

CIE Colour Chart-based Video Monitoring

Transferring video from one video standard to another or from one display system to another typically introduces slight changes of colour.

Two main factors are at play here. One is the different display primaries used by the different systems: the choice of display primaries strongly affects the range of colours that can be displayed. The other is the requirement to keep RGB or YUV values within gamut as video is transferred from one standard to another. Any illegal values that are generated by the conversion need to be brought back into gamut, typically by substituting the nearest legal value. This results in certain colours becoming de-saturated, together with some loss of detail particularly in darker areas of the image.

For some broadcast material, the resulting colour changes are not particularly important but the advent of digital cinema has brought these issues sharply into focus. For video to compete effectively with film distribution, it has to deliver good depth of colour, reproduced as faithfully as possible across many different displays. The limitations of display systems inevitably mean that some compromises have to be made. The need is to minimise the effect of these compromises.

The traditional approach to monitoring colour gamut in video test and measurement systems is useful in identifying where RGB and YUV values go outside the legal range but doesn't give a clear picture of how colour depth is being affected. In its latest OTM and OTR data analysis systems, OmniTek has introduced a CIE Colour Chart display that gives an unambiguous, real-time trace of the colour in each frame. This trace may further be overlaid with an outline showing the colour gamut supported either by the standard into which the video is being converted or by the monitor on which it is to be displayed. The colours that will be changed are the ones that lie outside this outline.

This white paper introduces the technology behind this new display and explains its benefits.

The OmniTek CIE Colour Chart

Introducing the CIE Colour Chart

The CIE Colour Chart is a plot of all the colours that the human eye can see (and hence of all the colours that anyone who works with video will ever need to worry about).

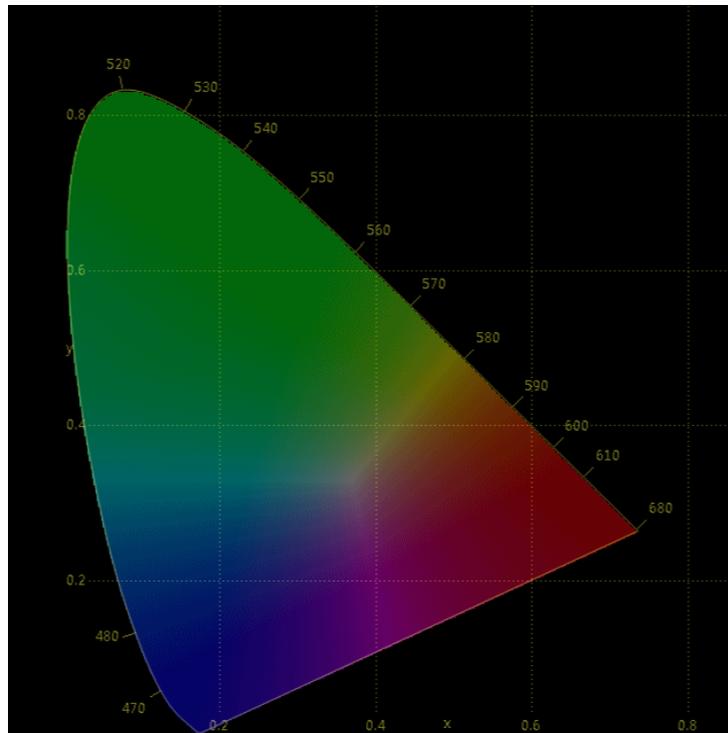


Figure 1: CIE Colour Chart

The chart is based on the expression of these colours in the 'XYZ' colour space. This colour space was devised by researchers who were looking for a way to express colour unambiguously. For this, they wanted to define a colour space that *met* the following criteria:

- Covered the full range of colours visible to the human eye
- Three independent and positive variables were necessary and sufficient to specify any colour
- Only the tri-stimulus values of the sources were relevant in expressing any colour, not their spectral composition
- If one or more of the colour sources are changed gradually, the resulting tri-stimulus values also change gradually.

