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Display Color Management Standard

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VESA DISPLAY COLOR MANAGEMENT (DCM) STANDARD

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Purpose

This document describes the overall requirements, data collection, data conversion and data storage format for monitor-specific data needed to perform display color management as a part of a color managed computer system.

Summary

This document is intended to provide interested parties with standardized enabling information in the area of Display Color Management.

Preface

Scope
This specification covers the following:
1) The collection of data that is related to display color management
2) The conversion of the data to a format suitable for storage in monitor EDID
3) The format for storage of the converted data into a single EDID descriptor block.
4) Color Management Descriptor (CMD) described is Version 3. Refer to Table in Section 4.

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Initial release of the standard

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Referenced Documents:

- VESA Enhanced Extended Display Identification Data Standard (E-EDID), Release A, Rev. 1, Feb 9, 2000
- VESA Display Specifications and Test Procedures (DSTP), Version 1.0 Revision 1.0, Oct 3, 1994
- VESA Flat Panel Display Measurements Standard (FPDM2), Version 2.0, May 2001
- ICC Specification ICC.1:2001-12 File Format for Color Profiles (Ver. 4.0) or newer – www.color.org
- VESA Display Information Extension Block Standard (DI-EXT), Release A, August 21, 2001
- Enhanced EDID Implementation Guide (companion document to E-EDID standard), Ver. 1, June 4, 2001

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1. Overview

With regard to computer displays, it is recognized that the colors produced by a display are a result of various proportional mixes of the primary display colors. It is also recognized that each primary color of a specific display could be different from one display to the next, and that the brightness response of each color channel may be different from one display to the next as well as from one color channel to the next on the same display. From a color management perspective then, it is difficult to render an exact desired shade of color by mixing uncontrolled amounts of unknown primary colors. To facilitate optimum color management it is necessary to characterize the brightness response of each display color channel as well as the exact shade of each primary color of each specific display device. This specification is fundamentally intended to address a standard by which these display specific characteristics that are pertinent to color matching may be consistently measured and efficiently stored within the basic EDID™ structure as defined in the VESA E-EDID Standard Release A, Revision 1, February 9, 2000.

From a display manufacturing point of view, involvement in color management boils down to executing the simple procedure outlined in this standard. However, this is one of the most critical and enabling steps for *seamless color management* (not involving the use of sensors or subjective user feedback in the usage scenario). When a color management enabled monitor is finally connected to a host computer, the color management data contained in the monitor EDID can be easily accessed by software resident on the computer. This software can then utilize the color management data to create a customized ICC profile for the specific display. The monitor-specific ICC profile contains display channel colorant tags as well as display channel tonal response curve tables. For details on how these tags are created, please refer to the ICC specification document.

It should be noted that the color management data measured at the factory is generally measured in the default factory-shipping color temperature setting. However, this is not necessarily a hard and fast rule so much as a guideline. A possible instance where this guideline may certainly be deviated from would be when a display has a pre-set, user selectable, color temperature setting intended for image viewing as opposed to computer data viewing. In this circumstance, it may be considered to be more appropriate to make the color management characterizing data measurements at the preferred color temperature setting. The understanding being that the data would be optimally utilized at this color temperature setting.

VESA provides support for Color Management related data with EDID2.0, E-EDID and DI-EXT. In base EDID there is a provision for defining a basic "gamma" value in the simple exponential display response model. In DI-EXT and EDID 2.0 there is a provision for defining either a white response curve or RGB response curves using a finite number of data points. This document provides a method for efficiently compressing a significant amount of color related data into a single 18-byte descriptor in the base 128-byte EDID or a possible future EDID extension block.

Individual manufacturers may select the most appropriate color data storage method based upon their specific applications and constraints.

Data Collection

The two aspects of color management related data that need to be collected are color channel chromaticity and tonal response. In the collection of this data, please conform to measurement techniques specified in FPDM2 for LCD displays and in DSTP 1.0 for CRT displays. In general, all measurements are made in darkroom lighting conditions of less than 1 lux.

