Understanding Colors and Gamut

Definitions

1. **gamut** – The range of colors allowed for a video signal. Valid color gamut is defined as all colors represented by all possible combinations of legal values of an R'G'B' signal. Signals in other formats may represent colors outside valid gamut, but still remain within their legal limits. These signals, when transcoded to the R'G'B' domain, will fall outside legal R'G'B' limits. This may lead to clipping, crosstalk, or other distortions.

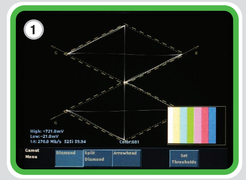
   The allowed range for R'G'B' is 0 to 700 mV, while allowed ranges for Y'P'bP'r are luma (Y'), 0 to 700 mV, and color difference (P'b/P'r), ±350 mV.

2. **legal/illegal** – A signal is legal if it stays within the gamut appropriate for the format in use. A legal signal does not exceed the voltage limits specified for the format of any signal channel. An illegal signal is one that is, at some time, outside the limits in one or more channels. A signal can be legal but still not be valid.

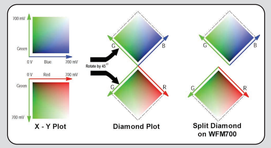
3. **valid signal** – A video signal where all colors represented lie within the valid color gamut. A valid signal will remain legal when translated to R'G'B' or other formats. A valid signal is always legal, but a legal signal is not necessarily valid. Signals that are not valid will be processed without problems in their current format, but may encounter problems when translated to another format.

DIAMOND DISPLAY

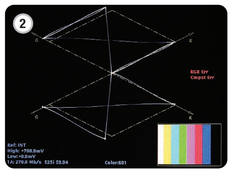
Correct Diamond Display



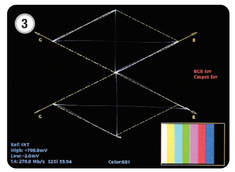
The Tektronix Diamond display using a 100% color bars signal. The 0 to 700 mV signal range of a 100% color bars signal falls exactly within the graticule. The 100% color bars signal is said to be within the gamut of R'G'B' color space.



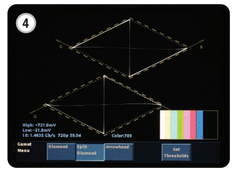
The Tektronix Diamond display is generated by combining R', G', and B' signals. If the video signal is in another format, the components are converted into R', G', and B'. (R'G'B' can be converted into a valid, legal signal in any format that can handle 100% color bars.) To predictably display all three components, they must lie between 700 mV to 0 V. Picture monitors handle excursions outside the standard range (gamut) in different ways. For a signal to be in gamut, all signal vectors must lie within the G-B and G-R diamonds. If a vector extends outside the diamond, it is out of gamut. Errors in green amplitude affect both diamonds equally, while blue errors affect only the top diamond and red errors affect only the bottom diamond. Using a color bars test signal, timing errors can be seen as bending of the transitions.



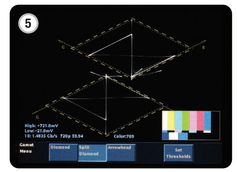
The color bars signal exceeds both the upper and lower diamonds along the G' axis. Therefore there is an amplitude error within the green channel and the signal gain should be corrected so that the waveform falls within the graticule. Note that the B' and R' components fall within the graticule and are therefore within correct limits.



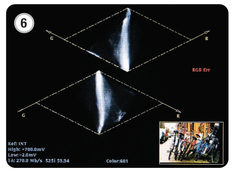
Here, the Tektronix Diamond display shows an error only in the lower display along the R' axis. This indicates an amplitude error within the red channel. The gain of the red channel should be adjusted to fall within the graticule. Similarly if only the upper waveform falls outside the limits along the B' axis, this would indicate a blue amplitude error.



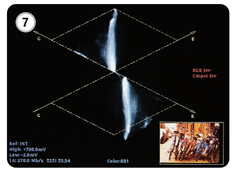
Tektronix improved upon the Diamond display by introducing the Split Diamond in the WFM700. This display separates the upper and lower components facilitating observation of gamut errors within the black region.



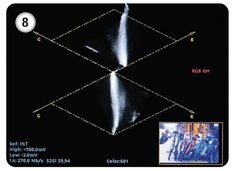
In the WFM700, the Diamond can be used for monitoring both standard definition and high definition formats. In this example using a high definition format, the NTSC SMPTE color bars signal is not legal when converted to R'G'B' color space. The waveform exceeds the graticules in the black region. This is due to the lower blue bars exceeding the R'G'B' limits and going below 0 mV.



