EG 36-2000

SMPTE ENGINEERING GUIDELINE

Transformations Between Television Component Color Signals

1 Introduction

The colorimetric characteristics of television component color signals are determined by three separate sets of parameters. They are:

a) Color primaries and reference white: These characteristics are specified by CIE colorimetric parameters and define the relationship between scene color and the linear RGB video signals. The primaries also define the maximum gamut of color that can be transmitted with all-positive RGB signals.

b) Opto-electronic transfer characteristics (gamma) used to derive the R′G′B′ gamma-corrected signals from the linear RGB values.

c) The luminance equation and the color channel coding matrix derived using that luminance equation. This coding matrix defines the relationship between the gamma corrected R′G′B′ values and the component color signals Y′ PB′ PR′ (analog) or Y′ CB′ CR′ (digital).

In current practice, the differences between the first two colorimetric characteristics are small and can usually be ignored. This guideline is concerned only with the third of these characteristics and assumes the first two to be identical. The analog and digital cases are treated separately because their color-difference gains differ slightly.

2 Scope

Existing television interface standards utilize at least two different color channel coding matrices to derive their corresponding analog Y′ PB′ PR′ or digital Y′ CB′ CR′ component color signals. Clearly, it will be necessary to perform transformations between these color component signal sets. This guideline describes the derivation of the transformation matrices and lists example transformations between color component signals adopting ITU-R BT.601 (see note 1) and ITU-R BT.709 (HD-CIF and 1125/60 [see note 2]) luma/chroma equations for both the digital and analog component signal sets. A parametric form of conversion matrix is derived for converting between signal sets with arbitrary source and target luma coefficients.

3 Derivation of transform matrices

A general form of the transform matrix for converting between arbitrary sets of luma/chroma coefficients is now derived.

3.1 Luma equations

The derivation starts with luma equations (1) and (2) for the source and target systems:

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$$E'_{YS} = Y_{RS} \cdot E'_R + Y_{GS} \cdot E'_G + Y_{BS} \cdot E'_B \quad (1)$$

$$E'_{YT} = Y_{RT} \cdot E'_R + Y_{GT} \cdot E'_G + Y_{BT} \cdot E'_B \quad (2)$$

where Y_{RS}, Y_{GS} , and Y_{BS} are the source set of coefficients, and Y_{RT}, Y_{GT}, and Y_{BT} are the target set. Using these coefficients, along with the required chroma scalings, separate coding matrices and the final source-to-target transform matrices are derived for the analog and digital component cases.

3.2 Analog derivation

Subscripted E′ variables, used for the analog representation, represent gamma-corrected component signals in the source and target luma equation sets. For E'_Y, E'_R, E'_G, and E'_B, black is at 0 and white at 1.0. E'_{PB} and E'_{PR} have 100% color ranges of –1/2 to +1/2. (Alternatively, the ranges could have been chosen to represent the common analog range, 0-700 mV for E'_Y, E'_R, E'_G, and E'_B, and ± 350 mV for E'_{PB} and E'_{PR}.)

AMTX signifies the coding matrix used for analog component transformations (DMTX is used later for the corresponding digital component transformations).

The conversion from the source to target luma/chroma equations is performed in equations (3)-(5). The source component signal is first converted to E'_{RS}, E'_{GS}, and E'_{BS}, by multiplying it by the inverse coding matrix for the source signal:

$$\begin{bmatrix} E'_R \\ E'_G \\ E'_B \end{bmatrix}_S = [AMTX_S]^{-1} \cdot \begin{bmatrix} E'_Y \\ E'_{PB} \\ E'_{PR} \end{bmatrix}_S \quad (3)$$