1.1 Chromaticity

Device specific chromaticity data is measured at maximum input for red, green, blue and white at the default color temperature setting condition in which the display is shipped. All settings on monitor are set to default shipping position.

1.2 Tonal Response

Tonal response is measured as color channel luminance response to multiple input levels ranging from minimum to maximum input level. Eight luminance measurements are made for each color channel at input levels from 0V (minimum) through 0.7V (maximum) in increments of 0.1V. In order to maximize measurement precision, the display should be driven with a calibrated pattern generator, which is accurate to better than +/- 0.01V on the video signal outputs. To avoid beam current limiting effects on CRT displays, it is necessary to make luminance measurements using a "center square" pattern. For LCD displays, measurements shall be made in the native resolution of the panel. For CRT displays, measurements shall be made using the preferred display-timing mode described in the EDID for the monitor. Luminance measurements made in this manner will be referred to below as $l_r(0.0)$, $l_g(0.0)$ & $l_b(0.0)$ through $l_r(0.7)$, $l_g(0.7)$ & $l_b(0.7)$.

2. Data Conversion

For each color channel, two numbers are stored in EDID that describe the tonal response of that channel. These numbers are described below as polynomial coefficients a_3 and a_2. So, for the three basic color channels on color displays, there are six coefficients: a_{3r} and a_{2r} for the red channel, a_{3g} and a_{2g} for the green channel and a_{3b} and a_{2b} for the blue channel. These coefficients are calculated based upon measured data $l_r(0.0)$ through $l_r(0.7)$, $l_g(0.0)$ through $l_g(0.7)$ & $l_b(0.0)$ through $l_b(0.7)$. The overall goal of this section is to describe the conversion process from measured luminance data to corresponding coefficient data.

Those interested in the theoretical derivation of the conversion process are referred to Appendix A at the end of this document.

There are two types of device specific data to be stored in EDID:

1) Chromaticity data.

2) Tonal response data.

The Red, Green, Blue, & White chromaticity data is stored into EDID as specified by the VESA E-EDID standard. The discrete device specific nature of this data is signified by the presence of a Color Management Descriptor that contains the coefficients discussed above.

Tonal response coefficients are stored into a Color Management Descriptor. The method for calculating these coefficients is described below:

STEP 1: Three input luminance **Matrices Lr**, **Lg** & **Lb**, are constructed as follows:

$$\mathbf{L_r} = \begin{vmatrix} l_r(0.0) - l_r(0.0) \\ l_r(0.1) - l_r(0.0) \\ l_r(0.2) - l_r(0.0) \\ l_r(0.3) - l_r(0.0) \\ l_r(0.4) - l_r(0.0) \\ l_r(0.5) - l_r(0.0) \\ l_r(0.6) - l_r(0.0) \\ l_r(0.7) - l_r(0.0) \end{vmatrix}$$

$$\mathbf{L_g} = \begin{vmatrix} l_g(0.0) - l_g(0.0) \\ l_g(0.1) - l_g(0.0) \\ l_g(0.2) - l_g(0.0) \\ l_g(0.3) - l_g(0.0) \\ l_g(0.4) - l_g(0.0) \\ l_g(0.5) - l_g(0.0) \\ l_g(0.6) - l_g(0.0) \\ l_g(0.7) - l_g(0.0) \end{vmatrix}$$

$$\mathbf{L_b} = \begin{vmatrix} l_b(0.0) - l_b(0.0) \\ l_b(0.1) - l_b(0.0) \\ l_b(0.2) - l_b(0.0) \\ l_b(0.3) - l_b(0.0) \\ l_b(0.4) - l_b(0.0) \\ l_b(0.5) - l_b(0.0) \\ l_b(0.6) - l_b(0.0) \\ l_b(0.7) - l_b(0.0) \end{vmatrix}$$

STEP 2: Each of the above matrices is an 8x1 matrix. Each matrix is then pre-multiplied by the following 2x8 Polynomial estimator matrix **P** (see Appendix A for theoretical details of derivation of this matrix).