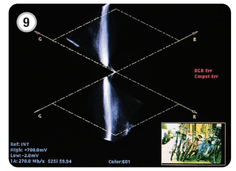
The Diamond and Split Diamond displays can be used for both live signals and test signals and are unsurpassed in their ability to simplify R'G'B' gamut monitoring. In this signal, there is a minor violation along the upper G' axis. The operator can decide if this condition is acceptable for their requirements. With the WFM700, the user can select gamut threshold limits appropriate for their production standards.



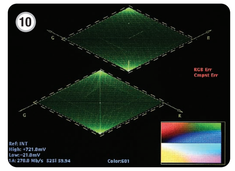
This signal has a significant red imbalance and falls outside the lower diamond graticule. Note also that the trace is offset to the right in the lower diamond. The red imbalance is caused by an offset in the black level of the red channel and should be color corrected.



This signal has a significant blue imbalance and falls outside the upper diamond graticule. Note that the trace is offset to the right in the upper diamond. The blue imbalance is caused by an offset in the black level of the blue channel and should be color corrected.



This signal shows an error indicating a green color imbalance. The signal is offset to the left in both upper and lower diamonds indicating a green setup error within the black region. Color correction of the signal is necessary to correct the imbalance.

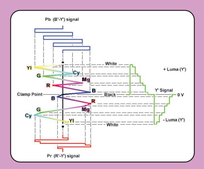


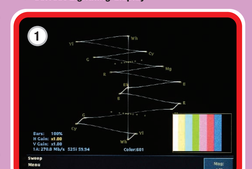
A color palette signal generated on the TG700 test signal generator containing the complete range of standard definition colors: this color range completely fills the graticule of the Split Diamond display.

LIGHTNING DISPLAY

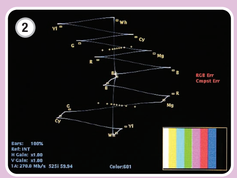
Tektronix developed the Lightning display to provide both amplitude and interchannel timing information for the three channels of a component signal – within a single display. This unique display requires only a single test signal, standard color bars, to make definitive measurements. Plotting luma versus P'b in the upper half of the screen and inverted luma versus P'r in the lower half – like two vector displays sharing the same screen – generates the Lightning display. The bright dot at the center of the screen is blanking (zero signal level). Increasing luma is plotted upward in the upper half of the screen and downward in the lower half.

Correct Lightning display

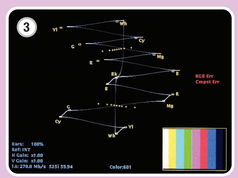




The Lightning display is an ideal tool for performing tape alignments quickly and easily. With a standard color bars signal at either 75% or 100%, select the appropriate scale on the waveform monitor and ensure that all the color components fall within the boxes.



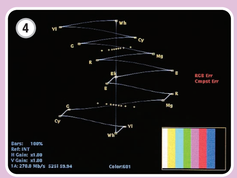
This example shows a luma amplitude error because both the upper and lower traces fall outside the individual graticule boxes. Decrease the amplitude of the luma signal until each component fits within the boxes.



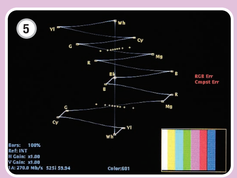
The upper half of this Lightning display shows an error: the traces are not within the graticule boxes. Specifically, this indicates a P'b amplitude error requiring adjustment of the P'b channel gain until each trace fits within the appropriate box. Similarly, if only the lower half of the display was in error, then this would point to a gain error within the P'r channel.

Using a color bars signal, and assuming correct gain and amplitude in the green-magenta transitions, the Lightning display can be used for interchannel timing measurement. On the WFM700 there are nine cross-hair graticules positioned spanning each green-magenta transition that can be used for timing measurements.

If the color-difference signal is not coincident with luma, the transitions between color dots will bend. The amount of this bending represents the relative signal delay between luma and color-difference signal. The upper half of the display measures the P'b to Y' timing, while the bottom half measures the P'r to Y' timing. If the transition bends in toward black, the color-difference signal is delayed with respect to luma. If the transition bends out toward white, the color difference signal is leading the luma signal.



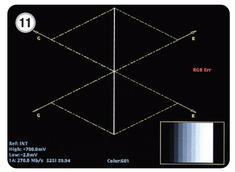
This example shows a bowing outward from the center in the upper half of the display. This indicates a timing error in the P'b channel where the P'b signal is leading the luma signal. The transition crosses the third cross-hair and indicates a timing error of 74 ns. In the lower half of the display, the green-magenta transition crosses the center mark – there is no timing error between the luma and P'r signals.



