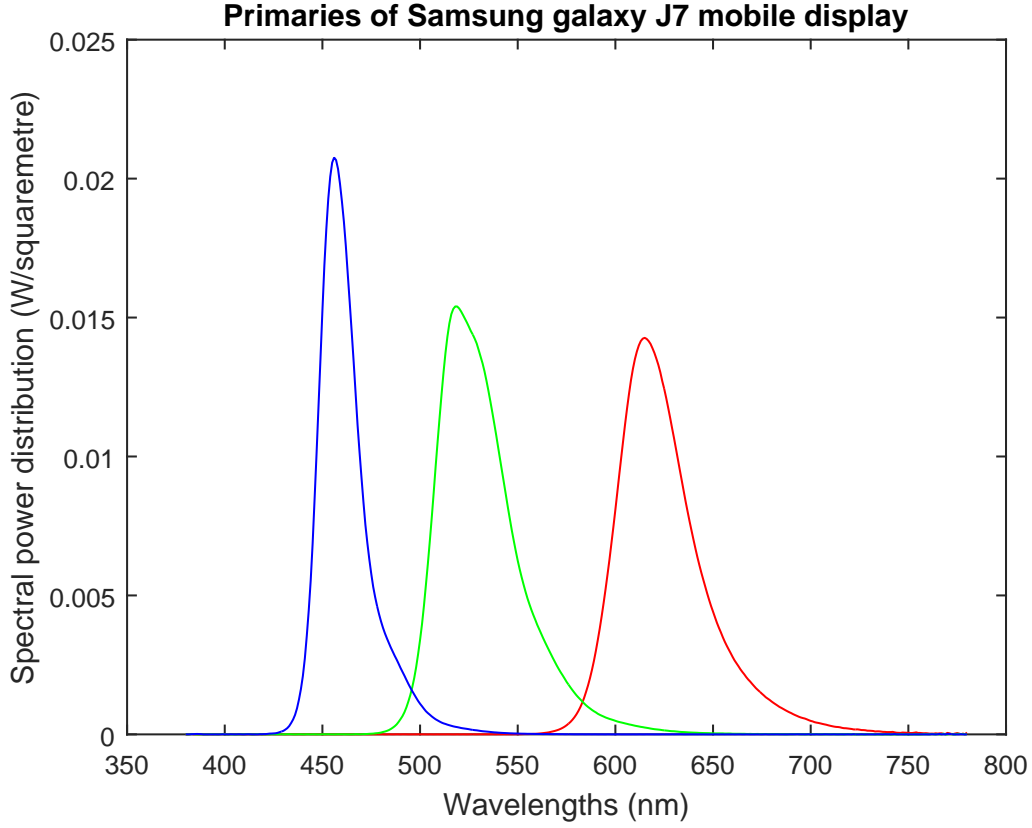


Figure 4.1: Primaries of Samsung galaxy J7 mobile display.

It was observed that the display showed a different behaviour when each channel was driven individually compared to the case where the channels were driven together and these differences were even more pronounced at higher channel intensities than at lower intensities. For example, in the figure below Fig. 4.1 it is seen that the intensity of the white of the display represented by the blue line is markedly lower than when the maximum of the individual red, green and blue channels were summed. This behaviour shows that the assumption of channel independence in the polynomial model is quite flawed and introduces significant errors in the estimation of the tristimulus values of the display using the polynomial model.

This difference is even more pronounced at higher channel intensities than at lower intensities as illustrated in the Fig 4.2-4.8 below:

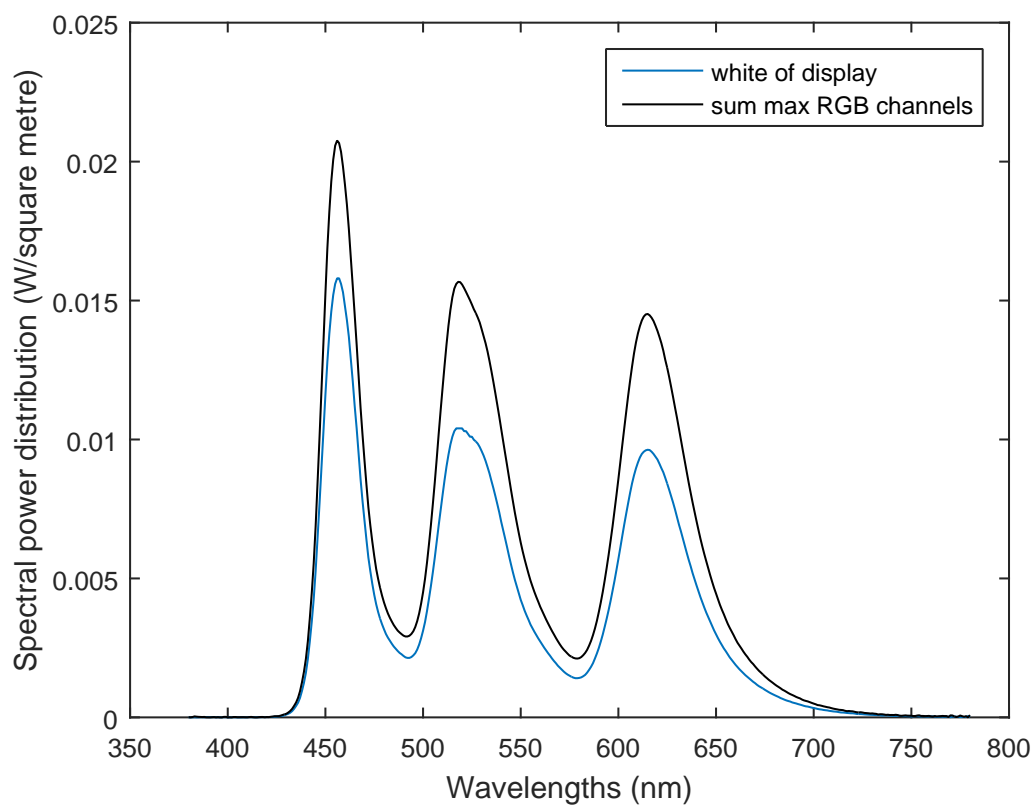
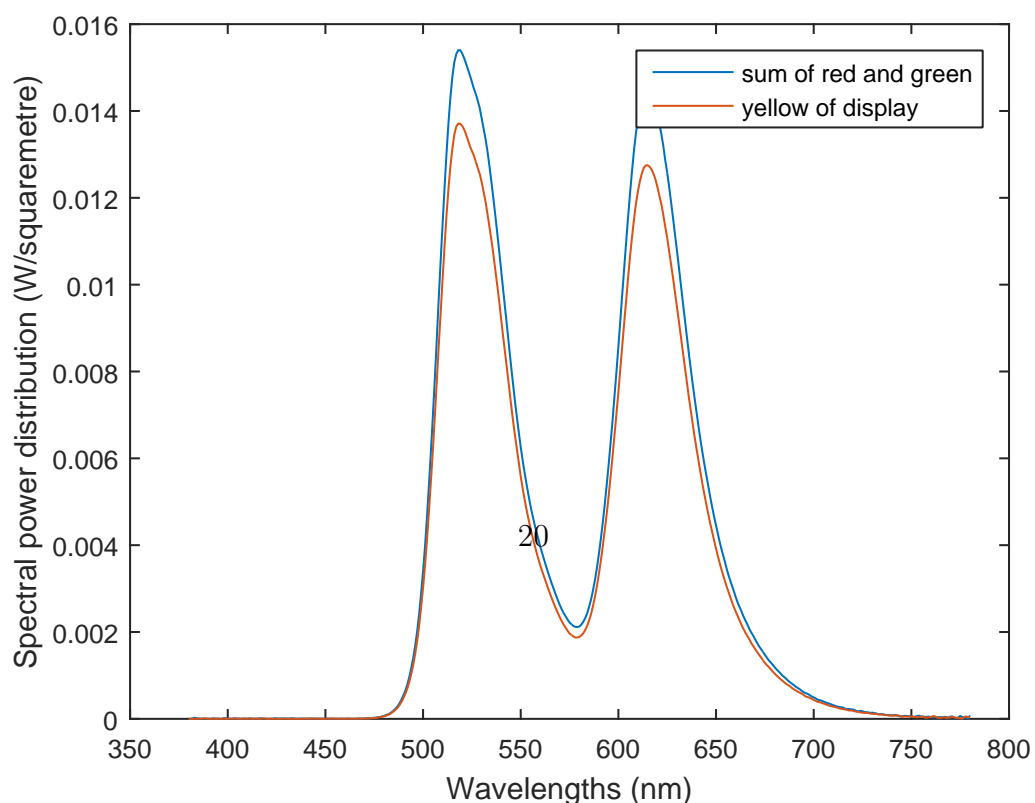


Figure 4.2: Intensity measurements of the white of the Samsung galaxy J7 mobile display.