$$\mathbf{P} = \begin{vmatrix} 0 & 0.001 & 0.008 & 0.027 & 0.064 & 0.125 & 0.216 & 0.343 \\ 0 & 0.01 & 0.04 & 0.09 & 0.16 & 0.25 & 0.36 & 0.49 \end{vmatrix}$$

The result is three 2x1 matrices A_r, A_g and A_b that contain the desired coefficients a_{3r} and a_{2r}, a_{3g} and a_{2g}, a_{3b} and a_{2b} respectively as their elements.

$$\mathbf{A_r} = \mathbf{P} * \mathbf{L_r} = \begin{vmatrix} a_{3r} \\ a_{2r} \end{vmatrix}$$

$$\mathbf{A_g} = \mathbf{P} * \mathbf{L_g} = \begin{vmatrix} a_{3g} \\ a_{2g} \end{vmatrix}$$

$$\mathbf{A_b} = \mathbf{P} * \mathbf{L_b} = \begin{vmatrix} a_{3b} \\ a_{2b} \end{vmatrix}$$

STEP 3: Each of the polynomial coefficients is then converted into two hexadecimal data bytes. The process for this conversion is as follows:

STEP 3a: Multiply coefficient by 100.

STEP 3b: Round product to integer.

STEP 3c: Convert integer value to 16-bit hexadecimal data (for negative values use two's complement conversion method).

STEP 3d: Form the least significant byte (LSB) as the lower 8 data bits.

STEP 3e: Form the most significant byte (MSB) as the upper 8 data bits.

3. Data Storage Format

After the measured luminance data is converted to polynomial coefficients as described above, the polynomial coefficients are stored into EDID in an 18 byte descriptor according to the following format:

COLOR MANAGEMENT DATA DESCRIPTOR

Offset	#Bytes	Description	Format
00h	2	Flag indicating that this is a descriptor	Set to 0000h
02h	1	Flag indicating that this is a descriptor	Set to 00h
03h	1	Data type tag indicating Color Management data (CMD) descriptor	Set to F9h
04h	1	Flag indicating that this is a descriptor	Set to 00h
05h	1	Version	Set to 03h*
06h	1	Red a_3 LSB	
07h	1	Red a_3 MSB	
08h	1	Red a_2 LSB	
09h	1	Red a_2 MSB	
0Ah	1	Green a_3 LSB	
0Bh	1	Green a_3 MSB	
0Ch	1	Green a_2 LSB	
0Dh	1	Green a_2 MSB	
0Eh	1	Blue a_3 LSB	
0Fh	1	Blue a_3 MSB	
10h	1	Blue a_2 LSB	
11h	1	Blue a_2 MSB	

* At the time of this standard's publication, it has already been in use by certain parties, and is at version 3 for continuity with existing users.

4. Numerical Example

The following example will clarify the data conversion process. The following data was measured from a typical LCD flat panel display using a calibrated color analyzer (it could be data from any display device and/or color analyzer):

INPUT	Symbol	R Data	Symbol	G Data	Symbol	B Data
0	$l_r(0.0)$	0.31	$l_g(0.0)$	0.31	$l_b(0.0)$	0.31
0.1	$l_r(0.1)$	0.35	$l_g(0.1)$	0.36	$l_b(0.1)$	0.34
0.2	$l_r(0.2)$	0.53	$l_g(0.2)$	1.14	$l_b(0.2)$	0.6
0.3	$l_r(0.3)$	1.46	$l_g(0.3)$	3.7	$l_b(0.3)$	1.23
0.4	$l_r(0.4)$	2.69	$l_g(0.4)$	7.15	$l_b(0.4)$	2.01
0.5	$l_r(0.5)$	3.78	$l_g(0.5)$	10.9	$l_b(0.5)$	2.79
0.6	$l_r(0.6)$	5.56	$l_g(0.6)$	16.6	$l_b(0.6)$	3.98
0.7	$l_r(0.7)$	7.74	$l_g(0.7)$	22.9	$l_b(0.7)$	5.23