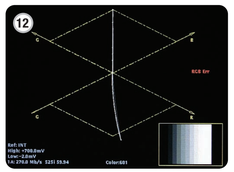
Here the trace is bowing inward from the center in the upper half of the display indicating a timing error in the P'b channel. The P'b signal is delayed with respect to the luma signal. The trace intersects the third cross-hair and indicates a timing error of 74 ns. In the lower half of the display, the green-magenta transition crosses the center cross-hair, thus there is no timing error between the luma and P'r signals.

Graticule	WFM700-HD Signal	WFM700-SD Signal	WFM601
Center	Aligned	Aligned	Aligned
1st Mark	2 ns	20 ns	40 ns
2nd Mark	5 ns	40 ns	80 ns
3rd Mark	13.5 ns *(1 luma sample)*	74 ns *(1 luma sample)*	160 ns
4th Mark	27 ns *(1 chroma sample)*	148 ns *(1 chroma sample)*	*N/A*

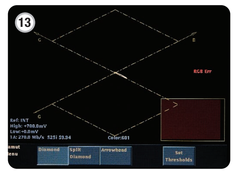
Timing Cross-Hair Positions on Lightning Display.



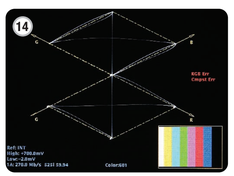
The Diamond display can be an essential tool for simplifying camera balancing. When the value of R'=G'=B', this produces a gray value. A resulting gray scale will therefore produce a vertical line in both upper and lower diamonds, provided the signal is aligned correctly. Any deviation can easily be observed within the Diamond display.



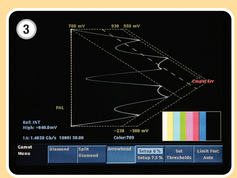
In this case, the camera has a red imbalance that is shown by the deviation of the lower diamond from the vertical axis toward the red axis. The camera should be adjusted to correct for this imbalance.



With the lens of the camera capped, the signal should be black and the Diamond display should show a dot at the center of the graticule. In this case, the capping produces a trace along the red axis in the lower diamond, indicating that the red channel has a setup error and should be adjusted until a dot is displayed at the center of the display.

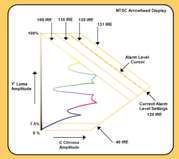


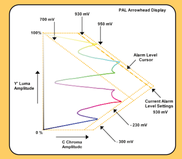
Timing errors can be detected with the Diamond display when a test signal such as color bars is used. The horizontal bowing in the upper diamond indicates a timing error in the blue channel. Note that the shift in timing of the blue channel gives rise to a larger transition at each color boundary – this produces a minor bowing at each transition on the Diamond display. If the bowing had occurred in the lower horizontal transition this would indicate a red channel timing error. The timing error cannot be measured within the Diamond display; it simply gives an indication of timing errors.



The PAL Arrowhead display has different graticule limits due to the different color space used. In this case, a PAL 100% color bars signal is within the 930 mV level of the graticule. The WFM700 has a Set Threshold range of 90 IRE to 135.7 IRE for NTSC and 630 mV to 950 mV for PAL. Additionally, the WFM700 allows for adjustment of setup between 0% and 7.5% to suit the broadcast format. In this case, the user set a threshold of 840 mV.

ARROWHEAD DISPLAY

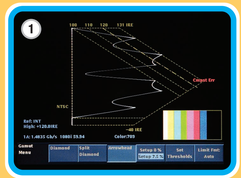


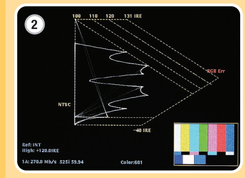


Tektronix developed the Arrowhead display to show out-of-gamut conditions in composite color space, without requiring a composite encoder. The Arrowhead display plots luma on the vertical axis, with blanking at the lower left corner of the arrow. The magnitude of the chroma subcarrier at each luma level is plotted on the horizontal axis, with zero subcarrier at the left edge of the arrow. The upper sloping line forms a graticule indicating 100% color bars total luma + subcarrier amplitudes. The lower sloping graticule indicates luma + subcarrier extending toward sync tip (maximum transmitter power). An adjustable modulation depth alarm setting offers the capability to warn the operator that the composite signal may be approaching a limit.