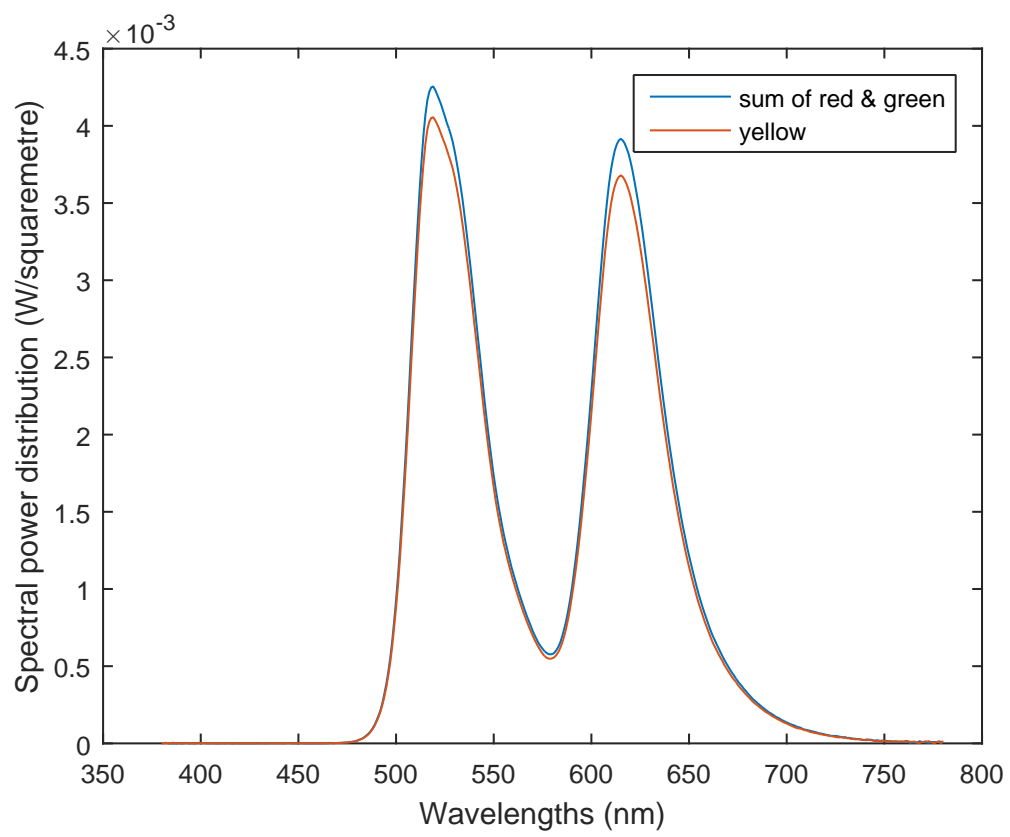


Figure 4.4: Yellow at channel intensity of 135.

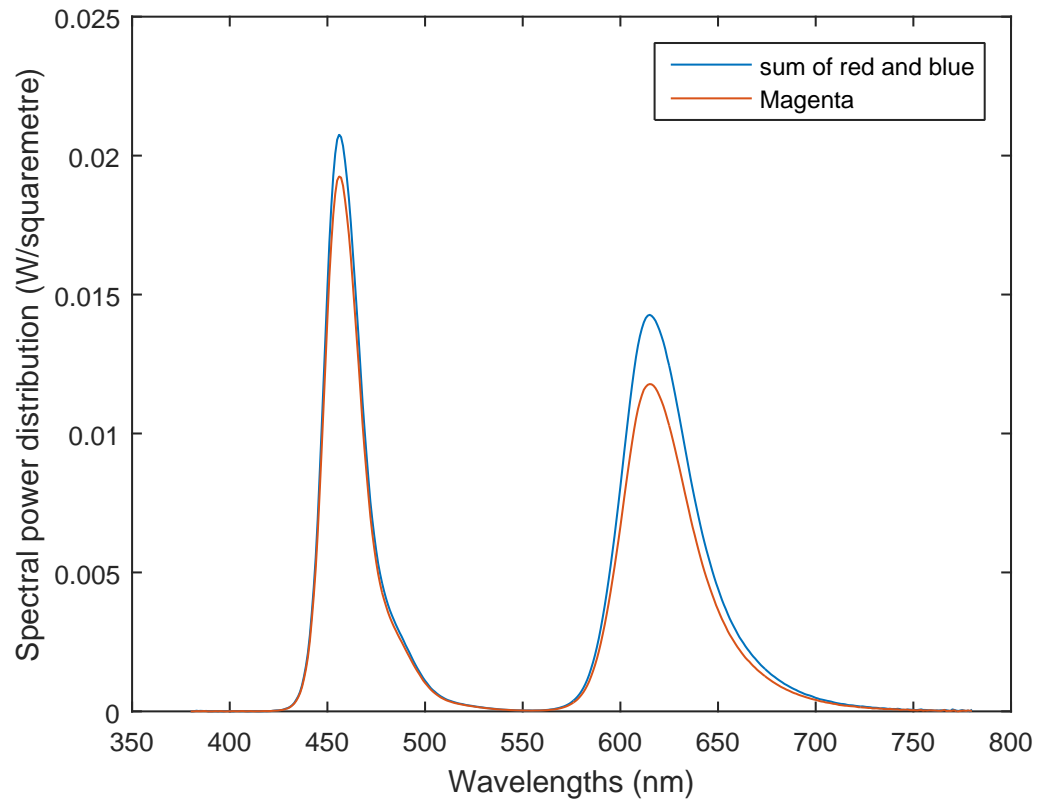


Figure 4.5: Magenta at channel intensity of 255.

