Victor Steinberg

Video Standards

Signals, Formats and Interfaces

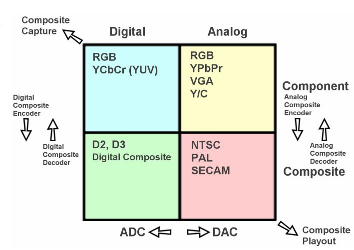
Part 6

Color Spaces, Formats, Levels, Ranges

www.videoq.com

Analog & Digital, RGB & YUV, Component & Composite

Some formats shown on this diagram have a local variants, e.g. NTSC-USA uses the 7.5 IRE setup, but NTSC-Japan does not; also there are variants restricted to particular scanning standard, e.g. SECAM exists only in 625i25 format, whilst for PAL there are several variants.



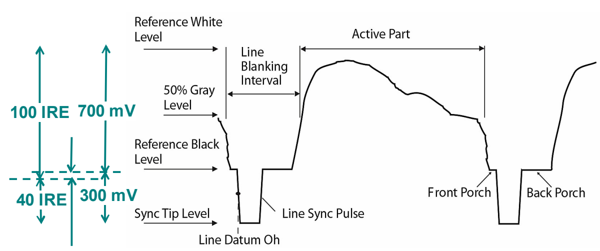
As to analog and digital **levels**, there are not so many variants.
For analog signals there are **two schemes**, the main difference is the signal **range** between **Reference Black** and **Reference White**:
700 mV in **50 Hz** countries
100 IRE (**714.285714 mV**) in **60 Hz** countries

Many years ago, the black and white video signal nominal peak-to-peak level was set at 1V (**1000 mV**) - a simple, elegant choice.

However, the **Sync** to **Luminance** ratio was different:
4 to **10** in America and **3** to **7** in other countries.

This difference resulted in a discrepancy between **nominal (reference) white levels**, i.e. the voltage change needed to go from black to white.

In 50 Hz countries it is **700 mV**, but in America it is 10000/14 = **714.285714 mV**. The latter figure does not exactly roll off the tongue, and so the Institute of Radio Engineers (IRE) devised a special unit of measurement: the "IRE".
1 IRE is defined as **7.14 mV**; the levels range from black to white is **100 IRE**, and the luminance plus sync peak-to-peak range is **140 IRE**.

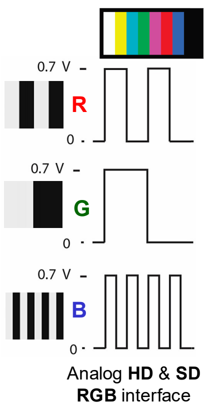


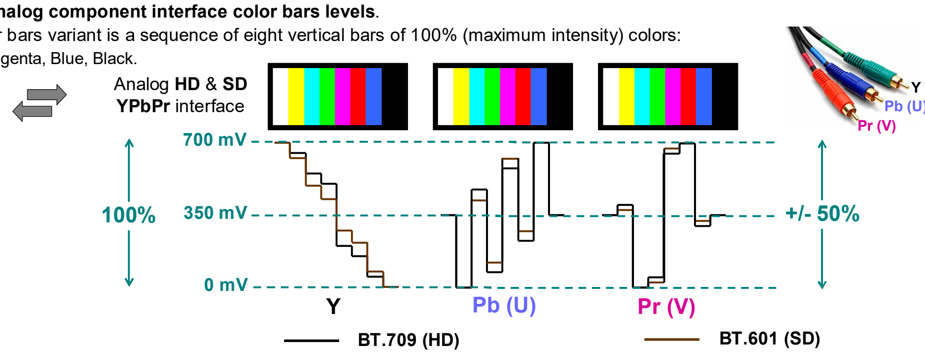
Color Bars – Checking RGB & YUV Levels

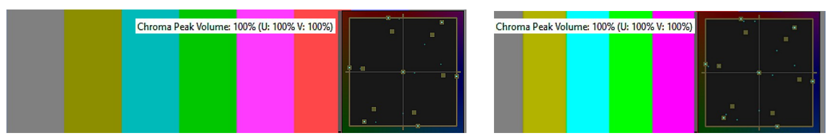
Color Bars are the most common pattern for testing video ADCs, DACs, RGB ⇔ YUV conversion, encoders, decoders, codecs, displays, etc.