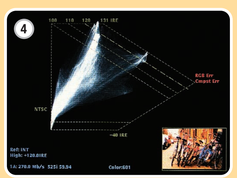
Correct Arrowhead Display

The NTSC Arrowhead display shows the constructed luma and chroma amplitudes of a 100% color bars signal. Notice that the 120 IRE alarm threshold is exceeded by the 100% color bars. Within NTSC color space a 100% color bars signal is not suitable for transmission and will saturate the system. Typically, therefore, 75% bars (such as SMPTE color bars) are used for NTSC systems. The multi-format nature of the WFM700 permits the Arrowhead display to be used not only for standard definition, but also for high definition video signals which may be down-converted to standard definition for broadcast or distribution.

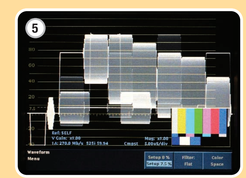




An NTSC SMPTE color bars signal has been applied to the Arrowhead display. In this case, the signal is within the limits of the graticule and will be passed easily through the transmission system. Note that the display indicates that SMPTE color bars are out of gamut within R'G'B' color space.



The Arrowhead display can be used for both test signals and live content. In this case, a threshold of 120 IRE has been set and this signal exceeds valid composite NTSC color space. The level of the signal should be adjusted to prevent clipping within NTSC transmission systems.



The WFM700 incorporates a pseudo-composite waveform mode that digitally recreates the composite signal waveform from the digital input. This feature allows the operator to visualize the familiar composite signal.

SCIENCE BEHIND THE TECHNOLOGY

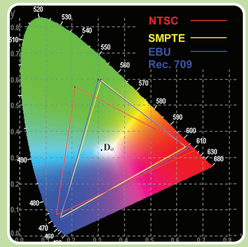


Figure 1
CIE xy Diagram with color coordinates used by NTSC, SMPTE and EBU Rec. 709

The television color specification is based on standards defined by the CIE (Commission Internationale de L'Éclairage) in 1931. The CIE specified an idealized set of primary XYZ tristimulus values. This set is a group of all-positive values converted from R'G'B' where Y is proportional to the luminance of the additive mix. This specification is used as the basis for color within today's video standards.

Table 2. Luma and chroma video components

Y', R'-Y', B'-Y' commonly used for analog encoding			
Format	1125/60/2:1, 720/60/1:1	525/59.94/2:1, 625/50/2:1, 1250/50/2:1	
Y'	0.2126 R' + 0.7152 G' + 0.0722 B'	0.299 R' + 0.587 G' + 0.114 B'	
R'-Y'	0.7874 R' - 0.7152 G' - 0.0722 B'	0.701 R' - 0.587 G' - 0.114 B'	
B'-Y'	-0.2126 R' - 0.7152 G' + 0.9278 B'	-0.299 R' - 0.587 G' + 0.886 B'	
Y', Pb, Pr analog component			
Format	1125/60/2:1 (SMPTE 240M)	1920 x 1080 (SMPTE 274M) 1280 x 720 (SMPTE 296M)	525/59.94/2:1, 625/50/2:1, 1250/50/2:1
Y'	0.212 R' + 0.701 G' + 0.087 B'	0.2126 R' + 0.7152 G' + 0.0722 B'	0.299 R' + 0.587 G' + 0.114 B'
P'b	(B'-Y')/1.826	[0.5/(1-0.0722)] (B'-Y')	0.564 (B'-Y')
P'r	(R'-Y')/1.576	[0.5/(1-0.2126)] (R'-Y')	0.713(R'-Y')
Y', Cb, Cr scaled and offset for digital quantization			
Format	1920x1080 (SMPTE 274M) 1280x720 (SMPTE 296M)	525/59.94/2:1, 625/50/2:1, 1250/50/2:1	
Y'	0.2126 R' + 0.7152 G' + 0.0722 B'	0.299 R' + 0.587 G' + 0.114 B'	
C'b	0.5389 (B'-Y') + 350 mV	0.564 (B'-Y') + 350 mV	
C'r	0.6350 (R'-Y') + 350 mV	0.713 (R'-Y') + 350 mV	

Table 1. CIE XY Coordinate Values for Various Formats

SMPTE	RED	GREEN	BLUE
	xr yr	xg yg	xb yb
	0.630 0.340	0.310 0.595	0.155 0.070
Illuminant D65	x = 0.3127	y = 0.3290	
EBU	RED	GREEN	BLUE
Rec 709	xr yr	xg yg	xb yb
	0.640 0.330	0.300 0.600	0.150 0.060
Illuminant D65	x = 0.3127	y = 0.3290	
PAL/SECAM	RED	GREEN	BLUE
	xr yr	xg yg	xb yb
	0.64 0.330	0.290 0.60	0.150 0.060
Illuminant D65	x = 0.3127	y = 0.3290	
NTSC	RED	GREEN	BLUE
(1953)	xr yr	xg yg	xb yb
	0.670 0.330	0.210 0.710	0.140 0.080
Illuminant C	x = 0.3101	y = 0.3162	