STEP 1: Three input luminance **matrices L_r, L_g & L_b** are constructed as:

$$
L_r = \begin{vmatrix} l_r(0.0) - l_r(0.0) \\ l_r(0.1) - l_r(0.0) \\ l_r(0.2) - l_r(0.0) \\ l_r(0.3) - l_r(0.0) \\ l_r(0.4) - l_r(0.0) \\ l_r(0.5) - l_r(0.0) \\ l_r(0.6) - l_r(0.0) \\ l_r(0.7) - l_r(0.0) \end{vmatrix} = \begin{vmatrix} 0.31 - 0.31 \\ 0.35 - 0.31 \\ 0.53 - 0.31 \\ 1.46 - 0.31 \\ 2.69 - 0.31 \\ 3.78 - 0.31 \\ 5.56 - 0.31 \\ 7.74 - 0.31 \end{vmatrix} = \begin{vmatrix} 0.00 \\ 0.04 \\ 0.22 \\ 1.15 \\ 2.38 \\ 3.47 \\ 5.25 \\ 7.43 \end{vmatrix}
$$

$$
L_g = \begin{vmatrix} l_g(0.0) - l_g(0.0) \\ l_g(0.1) - l_g(0.0) \\ l_g(0.2) - l_g(0.0) \\ l_g(0.3) - l_g(0.0) \\ l_g(0.4) - l_g(0.0) \\ l_g(0.5) - l_g(0.0) \\ l_g(0.6) - l_g(0.0) \\ l_g(0.7) - l_g(0.0) \end{vmatrix} = \begin{vmatrix} 0.31 - 0.31 \\ 0.36 - 0.31 \\ 1.14 - 0.31 \\ 3.7 - 0.31 \\ 7.15 - 0.31 \\ 10.9 - 0.31 \\ 16.6 - 0.31 \\ 22.9 - 0.31 \end{vmatrix} = \begin{vmatrix} 0.00 \\ 0.05 \\ 0.83 \\ 3.39 \\ 6.84 \\ 10.59 \\ 16.29 \\ 22.59 \end{vmatrix}
$$

$$
L_b = \begin{vmatrix} l_b(0.0) - l_b(0.0) \\ l_b(0.1) - l_b(0.0) \\ l_b(0.2) - l_b(0.0) \\ l_b(0.3) - l_b(0.0) \\ l_b(0.4) - l_b(0.0) \\ l_b(0.5) - l_b(0.0) \\ l_b(0.6) - l_b(0.0) \\ l_b(0.7) - l_b(0.0) \end{vmatrix} = \begin{vmatrix} 0.31 - 0.31 \\ 0.34 - 0.31 \\ 0.6 - 0.31 \\ 1.23 - 0.31 \\ 2.01 - 0.31 \\ 2.79 - 0.31 \\ 3.98 - 0.31 \\ 5.23 - 0.31 \end{vmatrix} = \begin{vmatrix} 0.00 \\ 0.03 \\ 0.29 \\ 0.92 \\ 1.70 \\ 2.48 \\ 3.67 \\ 4.92 \end{vmatrix}
$$

STEP 2: Each of the above Luminance matrices is then pre-multiplied by the polynomial estimator matrix **P** (see appendix A for theoretical details)

$$\mathbf{P} = \begin{vmatrix} 0 & 0.001 & 0.008 & 0.027 & 0.064 & 0.125 & 0.216 & 0.343 \\ 0 & 0.01 & 0.04 & 0.09 & 0.16 & 0.25 & 0.36 & 0.49 \end{vmatrix}$$

Resulting in the coefficient matrices A_r, A_g and A_b that contain the desired coefficients a_{3r} and a_{2r}, a_{3g} and a_{2g}, a_{3b} and a_{2b} respectively as their elements.