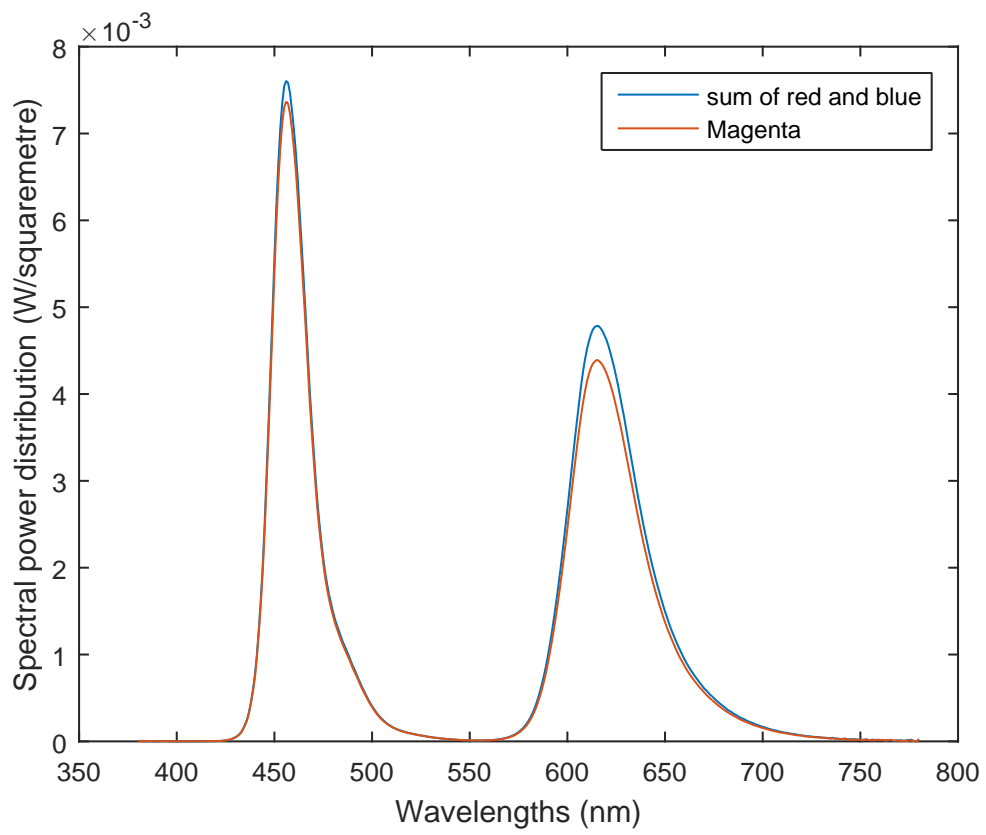


Figure 4.6: Magenta at channel intensity of 150.

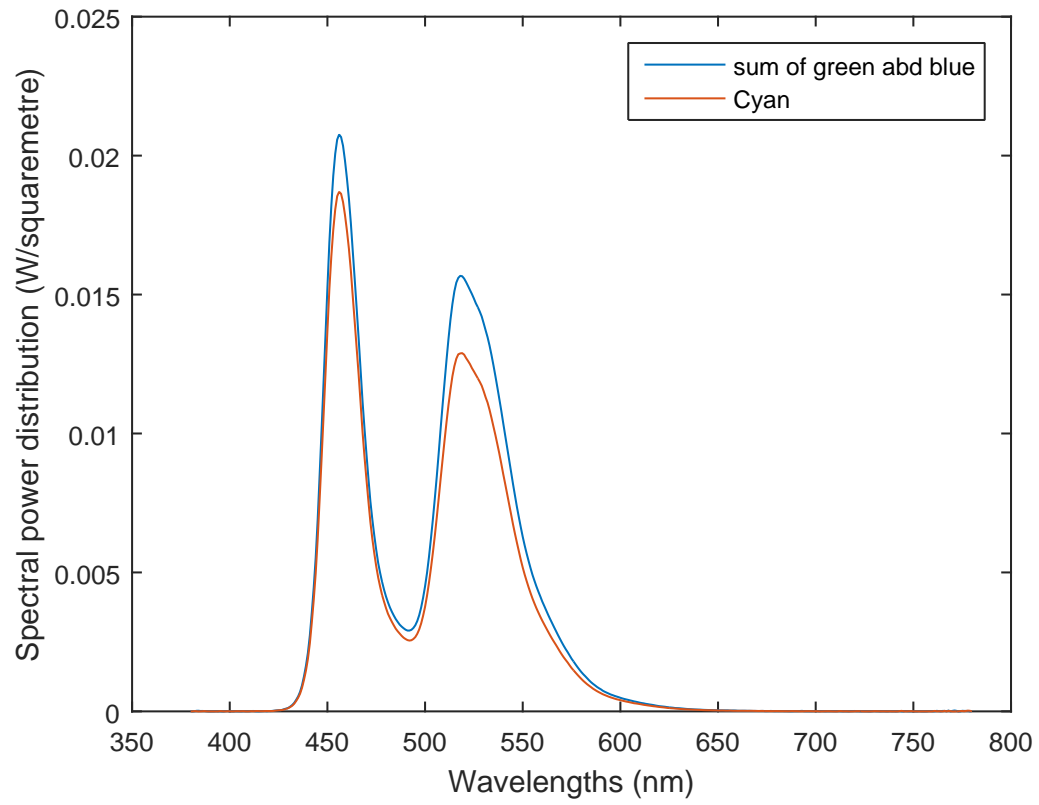


Figure 4.7: Cyan at channel intensity of 255.