The CIE standardized a procedure for normalizing XYZ tristimulus values to obtain a two-dimensional plot of values, x and y, of all colors for a relative value of luminance as specified by the following equations:

$$x = X / (X + Y + Z)$$
$$y = Y / (X + Y + Z)$$
$$z = Z / (X + Y + Z)$$
$$1 = x + y + z$$

Table 3

Illuminant A	x = 0.4476	y = 0.4075
Illuminant B	x = 0.3484	y = 0.3516
Illuminant C	x = 0.3101	y = 0.3162
Illuminant D65	x = 0.3127	y = 0.3290

Limits are defined for various video formats that show all possible colors for each format. Color-coded triangles (yellow for the SMPTE format, blue for EBU/PAL/SECAM, red for NTSC 1953) in Figure 1 are specified by x, y coordinates in Table 1.

White: The white point of the system within each format is defined by the addition of red, green, and blue in equal quantities. The CIE defined several standard sources in 1931 as shown in Table 3.

- Source A: A tungsten filament lamp with a color temperature of 2854K
- Source B: A model of noon sunlight with a color temperature of 4800K
- Source C: A model of average daylight with a color temperature of 6504K

Illuminant C (Source C) was used in the original definition of NTSC. The CIE later defined a series of daylight illuminants, called the Daylight D series. Illuminant D65 with a color temperature of 6504K, and slightly different x, y coordinates, is predominately used today.

The primary colors, red, green and blue, can be mapped onto a three-dimensional color cube. All colors can be represented within the bounds of the R'G'B' color cube.

Using the equations in Table 2 to convert the color values from R'G'B' space to Y'P'b P'r space limits the range of colors. Only about 25% of all possible signal values in the Y'P'b P'r domain are used to present the complete gamut of colors in the R'G'B' domain. Care must be taken when translating between formats to ensure that the dynamic gamut of the signal is not exceeded.

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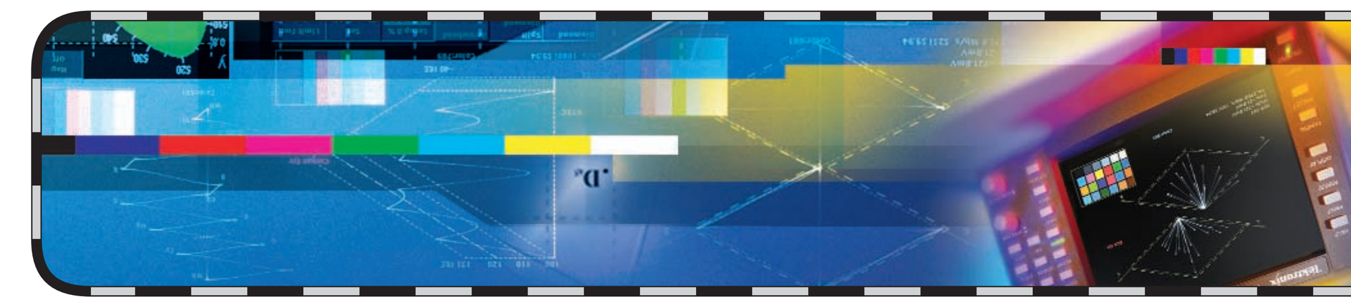

Understanding Colors and Gamut

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WFM700 Family of Waveform Monitors

- Monitors and measures HD and SD signals in a single unit
- HD and SD eye pattern measurements and jitter displays
- Configurable/modular architecture
- Up to four input channels of digital video
- Digital processing ensures reliable and repeatable measurements
- Color display is 50% larger than standard displays

WFM601 Family of Waveform Monitors

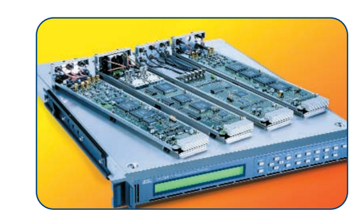
- Industry standard for SD-only monitoring and measurement
- Two input channels
- SD eye pattern measurements and jitter displays
- Three models tailored for specific applications

17XX Family of Waveform Monitors and Vectorscopes

- Available in PAL and/or NTSC
- Broad range of models address different needs
- Up to eight composite or two component input channels

TG700 Multiformat Video Generator

- Multiformat analog and digital test signal generation
- Modular expandable platform
- Ideal channel configuration and performance to support reference generator needs



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CIE xy diagram courtesy of Earl F. Glynn, efg's Computer Lab

Bicycle photo courtesy of Onno Zweers

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