$$\mathbf{A_r} = \quad \mathbf{P * L_r} = \begin{vmatrix} 5.359428 \\ 11.41368 \end{vmatrix}$$

$$\begin{vmatrix} a_{3r} \\ a_{2r} \end{vmatrix} \quad = \quad \begin{vmatrix} 5.359428 \\ 11.41368 \end{vmatrix}$$

$$\mathbf{A_g} = \quad \mathbf{P * L_g} = \begin{vmatrix} 18.5743 \\ 33.4178 \end{vmatrix}$$

$$\begin{vmatrix} a_{3g} \\ a_{2g} \end{vmatrix} \quad = \quad \begin{vmatrix} 18.5743 \\ 33.4178 \end{vmatrix}$$

$$\mathbf{A_b} = \quad \mathbf{P * L_b} = \begin{vmatrix} -0.2095 \\ 10.2213 \end{vmatrix}$$

$$\begin{vmatrix} a_{3b} \\ a_{2b} \end{vmatrix} \quad = \quad \begin{vmatrix} -0.2095 \\ 10.2213 \end{vmatrix}$$

So,

$a_{3r} = 5.359428$
$a_{2r} = 11.41368$
$a_{3g} = 18.5743$
$a_{2g} = 33.4178$
$a_{3b} = -0.2095$
$a_{2b} = 10.2213$

STEP 4: Each of the polynomial coefficients a_{3r} and a_{2r}, a_{3g} and $a_{2g,}$ a_{3b} and a_{2b} is then converted into two hexadecimal data bytes.

STEPS 4a & b: Multiplying coefficients by 100 and round to integer yields the following

	R	G	B
a_3	536	1857	-21
a_2	1141	3342	1022

STEP 4c: Convert integer values above to 16-bit hexadecimal data (for negative values use two's complement conversion method)

	R	G	B
a_3	0218h	0741h	FFEBh
a_2	0475h	0D0Eh	03FEh

STEPS 4d & e: Form the least significant byte (LSB) as the lower 8 data bits and the most significant byte (MSB) as the upper 8 data bits as follows:

	R	G	B
a_3 MSB	02h	07h	FFh
a_3 LSB	18h	41h	EBh
a_2 MSB	04h	0Dh	03h
a_2 LSB	75h	0Eh	FEh

The above example results in the following 18-byte CMD descriptor to be stored in EDID.

COLOR MANAGEMENT DATA DESCRIPTOR

Offset	#Bytes	Description	Format
00h	2	Flag indicating that this is a descriptor	0000h
02h	1	Flag indicating that this is a descriptor	00h
03h	1	Data type tag indicating Color Management data (CMD) descriptor	F9h
04h	1	Flag indicating that this is a descriptor	00h
05h	1	Version	Set to 03h
06h	1	Red a_3 LSB	18h
07h	1	Red a_3 MSB	02h
08h	1	Red a_2 LSB	75h
09h	1	Red a_2 MSB	04h
0Ah	1	Green a_3 LSB	41h
0Bh	1	Green a_3 MSB	07h
0Ch	1	Green a_2 LSB	0Eh
0Dh	1	Green a_2 MSB	0Dh
0Eh	1	Blue a_3 LSB	EBh
0Fh	1	Blue a_3 MSB	FFh
10h	1	Blue a_2 LSB	FEh
11h	1	Blue a_2 MSB	03h

Please refer to the E-EDID standard for clarification on how this data is stored as a monitor descriptor block.

END OF NUMERICAL EXAMPLE

Appendix A: Polynomial Representation of Tonal Response

This Appendix contains the mathematical derivation of the Polynomial Estimator Matrix **P**. The **P** matrix is required in order to determine the values of the polynomial coefficients (a_3 & a_2) for R, G & B.

The tonal response of a display can be represented by myriad mathematical expressions. One such representation, which turns out to be quite efficient, is to use the cubic and quadratic terms of a third order polynomial. An advantage to using a representation such as this is that the two coefficients in the expression can serve to represent the entire tonal response function, which by itself is a continuous function that would otherwise be difficult to describe concisely.