Premultiplying both sides of equation (3) by the target coding matrix, [$AMTX_T$], and assuming that the E'_R, E'_G and E'_B values for the source and target sets are identical, yields

$$\begin{bmatrix} E'_Y \\ E'_{PB} \\ E'_{PR} \end{bmatrix}_T = [AMTX_{S\ to\ T}] \cdot \begin{bmatrix} E'_Y \\ E'_{PB} \\ E'_{PR} \end{bmatrix}_S = [AMTX_T] \cdot [AMTX_S]^{-1} \cdot \begin{bmatrix} E'_Y \\ E'_{PB} \\ E'_{PR} \end{bmatrix}_S \quad (4)$$

with the overall conversion from the source to target being

$$[AMTX_{S\ to\ T}] = [AMTX_T] \cdot [AMTX_S]^{-1} \quad (5)$$

Essentially, the source component has been decoded back to R′G′B′ using the source luma coefficients and then reencoded to the target component signal using the forward matrix for the target luma coefficients.

3.3 Digital representation

For the component digital treatment, subscripted D′ variables are used, and all coding and transform matrices begin with the letter D. The digital representation uses the component definitions of ITU-R BT.601 which are commonly used in many subsequent digital video standards. The differences between the digital and analog cases are that

– The digital D'_R, D'_G, D'_B, and D'_Y, and D'_{CB} and D'_{CR} have different peak-to-peak signal levels of $219 \cdot 2^{n-8}$ and $224 \cdot 2^{n-8}$, where $n \geq 8$, respectively, whereas in the analog case treated here, the two ranges are the same. This causes the transform matrices to be scaled differently, by the factor 224/219, in a few of the terms.

– D'_R, D'_G, D'_B, and D'_Y have black-and-white reference levels of $16 \cdot 2^{n-8}$ and $235 \cdot 2^{n-8}$ respectively, and

– D'_{CB} and D'_{CR} are in offset binary form, with offsets of $128 \cdot 2^{n-8}$ where $n \geq 8$.

The integer n would be 8 or 10 for most of the digital video formats, but some applications might use higher values.

The correspondence between the digital D′ variables and corresponding analog E′ variables is given by

$$\begin{bmatrix} D'_R \\ D'_G \\ D'_B \end{bmatrix} = \mathrm{INT}\left\{\begin{bmatrix} (219\,E'_R + 16) \cdot 2^{n-8} \\ (219\,E'_G + 16) \cdot 2^{n-8} \\ (219\,E'_B + 16) \cdot 2^{n-8} \end{bmatrix}\right\} \qquad \begin{bmatrix} D'_Y \\ D'_{CB} \\ D'_{CR} \end{bmatrix} = \mathrm{INT}\left\{\begin{bmatrix} (219\,E'_Y + 16) \cdot 2^{n-8} \\ (224\,E'_{PB} + 128) \cdot 2^{n-8} \\ (224\,E'_{PR} + 128) \cdot 2^{n-8} \end{bmatrix}\right\} \quad (6)$$

where the INT{ } operator returns the nearest integer.

3.4 Source-to-target component digital transformation matrix

The derivation for component digital signals is the same as for the analog case except for the different representation. The respective inverse and forward codings are expressed as

$$\begin{bmatrix} D'_R \\ D'_G \\ D'_B \end{bmatrix}_S = \mathrm{INT}\left\{[\mathrm{DMTX}_S]^{-1} \cdot \begin{bmatrix} D'_Y \\ D'_{CB} - 128 \cdot 2^{n-8} \\ D'_{CR} - 128 \cdot 2^{n-8} \end{bmatrix}_S\right\} \quad (7)$$

and

$$\begin{bmatrix} D'_Y \\ D'_{CB} \\ D'_{CR} \end{bmatrix}_T = \mathrm{INT}\left\{[\mathrm{DMTX}_T] \cdot \begin{bmatrix} D'_R \\ D'_G \\ D'_B \end{bmatrix}_T + \begin{bmatrix} 0 \\ 128 \cdot 2^{n-8} \\ 128 \cdot 2^{n-8} \end{bmatrix}\right\} \quad (8)$$