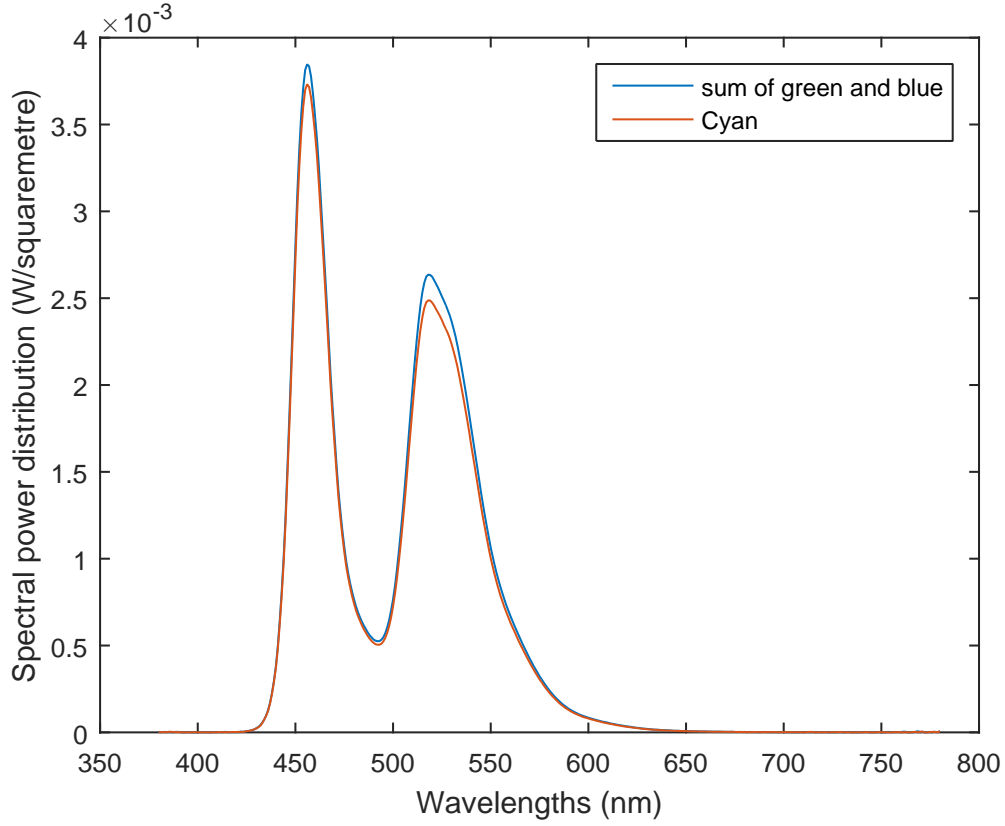


Figure 4.8: Cyan at channel intensity of 105.

This behaviour also varied depending on whether the colour displayed was from three channels as seen from *fig.2* where the difference between the white of the display and the sums of red, green and blue at maximum intensity is higher compared to when one of the channels was black and the colour displayed was from the contributions of two channels as seen from *figs 3a, 4a, and 5a* for yellow, magenta and cyan. In the case of both models, model predictions were compared with the measured values and differences were measured with the CIELAB colour difference. The average colour difference value for the polynomial model was 5.528 while the average colour difference for the masking model was 3.231. For all colours, the masking model performed better than polynomial model with the exception of four colours that corresponds to RGB values of (124,138,85), (157,127,53), (114,133,82) and (128,169,53). These colours were arbitrarily located in the vector of the test colours and as a result device instability is ruled out for this difference. Looking at

the RGB values, one can notice that the proportional amount of blue is lowest for the four colours. This does not explain why the polynomial model performed better because for many other colours where the proportional amount of blue was lowest, the masking model performed better. Typically, it is possible for the polynomial model to outperform masking model if the colour being characterized has significant contributions from only one channel compared to the other channels but this was not the case in this laboratory exercise. A better explanation will be the inaccuracies of the CIELAB ΔE^* colour difference formulas that do not always accurately predict colour differences. The colour differences in the case of these colours are shown in the table below: For the white of the display corresponding to RGB val-

Table 4.1: Colour difference for colours where Polynomial model gave better result to Masking model

RGB Channel inputs(R, G, B)	CIE ΔE^*	
	Polynomial	Masking
(124,138,85)	2.28	8.1400
(157,127,53)	2.25	5.9345
(114,133,82)	2.07	6.2563
(124,138,85)	2.63	4.1555

ues (255,255,255), the most significant difference for both models is observed. For the polynomial model, the ΔE^* was 18.34 and for the masking model, it was 0.339. The polynomial completely fails in predicting the significant contribution of the blue channel for the Samsung *J7* mobile as indicated in the figure of the primary for the displays. A summary of the significant ΔE^* colour differences for both models is presented below: From the results of the colour difference calculations it can be