The equation below is for the predicted display luminance response L to input voltage v for a display channel that is characterized by coefficients a_3 and a_2.

$$L = a_3 * v^3 + a_2 * v^2 \qquad\qquad \text{Equation 1}$$

In the above equation, Luminance prediction L may be l_r, l_g or l_b depending upon whether the coefficients a_3 & a_2 correspond to the red, green or blue channel respectively. This leads to the three equations below:

$$l_r = a_{3r} * v^3 + a_{2r} * v^2 \qquad\qquad \text{Equation 2}$$

$$l_g = a_{3g} * v^3 + a_{2g} * v^2 \qquad\qquad \text{Equation 3}$$

$$l_b = a_{3b} * v^3 + a_{2b} * v^2 \qquad\qquad \text{Equation 4}$$

Where l_r is red luminance, l_g is green luminance and l_b is blue luminance; $a_{3r\ and}$ a_{2r} are characterizing coefficients for the red channel, a_{3g} and a_{2g} are characterizing coefficients for the green channel, a_{3b} and a_{2b} are characterizing coefficients for the blue channel. v is any input voltage to the display channel.

It can be noted that the maximum luminance prediction is at 0.7 Volts input. A more astute observation would be that minimum luminance prediction at 0.0 Volts input is always 0. Obviously, most displays do not possess this property. However, the following points should be noted:

1) It is not possible to measure a single color channel dark luminance (luminance response to zero input voltage) in isolation from the other two. That is to say, dark luminance is the same for red, green and blue and is actually the sum of the actual dark luminance for each channel.

2) All other luminance measurements made on a display contain the dark luminance component.

From this discussion it follows that the display dark luminance, measured at 0.0 Volts input, is a constant additive component of all other display luminance measurements. This dark luminance can be subtracted out of any general luminance measurement at input voltage v to yield a pure channel luminance response to channel input voltage v.

The subject of this discussion is the optimum computation of coefficients a_3 & a_2 for each channel based upon a set of luminance measurements. Let us arbitrarily pick a set of 8 display input voltages ranging from 0.0 Volts to 0.7 Volts in increments of 0.1 Volts. These 8 inputs lead to 8 corresponding luminance measurements l(0.0) through l(0.7).

Equation 1 dictates the pure channel luminance response l_p for *any* input v, so equation 1 can be applied for each of the eight inputs as follows:

$l_p(0.0) = a_3 * (0.0)^3 + a_2 * (0.0)^2$ Equation 5

$l_p(0.1) = a_3 * (0.1)^3 + a_2 * (0.1)^2$ Equation 6

$l_p(0.2) = a_3 * (0.2)^3 + a_2 * (0.2)^2$ Equation 7

$l_p(0.3) = a_3 * (0.3)^3 + a_2 * (0.3)^2$ Equation 8

$l_p(0.4) = a_3 * (0.4)^3 + a_2 * (0.4)^2$ Equation 9

$l_p(0.5) = a_3 * (0.5)^3 + a_2 * (0.5)^2$ Equation 10

$l_p(0.6) = a_3 * (0.6)^3 + a_2 * (0.6)^2$ Equation 11

$l_p(0.7) = a_3 * (0.7)^3 + a_2 * (0.7)^2$ Equation 12

It may be noted here that we are equating *predicted* luminance values, on the left hand side of the equality symbol, with the partial polynomial expression on the right hand side of the equality symbol. If polynomial coefficients a_3 and a_2 were suitably chosen, then all eight equations (5 through 12) would be simultaneously true. **The issue at hand is the choice of a_3 and a_2.**

An important point to note is that the *predicted* values l_p in the equations above are related to the *measured* values l as follows:

$l_p(0.0) = l(0.0) - l(0.0 + e(0)$ Equation 13

$l_p(0.1) = l(0.1) - l(0.0) + e(1)$ Equation 14

$l_p(0.2) = l(0.2) - l(0.0) + e(2)$ Equation 15

$l_p(0.3) = l(0.3) - l(0.0) + e(3)$ Equation 16

$l_p(0.4) = l(0.4) - l(0.0) + e(4)$ Equation 17

$l_p(0.5) = l(0.5) - l(0.0) + e(5)$ Equation 18

$l_p(0.6) = l(0.6) - l(0.0) + e(6)$ Equation 19

$l_p(0.7) = l(0.7) - l(0.0) + e(7)$ Equation 20

e(0) through e(7) in the above equations represents random measurement errors. If we assume that l_p is the true display response then e is the difference between the true response and the dark luminance corrected measurement of that response. Our problem is reduced to the choice of a_3 and a_2 that simultaneously minimizes the errors e(0) .. e(7) in an acceptable manner.