The obvious choice to meet these criteria was a colour space based on the individual responses of the red, green and blue cones of the human eye and so was born the XYZ colour space in which:

$$X = \int I(\lambda) \cdot \bar{x}(\lambda) d\lambda = \text{Signal from Red cones}$$

$$Y = \int I(\lambda) \cdot \bar{y}(\lambda) d\lambda = \text{Signal from Green cones}$$

$$Z = \int I(\lambda) \cdot \bar{z}(\lambda) d\lambda = \text{Signal from Blue cones}$$

(You can read about this colour space in a white paper entitled 'The XYZ Colour Space'.)

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Having established X, Y and Z as the parameters, the question then turns to how to plot the XYZ values corresponding to the colours seen by the human eye and/or the XYZ values corresponding to the RGB/YCbCr signals of any video.

Fortunately, any three-dimensional colour space can be readily be transformed into a corresponding space based on luminance as one dimension with the other two dimensions defining the 'chromaticity' of the colour and chromaticity is the only part of the colour that is of interest here.

Luminance is additive and is given by $X + Y + Z$. Dividing X and Y by the luminance gives x and y values that together represent the chromaticity. (There is no need to include the equivalent z factor in the plot because $z = 1 - (x + y)$.) The resulting suitably-coloured plot of x and y is known as the CIE Colour Chart.

The Key Features of the CIE Colour Chart

The CIE Colour Chart has a number of important properties.

The colours visible to the eye occupy the approximately horse-shoe shaped area of the chart – which is traditionally coloured in line with the colours corresponding to the different x , y values. This area represents the gamut of human vision, normalized for brightness. (The limitations of display / printing technology of course mean that the colours shown on any image of the CIE Colour Chart never accurately reflect the colours that really correspond to those x , y values but they are good enough to give the general feel.)

The area outside the coloured area represents values of x and y that don't correspond to a colour that can be seen by the human eye, and as such represent illegal X, Y, Z combinations. It should also be noted that all the x , y values shown are positive and correspond to positive values of X, Y and Z.

The curved edge of the human gamut is called the *spectral locus* and corresponds to monochromatic light. These are the fully saturated versions of the rainbow colours. The lower straight edge is called the *line of purples*, none of which have any counterpart in a rainbow.

Within these outer edges, the colours become progressively less saturated culminating in white at the 'middle'.

Any colour source can be represented by a single point, somewhere within the coloured region of the human gamut. Where you have two colour sources, the straight line between the two points that represent those light sources represents all the colours that can be formed by mixing light from those two sources. Where you have three light sources, the colours that can be formed by mixing light from those sources are encompassed by the triangle formed by joining the points representing the three light sources. Any such triangle formed from real sources (each lying within the human gamut) will inevitably be smaller than the human gamut which is a convex horse-shoe shape. This in turn means that no group of three real sources can cover the whole of the human gamut.

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OmniTek Implementation of CIE Colour Chart

The basic CIE Colour Chart display offered by OmniTek is illustrated in *Figure 2*. This display is added to OTM and OTR systems by installing the VIDEO_XR_DCI software option,

The background to this display is an x, y plot of the standard CIE Colour Chart. (The colours shown in the outer regions of the coloured area are of course purely representational as the monitor on which the chart is being displayed is unable to produce any colours that lie outside its own RGB triangle.)

Over this may be superposed one or two gamut triangles together with an interpolated plot of the x, y values associated by the individual pixels of the video frame currently being analysed. One of the triangles is automatically set to reflect the colour primaries of the video source. The other triangle is up to the user but will typically be set to reflect the video standard to which the input is being converted or the colour primaries used by the particular monitor on which the video is to be displayed. (The triangles associated with the different video standards are available for selection from a menu.)