Table 4.2: Masking Model

Mean ΔE^*	Highest ΔE^*	digital counts	Least ΔE^*	digital counts	ΔE^* white
3.231	12.75	(51,139,253)	0.4381	(90,79,78)	0.339

seen that for the mobile display, the masking model better predicts the character of the display and while the polynomial model has its merits as well in that it can

Table 4.3: Polynomial Model

Mean ΔE^*	Highest ΔE^*	digital counts	Least ΔE^*	digital counts	ΔE^* white
5.528	17.81	(51,139,253)	0.7704	(3,145,4)	18.34

properly characterise a LCD (see appendix), for the AMOLED driven display of a J7 mobile device, the effect of channel interaction makes the masking model a more accurate model for characterisation. Our findings in estimating the colour differences between the measured XYZ tristimulus values and the predicted tristimulus values for both models for all 50 test colours and the white of the display are presented in appendix section.

In this project, the spectral radiance measurements of a LCD and Samsung galaxy J7 mobile were obtained with CS-2000 spectroradiometer in order to study the colour characterization of both display devices. Two model were developed for this purpose ; the first model was the polynomial model where we used only there channels (Red, Green,Blue) to reproduced all the colours. The second model was the masking model in which we took into account the channel interaction and used seven colours(Red, Green, Blue, Yellow, Cyan, Magenta and Gray)with a scale of fifteen equal step from 0-255 for each colour. The test for colour reproduction accuracies was done using the CIELAB(ΔE^*) for colour differences to compare the polynomial and masking model colour reproduction of both the Samsung J7 mobile phone were 50 random test sample colours were in the compared. The result shows that the masking model has lower colour difference than the polynomial model which suggests that it has a higher reproduction accuracy for the display device. The highest colour difference of the masking for the Samsung J7 mobile was $\Delta E^*=12.75$,while the highest colour difference obtain by the polynomial model $\Delta E^*=17.81$ was for the mobile phone. AS for the LCD, the colour difference for white is $\Delta E^*= 0.2135$ by the polynomial model and by the masking model is $\Delta E^*=0.0022$ One of the limitation was that our test samples didn't contain very chromatic colours and didn't cover a wide range of different colours. Another limitation was that the colour difference accuracy test was done for all colour at maximum illuminance, so the effect of the different illumination level on the colour reproduction is unknown. Further accuracy could be done replying the CIELAB(ΔE^*)for colour difference with more advance model CIE2000 for colour difference.

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A.1 Polynomial model

```
function [XYZtri]=Display2(drr,dgg,dbb)
load('data2');
Black =[spdred(:,1),spdgreen(:,1),spdblue(:,1)];
XYZblack=(683*Black'*cmf)';
spdred1 = spdred-Black(:,1)*ones(1,18);
spdgreen1 = spdgreen-Black(:,2)*ones(1,18);
spdblue1 = spdblue-Black(:,3)*ones(1,18);
L=find(spdred1<0);spdred1(L)=0;
M=find(spdgreen1<0);spdgreen1(M)=0;
N=find(spdblue1<0);spdblue1(N)=0;
A=spdred1(:,18);B=spdgreen1(:,18);C=spdblue1(:,18);ABC=[A,B,C];
XYZmax=(683*ABC'*cmf)';
dr=[0:15:255];
T=[0:255];
R= sum(spdred1)/sum(A);
Rr=interp1(dr',R,T', 'spline');
a=[T' Rr];
G= sum(spdgreen1)/sum(B);Bl= sum(spdblue1)/sum(C);Gg=interp1(dr',G,T', 'spline');
Bb=interp1(dr',Bl,T', 'spline');
a(a(:,1)==round(drr),2);
r=a(a(:,1)==round(drr),2);
b=[T' Gg];c=[T' Bb];g=b(b(:,1)==round(dgg),2);bb=c(c(:,1)==round(dbb),2);
```

```

plot(T',Rr,'r');hold on;plot(T',Gg,'g');plot(T',Bb,'b');
rgb=[r;g;bb];
XYZtri=(XYZmax*rgb)+XYZblack(:,1);
end