By inspection it may be observed that equations 5 – 12 can conveniently be represented in matrix form as:

L = V ∗ A   **Matrix** Equation 21

Provided that we define the luminance matrix **L**, polynomial coefficient matrix **A**, and input voltage matrix **V** as follows:

$$\mathbf{L} = \begin{vmatrix} l(0.0) - l(0.0) \\ l(0.1) - l(0.0) \\ l(0.2) - l(0.0) \\ l(0.3) - l(0.0) \\ l(0.4) - l(0.0) \\ l(0.5) - l(0.0) \\ l(0.6) - l(0.0) \\ l(0.7) - l(0.0) \end{vmatrix} \qquad \textbf{Matrix } \text{Equation 22}$$

$$\mathbf{A} = \begin{vmatrix} a_3 \\ a_2 \end{vmatrix} \qquad \textbf{Matrix } \text{Equation 23}$$

$$\mathbf{V} = \begin{vmatrix} 0.0^3 & 0.0^2 \\ 0.1^3 & 0.1^2 \\ 0.2^3 & 0.2^2 \\ 0.3^3 & 0.3^2 \\ 0.4^3 & 0.4^2 \\ 0.5^3 & 0.5^2 \\ 0.6^3 & 0.6^2 \\ 0.7^3 & 0.7^2 \end{vmatrix} \qquad \textbf{Matrix } \text{Equation 24}$$

That is,

$$\mathbf{V} = \begin{vmatrix} 0.0 & 0.0 \\ 0.001 & 0.01 \\ 0.008 & 0.04 \\ 0.027 & 0.09 \\ 0.064 & 0.16 \\ 0.125 & 0.25 \\ 0.216 & 0.36 \\ 0.343 & 0.49 \end{vmatrix} \qquad \textbf{Matrix } \text{Equation 25}$$

Pre-multiplying both sides of equation 21 by $\mathbf{V^T}$ (the transpose of input voltage matrix **V**) we get

$$\mathbf{V^T} * \mathbf{L} = [\mathbf{V^T} * \mathbf{V}] * \mathbf{A} \qquad \textbf{Matrix } \text{Equation 26}$$

Obviously, $\mathbf{V^T}$ (the transpose of input voltage matrix **V**) is,

$$\mathbf{V^T} = \begin{vmatrix} 0 & 0.001 & 0.008 & 0.027 & 0.064 & 0.125 & 0.216 & 0.343 \\ 0 & 0.01 & 0.04 & 0.09 & 0.16 & 0.25 & 0.36 & 0.49 \end{vmatrix} \qquad \textbf{Matrix } \text{Equation 27}$$

Multiplying both sides of equation 26 by the square matrix $[\mathbf{V^T} * \mathbf{V}]^{-1}$ we get:

$$\mathbf{A} = [\mathbf{V^T} * \mathbf{V}]^{-1} * \mathbf{V^T} * \mathbf{L} \qquad\qquad \textbf{Matrix Equation 28}$$

For purpose of simplification, we now define the square matrix $\mathbf{S}$ as

$$\mathbf{S} = [\mathbf{V^T} * \mathbf{V}]^{-1} \qquad\qquad \textbf{Matrix Equation 29}$$

Substituting matrix equation 29 in matrix equation 28 we get the simplified

$$\mathbf{A} = [\mathbf{S} * \mathbf{V^T}] * \mathbf{L} \qquad\qquad \textbf{Matrix Equation 30}$$

If we define the polynomial estimator matrix $\mathbf{P}$ as

$$\mathbf{P} = \mathbf{S} * \mathbf{V^T} \qquad\qquad \textbf{Matrix Equation 31}$$

We then get the final solution for $\mathbf{A}$ as

$$\mathbf{A} = \mathbf{P} * \mathbf{L} \qquad\qquad \textbf{Matrix Equation 32}$$

Matrix equation 32 gives us our desired values for coefficients a_3 and a_2, which are the first and second row elements of Matrix $\mathbf{A}$ respectively.