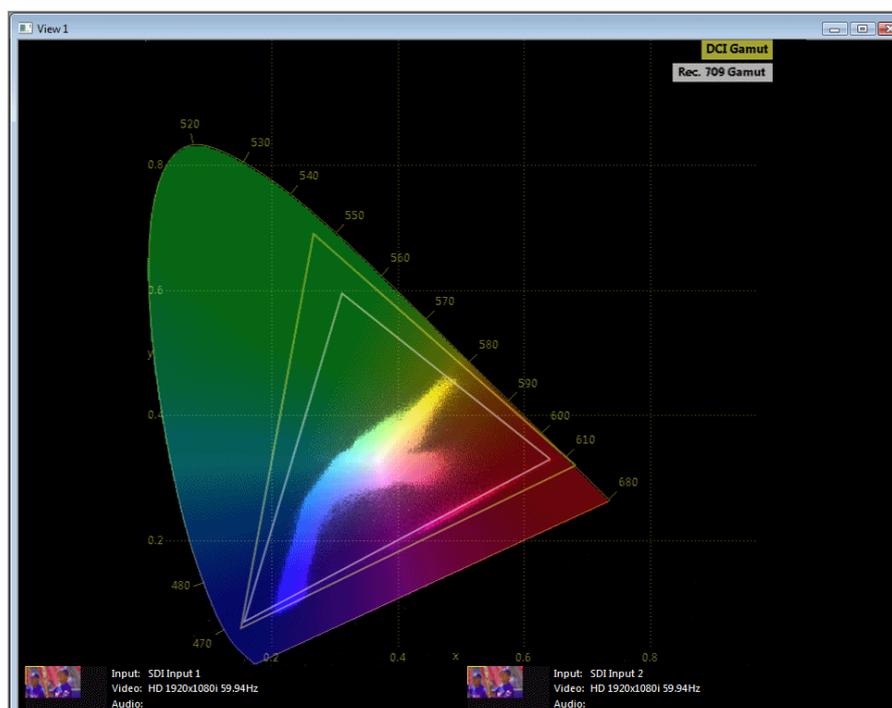


Figure 2: Example OmniTek CIE Colour Chart Display

Viewing the interpolated plot alongside these triangles allows precise appreciation of the colours within the video being analysed that will be affected by the change to different colour primaries (being the ones that lie within the triangle associated with the source primaries but outside of the triangle associated with the system for which the video is being converted). The distance by which these colours lie outside of the destination triangle also provides a measure of the degree to which these colours will become de-saturated by the conversion.

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Among the facilities offered to the user are:

- User selection of colour primaries used for XYZ and RGB inputs. (The colour primaries used with YCbCr inputs are selected automatically, based on the video standard.)
- The option of limiting the display to just those pixels whose luminance lies between particular luma levels. (This is known as ‘Luma Qualification’.)
- The option of limiting the display to the pixels on a particular line or to the pixels within a particular region of interest.

A key advantage of this chart over the vectorscope display, for instance, is that it is independent of the luma level.

Colour Issues in Converting between Video Standards

The results produced from an RGB display depend on exactly what red, green and blue primaries it uses.

You may not have realised but PAL, NTSC and HD transmissions each define a set of RGB primaries that are subtly different from each other (see *Table 1*), while digital cinema (DCI) uses yet another set of primaries.

Video Standard	Red		Green		Blue	
	<i>x</i>	<i>y</i>	<i>x</i>	<i>y</i>	<i>x</i>	<i>y</i>
PAL	0.64	0.33	0.29	0.60	0.15	0.06
NTSC	0.63	0.34	0.31	0.595	0.155	0.07
HD	0.640	0.330	0.300	0.600	0.150	0.060
DCI	0.680	0.320	0.265	0.690	0.150	0.060

Table 1: Display primaries defined by the different video standards.

The RGB primaries used by the PAL, NTSC and HD standards were defined on a practical basis and are all very close in colour to the light emitted by the red, green and blue phosphors in a CRT television set. As a result, signals generated for any of these standards can be used directly to drive a CRT and will correctly reproduce the colours seen by the camera (assuming the pixel values are all in gamut).

A feature of three-colour colour spaces is that any tri-stimulus value in one colour space can be converted to the corresponding tri-stimulus value in another colour space by applying a linear transform (i.e. one involving just multiplication and addition). Thus the RGB value that applies for the ‘source’ set of colour primaries can be converted into the equivalent ‘destination’ RGB value by applying a linear transform. This is represented mathematically as:

$$\begin{bmatrix} R_D \\ G_D \\ B_D \end{bmatrix} = \begin{bmatrix} & & \\ & 3 \times 3 & \\ & & \end{bmatrix} \begin{bmatrix} R_S \\ G_S \\ B_S \end{bmatrix}$$

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The mathematics involved in determining the 3 x 3 matrix to apply in any particular case is fairly complex but it is given, along with a worked example, in SMPTE RP 177 (and reproduced as an appendix to this white paper).