```

A.2 Figures and Tables

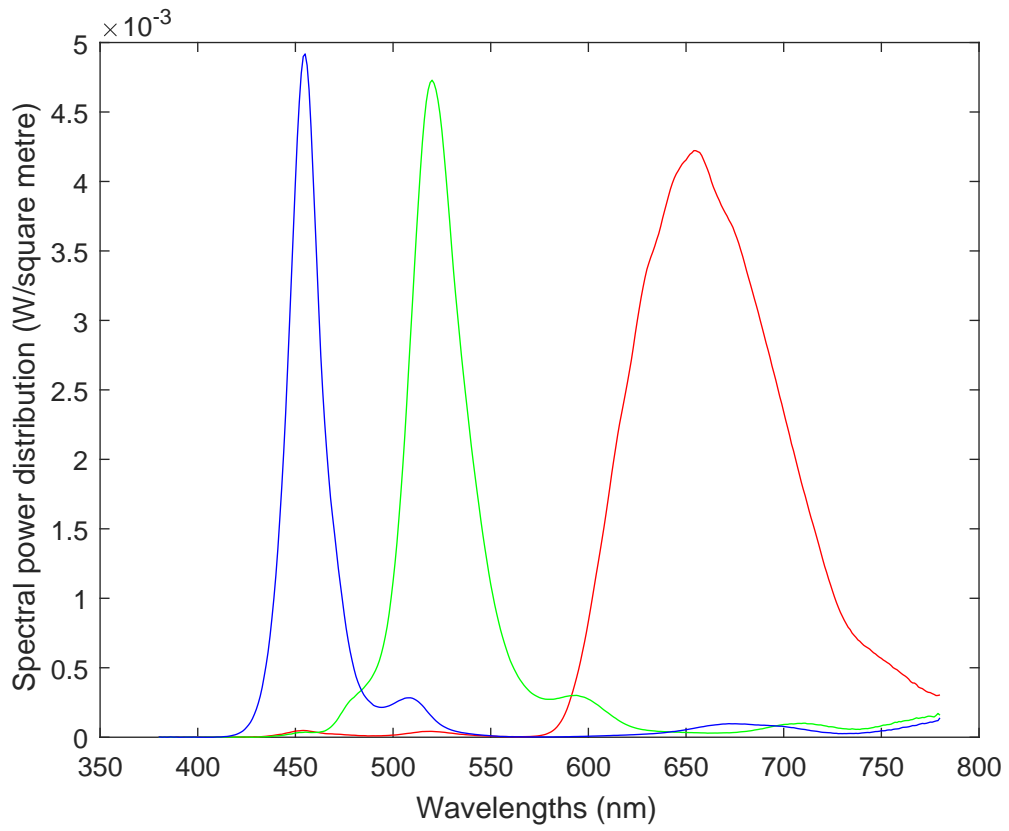


Figure A.1: LCD Primaries.

Table A.1: RGB digital values for test colors.

R	G	B
255	255	255
242	49	149
54	174	108
155	77	131
124	138	85
227	38	110
194	178	58
116	96	148
5	219	194
209	218	135
113	151	163
157	127	53
202	229	97
235	210	200
188	164	174
45	209	118
103	168	145
239	87	203
234	74	15
105	87	154
228	136	13
15	185	106

Table A.2: Continues RGB digital values for test colors.

R	G	B
90	79	78
207	214	223
3	145	4
35	94	196
52	179	248
51	139	252
154	153	201
169	177	112
51	158	127
4	203	55
190	244	164
113	133	82
238	240	245
119	44	185
107	250	105
216	69	190
134	64	68
52	223	112
171	188	238
214	35	174
5	3	54
174	228	214
97	51	160
212	76	34
128	169	53
181	73	155
109	120	161
78	17	94
48	252	147

Table A.3: Tristimulus values calculated directly from the measured spectral radiance of Samsung galaxy J7 display.

X	Y	Z
375.06	389.85	441.27
319.08	164.61	176.56
82.30	176.65	112.24
145.22	93.70	146.05
111.48	139.06	72.27
274.32	140.68	98.04
231.07	255.48	43.33
104.91	85.68	189.35
127.27	261.53	327.23
277.25	330.85	152.45
125.46	152.68	230.40
147.36	144.38	33.983
269.25	358.36	92.85
323.27	313.06	299.80
226.85	211.65	245.72
100.17	248.42	133.94
118.55	177.21	185.89
316.34	175.08	324.26
284.89	221.34	9.82
74.01	62.77	334.13
59.29	59.29	58.75
278.14	293.53	374.80
36.56	119.29	11.22
74.66	62.77	334.13
139.14	176.56	510.62

Table A.4: Continues tristimulus values calculated directly from the measured spectral radiance of Samsung galaxy J7 display.

X	Y	Z
125.28	117.16	531.38
174.03	124.95	342.38
89.93	184.56	119.13
75.82	145.88	146.57
75.80	234.49	48.76
257.40	362.20	215.83
97.12	126.19	247.70
335.05	324.59	426.05
113.34	56.164	293.50
163.39	369.21	115.73
266.87	142.65	293.17
147.36	144.38	33.983
269.25	358.36	92.85
323.27	313.06	299.80
226.85	211.65	245.72
100.25	68.25	44.31
111.69	283.81	124.80
223.31	224.76	438.43
257.77	126.67	247.70
5.48	2.054	30.23
237.18	305.82	357.50
84.011	47.64	221.18
235.13	142.75	11.88
125.62	193.73	40.15
109.32	107.48	200.93
125.62	193.73	224.42
44.26	21.040	80.71
141.80	356.40	198.95

Table A.5: Colour difference for Masking and Polynomial model .