For a start, let's look at the **analog component interface color bars levels**.

The simplest and oldest color bars variant is a sequence of eight vertical bars of 100% (maximum intensity) colors:
White, Yellow, Cyan, Green, Magenta, Blue, Black.







No **analog** RGB or YPbPr interface for **UHD**, only **digital**

VideoQ VQV: In **VectorScope** all HD and SD **UV vectors** hit the 100% Bars target boxes.
YUV waveforms and the target boxes positions are different, but peak-to-peak HD & SD **ranges** are **equal**.

Digital RGB & YUV Ranges

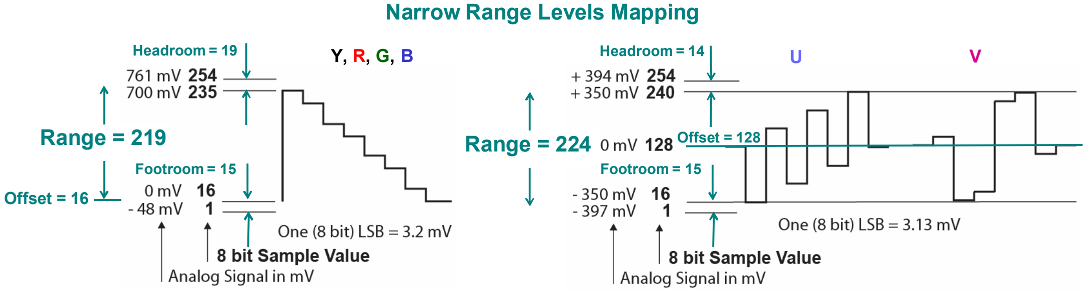
In broadcast environment Y, R, G and B 8 bit values are conventionally shifted and scaled to the range [**16, 235**] referred to as "**Narrow Range**" = "**NR**" (aka "Limited Range", "Low RGB", "TV", "Broadcast", etc).
Thus, the digital 8 bit Reference White Level is **235** (**940** on 10 bit scale) and the 8 bit Reference Black Level is **16** (**64** on 10 bit scale).
The headroom above 235 and the footroom below 16 accommodate signal overshoots ("ringing") due to filtering and specular highlights.

The [**0, 255**] range referred to as "**Full Range**" = "**FR**" (aka "High RGB", "PC", "CG", etc) is also widely used for digital **RGB** interfaces, e.g. HDMI.

For **YUV** signals the Narrow Range ([**16, 235 Y**], [**16, 240 UV**]) is **mandatory**; some consumer product use non-standard "yuvj" [0, 255] color space.

In broadcast environment levels from **1** to **254** are available for video, levels **0** and **255** are used **exclusively** for SDI interface **synchronization**.
In file based environment **all levels** from **0** to **255** are available for video.

Narrow Range Levels Mapping



RGB ⇔ YUV Conversion Matrices

Fundamental **RGB to Y conversion** coefficients are defined by the international standards:

BT.601 (**SD**)

$$RGB2YSD \equiv \begin{pmatrix} .299 \\ .587 \\ .114 \end{pmatrix} \begin{matrix} R \\ G \\ B \end{matrix}$$

BT.709 (**HD**)

$$RGB2YHD \equiv \begin{pmatrix} .2126 \\ .7152 \\ .0722 \end{pmatrix} \begin{matrix} R \\ G \\ B \end{matrix}$$

BT.2020-NCL (**UHD-SDR**),
BT.2100-NCL (**UHD-HDR** & **HD-HDR**)

$$RGB2YUHD \equiv \begin{pmatrix} .2627 \\ .6780 \\ .0593 \end{pmatrix} \begin{matrix} R \\ G \\ B \end{matrix}$$

1. All matrices are **balanced**, i.e. the sums of their coefficients = 1, so the **R = G = B = 1** (100% white) input produces **Y = 1** (max Y value) output.
2. The **Y signal** produced by these matrices has ***not much in common*** with the **CIE1931 Luminance Y**. It is a "codec Y" re-using the same letter Y.
   The choice of these RGB to Y matrices coefficients was not based on the colorimetry factors, but on the content delivery quality factors.
3. The RGB ⇔ YUV matrices are just **derivatives** of the 3 fundamental column matrices as above; the **unity range** principle remains, i.e. on black Y = R = G = B = 0 and U = V = 0, on white Y = R = G = B = 1 and U = V = 0. Y range is [0,1] and UV range is [-0.5,+0.5]:

In: R G B → Out: Y U V

$$\begin{pmatrix} 0.299 & 0.587 & 0.114 \\ -0.16874 & -0.33126 & 0.5 \\ 0.5 & -0.41869 & -0.08131 \end{pmatrix} \quad \begin{pmatrix} 0.2126 & 0.7152 & 0.0722 \\ -0.11457 & -0.38543 & 0.5 \\ 0.5 & -0.45415 & -0.04585 \end{pmatrix} \quad \begin{pmatrix} 0.2627 & 0.678 & 0.0593 \\ -0.13963 & -0.36037 & 0.5 \\ 0.5 & -0.45979 & -0.04021 \end{pmatrix}$$

In: Y U V → Out: R G B

$$\begin{pmatrix} 1 & 0 & 1.402 \\ 1 & -0.34414 & -0.71414 \\ 1 & 1.772 & 0 \end{pmatrix} \quad \begin{pmatrix} 1 & 0 & 1.5748 \\ 1 & -0.18732 & -0.46812 \\ 1 & 1.8556 & 0 \end{pmatrix} \quad \begin{pmatrix} 1 & 0 & 1.4746 \\ 1 & -0.16455 & -0.57135 \\ 1 & 1.8814 & 0 \end{pmatrix}$$

Full Range ⇔ Narrow Range – Digital Levels Mapping

Standards define the matrix coefficients in relative units, e.g. [0,1] or [0%,100%].
Digital signals are usually defined not in percents, but in 8, 10 or 12 bit levels.
Also there two types of digital signal ranges in use: Full & Narrow.

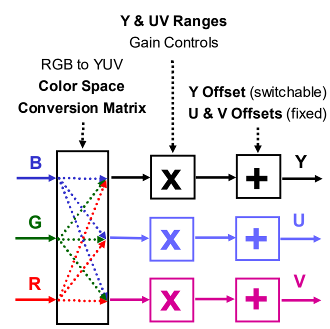
For example, whilst mapping the [0%,100%] range to 8, 10 or 12 bit Narrow Range, the YUV offsets and gains look like this:

$$BAF \equiv 2^{Bits-8} \qquad YUV2D1 \equiv \begin{pmatrix} BAF \cdot 16 & BAF \cdot \frac{219}{100} \\ BAF \cdot 128 & BAF \cdot \frac{224}{100} \\ BAF \cdot 128 & BAF \cdot \frac{224}{100} \end{pmatrix}$$

where BAF is Bit Accuracy Factor,
function of Bit Depth = 8, 10, 12, etc. bits

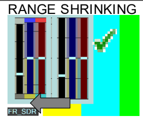
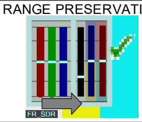
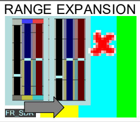
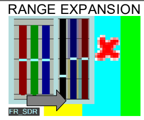
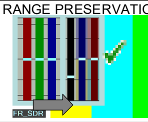
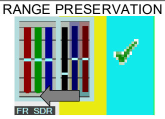
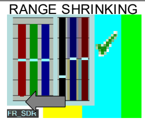
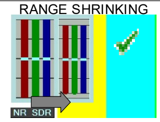
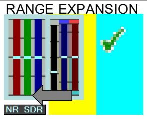
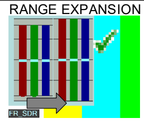
Full to Narrow digital video signal range mapping is the recommended **default** for **RGB to YUV** conversion in file based environment.
For the inverse **YUV to RGB** conversion the recommended default is obviously **Narrow to Full** range mapping.
But, in practice, there are also other RGB/YUV conversion schemes in use, e.g.:
- Full YUV to Full RGB
- Narrow YUV to Narrow RGB
- Narrow RGB to Narrow YUV