This technique (above) for calculating a_3 and a_2 minimizes the sum of the squares of the errors $e(0)$ through $e(7)$ in equations 13 through 20.

Computation of the Polynomial Estimator Matrix $\mathbf{P}$:

In **Matrix** Equation 29, the matrix $\mathbf{S}$ is defined for simplicity. To compute this matrix, we can first compute the inverse matrix $\mathbf{S^{-1}}$. Then the **Matrix S** can be obtained by simply inverting the $\mathbf{S^{-1}}$ matrix. So, inverse matrix $\mathbf{S^{-1}}$ is calculated as,

$$\mathbf{S^{-1}} = [\ \mathbf{V^T} * \mathbf{V}] \qquad\qquad \textbf{Matrix Equation 33}$$

Substituting Matrix Equations 27 & 25 into Matrix Equation 33 yields

$$\mathbf{S^{-1}} = \begin{vmatrix} 0 & 0.001 & 0.008 & 0.027 & 0.064 & 0.125 & 0.216 & 0.343 \\ 0 & 0.01 & 0.04 & 0.09 & 0.16 & 0.25 & 0.36 & 0.49 \end{vmatrix} * \begin{vmatrix} 0.0 & 0.0 \\ 0.001 & 0.01 \\ 0.008 & 0.04 \\ 0.027 & 0.09 \\ 0.064 & 0.16 \\ 0.125 & 0.25 \\ 0.216 & 0.36 \\ 0.343 & 0.49 \end{vmatrix} \qquad \textbf{Matrix Equation 34}$$

Therefore the Inverse Matrix **S^{-1}** is given as

$$\mathbf{S^{-1}} = \begin{vmatrix} 0.18482 & 0.29008 \\ 0.29008 & 0.4676 \end{vmatrix}$$ **Matrix** Equation 35

Thus the matrix **S** is given as,

$$\mathbf{S} = \begin{vmatrix} 205.5 & -127.484 \\ -127.484 & 81.22437 \end{vmatrix}$$ **Matrix** Equation 36

Finally, the matrix **P** can be computed as

$$\mathbf{P} = \mathbf{S} * \mathbf{V^T}$$ **Matrix** Equation 37

Substituting Matrix Equations 36 & 27 into Matrix Equation 37, the matrix **P** can be computed as

$$\mathbf{P} = \begin{vmatrix} 205.5 & -127.484 \\ -127.484 & 81.22437 \end{vmatrix} * \begin{vmatrix} 0 & 0.001 & 0.008 & 0.027 & 0.064 & 0.125 & 0.216 & 0.343 \\ 0 & 0.01 & 0.04 & 0.09 & 0.16 & 0.25 & 0.36 & 0.49 \end{vmatrix}$$ **Matrix** Eq. 38

And so the polynomial estimator matrix **P** is given as

$$\mathbf{P} = \begin{vmatrix} 0.0000 & -1.0693 & -3.4554 & -5.9250 & -7.2454 & -6.1835 & -1.5062 & 8.0194 \\ 0.0000 & 0.6848 & 2.2291 & 3.8681 & 4.8369 & 4.3706 & 1.7043 & -3.9270 \end{vmatrix}$$ **Matrix** Eq. 39

5. GLOSSARY

Primary Colors: The basic colors (generally three) that a display is capable of displaying in response to inputs to each individual input channel.

Chromaticity: Description of color, defined by an ordered set of Cartesian coordinates that reference the appropriate color stimulus on a color chart defined by the CIE (Reference 1931 CIE Chromaticity Diagram).

Dark Luminance: The luminance response of a display to a zero input voltage on all three input channels.

Tonal Response Curve: Graph of display luminance response to input level that is varied from minimum to maximum.

Color Temperature: A term used to refer to the white point setting of the monitor; the temperature is generally measured in degrees on the Kelvin temperature scale. There is a metameric color match between the color of the display white and the light color radiated by an ideal black body that has been heated up to the corresponding temperature in degrees, Kelvin.

Metameric Color Match: A term used to describe visually identical color stimuli that have different spectral energy content.