CIELab ΔE^* Masking Model	CIELab ΔE^* Polynomial Model
2.2210	2.9700
1.3000	1.9800
2.4500	3.6000
8.1400	2.2900
2.1900	2.7180
2.7800	3.0000
2.6640	5.0900
0.9233	6.8510
3.3550	6.7600
2.0196	5.4400
5.9345	2.2543
3.9600	5.4540
2.9000	12.0120
1.8014	7.8107
1.9800	2.5140
1.9190	3.8410
5.0850	7.1560
2.5900	3.0400
2.8600	5.1090
2.8264	3.9940
1.3080	2.0506
0.4400	1.7250
1.4300	13.2800
0.5340	0.7703
7.8813	10.3180

Table A.6: Continues Colour difference for Masking and Polynomial model .

CIELab ΔE^* Masking Model	CIELab ΔE^* Polynomial Model
8.4900	16.3000
12.7500	17.8046
5.9420	9.1400
1.6064	2.5080
0.8950	2.6630
1.8200	2.2084
4.3400	8.7200
6.2600	2.0710
2.4223	2.9700
1.3000	16.4511
4.1350	5.3500
3.7173	6.0200
3.9920	5.4600
0.8807	1.7800
2.4040	3.0011
5.4202	14.1955
1.4000	3.4800
1.1001	1.4864
3.8540	11.3900
2.8407	3.8231
2.5101	3.8231
4.1555	2.6400
3.4400	4.3740
2.1640	5.7219
0.5250	1.2724
2.9518	3.5052

Table A.7: XYZ tristimulus values of test colours predicted with polynomial model.

X	Y	Z
547.23	575.31	580.37
342.87	179.90	198.62
89.39	187.82	122.35
158.98	105.36	156.35
121.83	150.62	79.47
288.16	149.52	110.80
252.59	278.83	51.52
117.54	98.76	199.43
334.68	394.08	187.97

Table A.8: Continues XYZ tristimulus values of test colours predicted with polynomial model.

X	Y	Z
157.49	155.35	37.61
314.97	410.24	116.26
423.62	416.73	374.69
272.71	259.11	281.20
108.60	262.77	148.75
134.82	198.41	201.84
372.44	214.67	365.24
293.83	175.36	5.51
105.70	84.88	214.29
300.78	239.79	11.80
78.18	201.70	120.97
63.04	61.34	61.34
373.60	397.57	453.80
36.50	119.72	11.63
80.63	74.42	342.12
159.97	220.10	534.80
139.97	147.79	543.37
203.60	153.31	360.96

Table A.9: Continues XYZ tristimulus values of test colours predicted with polynomial model.

X	Y	Z
99.25	197.70	130.30
82.28	157.75	157.47
77.13	237.61	53.32
328.67	447.47	269.68
105.71	135.88	74.13
468.86	464.54	533.61
127.17	65.89	302.29
184.00	393.13	134.65
303.89	168.07	320.24
105.78	135.88	74.13
120.74	298.62	140.31
293.09	304.42	500.04
284.00	141.63	267.54
5.45	1.94	30.04
313.18	398.19	426.36
92.27	54.09	227.90
243.09	151.00	14.70
136.47	205.40	44.32
213.13	128.03	215.83
124.28	124.67	236.70
46.98	22.60	83.32
156.32	381.49	226.09

Table A.10: XYZ tristimulus values of test colours predicted with masking model.

X	Y	Z
377.22	391.90	445.31
332.07	174.12	191.83
86.71	183.15	118.16
150.47	99.31	150.55
97.30	121.70	74.51
284.23	147.32	108.01
236.60	261.44	49.23
109.64	91.33	193.73
129.90	266.86	335.11
300.94	356.60	174.94
132.14	158.56	234.25
137.98	132.60	35.20
287.36	379.02	110.09
347.50	334.36	316.04
237.44	222.83	256.36
105.90	257.10	143.70
125.15	183.85	190.89
341.28	196.77	347.22
292.48	173.88	5.32
100.04	79.41	209.95
294.58	233.31	11.28
76.60	198.01	117.29

Table A.11: Continues XYZ tristimulus values of test colours predicted with masking model.

X	Y	Z
59.51	57.57	59.60
288.84	304.26	384.32
36.63	119.84	11.55
79.33	71.59	339.34
150.85	198.78	517.94
135.62	138.20	535.34
186.60	139.35	349.86
95.38	191.88	125.45
78.87	150.58	151.14
76.89	237.03	52.50
289.68	404.94	246.06
87.11	114.09	69.91
349.51	341.56	441.03
121.85	62.82	298.83
173.73	381.51	128.85
279.42	154.75	306.09
103.41	70.94	46.42
118.16	293.66	135.89
251.08	255.35	465.73
266.30	132.75	257.32
5.39	1.94	29.92
263.14	334.51	380.10
89.68	52.18	225.56
241.46	149.16	14.24
118.61	184.72	42.04
199.54	119.77	207.41
115.38	114.06	229.26
45.36	21.75	82.18
151.14	370.02	216.66