RGB ⇒ YUV Conversion
Full ⇔ Narrow Range Conversion Control



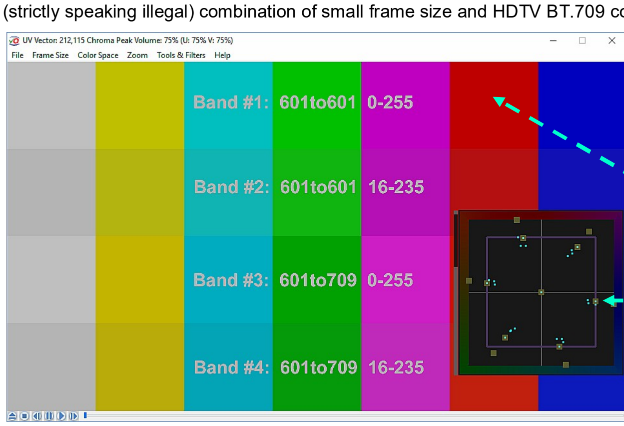
For any bit depth the RGB to YUV gain factors are:
Full to Narrow conversion (shrinking the range, ***default***):
Y mapping gain = 219/255, UV mapping gain = 224/255
Narrow to Full conversion (expanding the range, ***seldom used***):
Y mapping gain = 255/219, UV mapping gain = 255/224

RGB & YUV Conversion Variants

Source: Destination	**YUV NR** *default*	**YUV FR** *seldom used, e.g. “yuvj”*	**RGB NR** *default*	**RGB FR** *used quite often*
YUV NR *default*	COLOR SPACE CONVERSION NOT NEEDED	RANGE SHRINKING 	RANGE PRESERVATION 	RANGE SHRINKING 
YUV FR *seldom used, e.g. “yuvj”*	RANGE EXPANSION 	COLOR SPACE CONVERSION NOT NEEDED	RANGE EXPANSION 	RANGE PRESERVATION 
RGB NR *default*	RANGE PRESERVATION 	RANGE SHRINKING 	COLOR SPACE CONVERSION NOT NEEDED	RANGE SHRINKING 
RGB FR *used quite often*	RANGE EXPANSION 	RANGE PRESERVATION 	RANGE EXPANSION 	COLOR SPACE CONVERSION NOT NEEDED

YUV ⇒ RGB – Selecting Conversion Mode

In the ideal world, the **Source Color Space** (Color Matrix and YUV Range used upstream) is specified in the **embedded metadata**.
If so, the AUTO controller takes care about all YUV to RGB conversion parameters.
But in real world the metadata may be **wrong** or **missing**. In such case the “safe default” AUTO approach may help.
E.g. if the frame height is smaller than 600 and the aspect ratio is about 4:3, then the **assumed** matrix **should be** BT.601.
If HD originated video was down-scaled (without color matrix conversion) to the anamorphic 720x576 frame size for Internet distribution, i.e. to the (strictly speaking illegal) combination of small frame size and HDTV BT.709 color space, then only a QA/QC operator manual intervention may help.



VideoQ VQV Color Matrix selection menu:

YUV <> RGB Color Matrix:
- ✓ AUTO (default, by format, frame size & aspect ratio)
- BT.2020-NCL (UHD-SDR), BT.2100-NCL (UHD-HDR & HD-HDR)
- ✓ BT.709 (HD-SDR)
- BT.601 (SD) - mandatory for some graphic Image formats

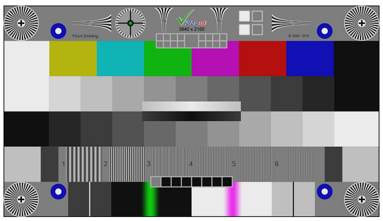
Only in Band #1 of this test all colors are correct.

VideoQ VQV VectorScope shows how far away UV vectors may go in case of incorrect selection of Color Matrix and Digital Range.

YUV Color Space Problems Auto Detection

VideoQ VQMA Analyzer in 2 seconds checks, among other parameters, all color values within the VQMA Test Pattern and produces:

- Machine-readable Report for robots
- Visual Report for QA/QC operator



Color Bars: Y,U,V,R,G,B Levels, 8 bit values

		White	Yellow	Cyan	Green	Magenta	Red	Blue	Black	Max_Error
Captured Data	Y / Yref diff	235 / 235 (0)	170 / 170 (0)	137 / 137 (0)	127 / 127 (0)	69 / 69 (0)	59 / 59 (0)	26 / 26 (0)	16 / 16 (0)	0
	U / Uref diff	128 / 128 (0)	44 / 44 (0)	151 / 151 (0)	68 / 68 (0)	188 / 188 (0)	105 / 105 (0)	212 / 212 (0)	128 / 128 (0)	0
	V / Vref diff	128 / 128 (0)	135 / 135 (0)	44 / 44 (0)	51 / 51 (0)	205 / 205 (0)	212 / 212 (0)	121 / 121 (0)	128 / 128 (0)	0
Derived Values	R / Rref diff	235 / 235 (0)	180 / 180 (0)	16 / 16 (0)	16 / 16 (0)	180 / 180 (0)	180 / 180 (0)	16 / 16 (0)	16 / 16 (0)	0
	G / Gref diff	235 / 235 (0)	180 / 180 (0)	180 / 180 (0)	180 / 180 (0)	16 / 16 (0)	16 / 16 (0)	16 / 16 (0)	16 / 16 (0)	0
	B / Bref diff	235 / 235 (0)	15 / 15 (0)	179 / 179 (0)	17 / 17 (0)	179 / 179 (0)	17 / 17 (0)	181 / 181 (0)	16 / 16 (0)	0

Max RGB Error: 0

VQMA Test Pattern detected

Automatically selected BT.2020(UHD) YUV<>RGB Matrix

Somewhere in the long processing chain the original UHD color space BT.2020 was converted by mistake to BT.601. But, according to the UHD frame size, it should be BT.2020.

VQMA spotted the error and produced a **failure** Report for robots as well as the **warning message** for QA/QC operator.

Color Bars: Y,U,V,R,G,B Levels, 8 bit values

		White	Yellow	Cyan	Green	Magenta	Red	Blue	Black	Max_Error
Captured Data	Y / Yref diff	218 / 235 (-17)	154 / 170 (-16)	128 / 137 (-9)	113 / 127 (-14)	88 / 69 (19)	72 / 59 (13)	46 / 26 (20)	30 / 16 (14)	20
	U / Uref diff	128 / 128 (0)	56 / 44 (12)	152 / 151 (1)	80 / 68 (12)	176 / 188 (-12)	104 / 105 (-1)	200 / 212 (-12)	128 / 128 (0)	12
	V / Vref diff	128 / 128 (0)	139 / 135 (4)	56 / 44 (12)	67 / 51 (16)	189 / 205 (-16)	200 / 212 (-12)	117 / 121 (-4)	128 / 128 (0)	16
Derived Values	R / Rref diff	218 / 235 (-17)	170 / 180 (-10)	25 / 16 (9)	26 / 16 (10)	176 / 180 (-4)	176 / 180 (-4)	30 / 16 (14)	30 / 16 (14)	17
	G / Gref diff	218 / 235 (-17)	159 / 180 (-21)	165 / 180 (-15)	154 / 180 (-26)	47 / 16 (31)	36 / 16 (20)	41 / 16 (25)	30 / 16 (14)	31
	B / Bref diff	218 / 235 (-17)	22 / 15 (7)	172 / 179 (-7)	25 / 17 (8)	176 / 179 (-3)	28 / 17 (11)	179 / 181 (-2)	30 / 16 (14)	17

Max RGB Error: 31

VQMA Test Pattern detected

Automatically selected BT.2020(UHD) YUV<>RGB Matrix

Warning: BT.601(SD) YUV<>RGB Matrix detected

About This Presentation

Produced by	**Josef Marc**
Written by	**Victor Steinberg, PhD**
Narrated by	**Josef Marc**
Conceived by	**Roderick Snell**
Technical consulting by	**Maxim Levkov**

Based on the book
"Video Standards: Signals, Formats and Interfaces" by Victor Steinberg
Published by Snell & Wilcox

For further reading we recommend wikipedia.org

About VideoQ

Company History

- Founded in 2005
- Formed by an Engineering Awards winning team sharing between them decades of global video technology.
- VideoQ is a renowned player in calibration and benchmarking of video processors, transcoders and displays, providing tools and technologies instantly revealing artifacts, problems and deficiencies, thus raising the bar in productivity and video quality experience.
- VideoQ products and services cover all aspects of video processing and quality assurance - from visual picture quality estimation and quality control to fully automated processing, utilizing advanced VideoQ algorithms and robotic video quality analyzers, including latest UHD and HDR developments.

Operations

- Headquarters in Sunnyvale, CA, USA
- Software developers in Silicon Valley and worldwide
- Distributors and partners in several countries
- Sales & support offices in USA, UK