The issue with these conversions, however, is in the different ranges of colours that the different RGB systems offer. These differences mean that colours that are perfectly valid in one RGB system can fall outside the valid colour gamut in another RGB system. This is particularly likely where images are being converted from traditional film to digital cinema and from digital cinema to SD or HD video for transmission, film supporting a wider colour gamut than digital cinema which itself supports a wider colour gamut than SD or HD.

The simplest action to take when the red, green or blue signal at a particular pixel is out of gamut is to force that signal to either the minimum or the maximum permitted value as appropriate. The effect of that action is move the colour towards the white, de-saturating the colour and generally reducing the depth of colour across the image, losing definition particularly in darker areas of the image.

It should also be noted that LCD displays work by blocking unwanted colours and inevitably a proportion of the blocked light comes through, de-saturating the resulting image and shrinking still further the triangle outlining the supported colour range – though Hewlett-Packard's DreamColor LP2480zx Professional LCD Display counteracts this effect through three-colour LED backlighting and colour-space remapping technology.

Such changes can significantly change the look and feel of a video sequence.

Counteracting these Effects

The worst effects of these changes are minimised by skilful colour-grading of the converted image in a post production studio.

While colorists do a lot of their work by eye, they also make use of the various analytical displays available to them from the video test & measurement equipment they use.

The typical video test & measurement system will offer waveform histograms, gamut plots and vectorscope plots. However, the information these provide is limited. For instance, the data shown on waveform histograms and gamut plots summarise the signal excursions seen across a complete frame rather than offering pixel by pixel data, while the colour information in a vectorscope plot takes considerable practice to identify and is anyway strongly affected by luminance level.

To achieve the best result, it is important to be able to tell *on a per pixel level* what compromises are being made in the colours being used.

The CIE Colour Chart offered on the OmniTek OTM and OTR systems provides a very precise way of identifying the colours associated with any particular set of colour primaries.

Of particular importance are triangles that are overlaid on this display. Each triangle is formed from the points representing the three colour primaries associated with a particular video standard and encompasses all the colours that that video standard supports. Two triangles may be displayed – a yellow triangle and a white one. The yellow triangle marks out the range of colours supported in the source video format. The white triangle marks out the range of colours supported by a destination video format selected by the user.

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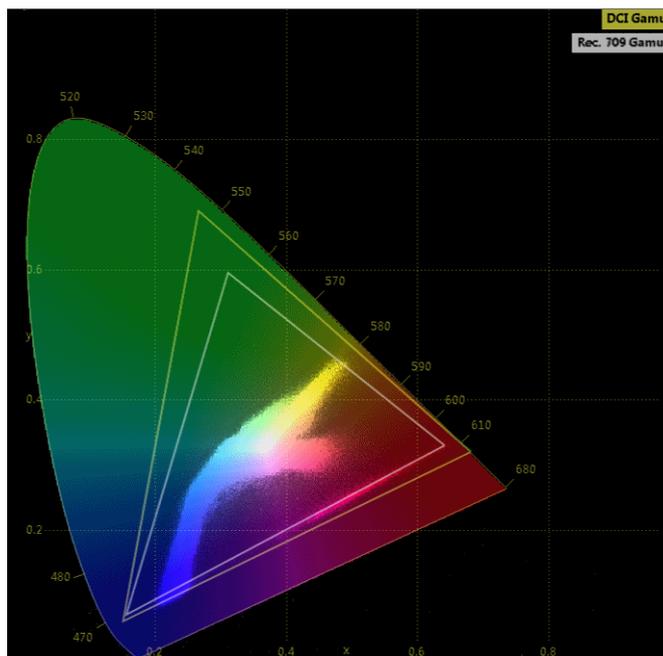


Figure 3: CIE Colour Chart showing how colours within the gamut of the digital cinema source may lie outside the gamut of HD video transmission.

The bright points on the display each represent the colour of a pixel in the frame that is currently being analysed.

The chart shows directly how the colour will be changed on conversion to the selected destination video format simply by looking at those bright spots that fall between the two triangles because any pixel where the colour falls inside the yellow triangle but outside the white triangle on the CIE Chart display will be modified in order to conform with the new standard.

Inevitably these modifications result in some de-saturation of the image as the move from the original colour to the final colour is always a move towards the centre of the chart and hence a move towards the white.

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Appendix: Transforming between sets of RGB primaries

SMPTE RP (Recommended Practice) 177 includes the following description of how to derive the matrix used to convert between the representation of a colour using one set of RGB colour primaries and its representation using another set of RGB colour primaries.

4.1 Input data

The input data consists of the normalized primary matrices for a source system (NPM_S) and for a destination system (NPM_D). Ideally these matrices should have been generated directly from the 3-digit primary chromaticities and 4-digit reference white and, therefore, be of 10-digit accuracy. However, normalized reference primary matrices rounded to four digits may be used. It must be recognized that this will result in a lower precision transformation.

4.2 General procedure

4.2.1 Given the normalized primary matrices for the source (NPM_S) and destination (NPM_D) systems, the following equations relate CIE tri-stimulus values to the linear RGB signals in both source and destination systems:

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \text{NPM}_S * \begin{bmatrix} R_S \\ G_S \\ B_S \end{bmatrix} \quad \text{and} \quad \begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \text{NPM}_D * \begin{bmatrix} R_D \\ G_D \\ B_D \end{bmatrix}$$

The inverse relationships, predicting RGB from XYZ, may also be written:

$$\begin{bmatrix} R_S \\ G_S \\ B_S \end{bmatrix} = \text{NPM}_S^{-1} * \begin{bmatrix} X \\ Y \\ Z \end{bmatrix} \quad \text{and} \quad \begin{bmatrix} R_D \\ G_D \\ B_D \end{bmatrix} = \text{NPM}_D^{-1} * \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}$$

Again, the (⁻¹) notation of the NPM matrices indicates matrix inversion.

4.2.2 The objective is to determine a matrix which transforms RGB signals from the source system into appropriate signals for the destination system. Start from the source, using its NPM to predict XYZ values from source RGB signal values as shown in the left equation below. Then write the equation predicting the destination RGB signals from XYZ values as shown in the right equation below:

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \text{NPM}_S * \begin{bmatrix} R_S \\ G_S \\ B_S \end{bmatrix} \quad \text{and} \quad \begin{bmatrix} R_D \\ G_D \\ B_D \end{bmatrix} = \text{NPM}_D^{-1} * \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}$$

Since the values of XYZ should be the same for both source and destination systems, the XYZ vector on the right side of the right equation can be replaced with the entire right side of the left equation:

$$\begin{bmatrix} R_D \\ G_D \\ B_D \end{bmatrix} = \text{NPM}_D^{-1} * \text{NPM}_S * \begin{bmatrix} R_S \\ G_S \\ B_S \end{bmatrix}$$

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4.2.3 The desired transformation matrix TRA is the product of NPM_D inverse and NPM_S :

$$TRA = NPM_D^{-1} * NPM_S$$

and

$$\begin{bmatrix} R_D \\ G_D \\ B_D \end{bmatrix} = TRA * \begin{bmatrix} R_S \\ G_S \\ B_S \end{bmatrix}$$

Annex C (informative)

Example derivation of primary transformation matrix

C.1 Given a source NPM:

$$NPM_S = \begin{bmatrix} 0.5671181859 & 0.1903210663 & 0.1930166748 \\ 0.2793268677 & 0.6434664624 & 0.0772066699 \\ 0.0000000000 & 0.0725032634 & 1.0165544874 \end{bmatrix}$$

and a destination NPM:

$$NPM_D = \begin{bmatrix} 0.4123907993 & 0.3575843394 & 0.1804807884 \\ 0.2126390059 & 0.7151686788 & 0.0721923154 \\ 0.0193308187 & 0.1191947798 & 0.9505321522 \end{bmatrix}$$

C.2 The resulting transformation matrix TRA before rounding is:

$$TRA_{S \rightarrow D} = \begin{bmatrix} 1.4085805665 & -.4085805667 & 0.0000000000 \\ -.0256675666 & 1.0256675666 & -.0000000001 \\ -.0254274151 & -.0440308720 & 1.0694582872 \end{bmatrix}$$

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