As in the analog equations (3)-(5), the overall conversion matrix is expressed as:

$$\begin{bmatrix} D'_Y \\ D'_{CB} \\ D'_{CR} \end{bmatrix}_T = \mathrm{INT}\left\{[\mathrm{DMTX}_{S\ \mathrm{to}\ T}] \cdot \begin{bmatrix} D'_Y \\ D'_{CB} - 128 \cdot 2^{n-8} \\ D'_{CR} - 128 \cdot 2^{n-8} \end{bmatrix}_S + \begin{bmatrix} 0 \\ 128 \cdot 2^{n-8} \\ 128 \cdot 2^{n-8} \end{bmatrix}\right\} \quad (9)$$

where the overall source to target transformation is

$$[\mathrm{DMTX}]_{S\ \mathrm{to}\ T} = [\mathrm{DMTX}]_T \cdot [\mathrm{DMTX}]_S^{-1} \quad (10)$$

3.5 General parametric form for coding and decoding matrices

The conversion matrices in the clause above can be derived by algebraic manipulation from the source and target equations (1) and (2). A single matrix, MTX, is used for both the analog and digital cases with the different chroma scalings accounted for with the factor α, which could be either 1 or 224/219. MTX should read AMTX using $\alpha = 1$ for the analog case, and DMTX using $\alpha = 224/219$ for the digital case.

The inverse coding matrix for the source luma coefficient set is

$$MTX_S^{-1} = \begin{bmatrix} 1 & 0 & 2(1-Y_{RS}) \cdot \frac{1}{\alpha} \\ 1 & -\frac{Y_{BS} \cdot 2(1-Y_{BS})}{Y_{GS}} \cdot \frac{1}{\alpha} & -\frac{Y_{RS} \cdot 2(1-Y_{RS})}{Y_{GS}} \cdot \frac{1}{\alpha} \\ 1 & 2(1-Y_{BS}) \cdot \frac{1}{\alpha} & 0 \end{bmatrix} \quad (11)$$

The forward coding matrix for the target set is

$$MTX_T = \begin{bmatrix} Y_{RT} & Y_{GT} & Y_{BT} \\ \frac{-Y_{RT}}{2(1-Y_{BT})} \cdot \alpha & \frac{-Y_{GT}}{2(1-Y_{BT})} \cdot \alpha & \frac{\alpha}{2} \\ \frac{\alpha}{2} & \frac{-Y_{GT}}{2(1-Y_{RT})} \cdot \alpha & \frac{-Y_{BT}}{2(1-Y_{RT})} \cdot \alpha \end{bmatrix} \quad (12)$$

The overall conversion matrix, below, from source to target is obtained by manually multiplying equations (11) and (12) together:

$$MTX_{S\ to\ T} = \begin{bmatrix} 1 & \left(Y_{BT} - \frac{Y_{GT} \cdot Y_{BS}}{Y_{GS}}\right) \cdot 2(1-Y_{BS}) \cdot \frac{1}{\alpha} & \left(Y_{RT} - \frac{Y_{GT} \cdot Y_{RS}}{Y_{GS}}\right) \cdot 2(1-Y_{RS}) \cdot \frac{1}{\alpha} \\ 0 & \left(\frac{Y_{GT} \cdot Y_{BS}}{Y_{GS} \cdot 2(1-Y_{BT})} + \frac{1}{2}\right) \cdot 2(1-Y_{BS}) & \left(\frac{Y_{GT} \cdot Y_{RS}}{Y_{GS}} - Y_{RT}\right) \cdot \frac{2(1-Y_{RS})}{2(1-Y_{BT})} \\ 0 & \left(\frac{Y_{GT} \cdot Y_{BS}}{Y_{GS}} - Y_{BT}\right) \cdot \frac{2(1-Y_{BS})}{2(1-Y_{RT})} & \left(\frac{Y_{GT} \cdot Y_{RS}}{Y_{GS} \cdot 2(1-Y_{RT})} + \frac{1}{2}\right) \cdot 2(1-Y_{RS}) \end{bmatrix} \quad (13)$$

Factors of two are maintained in some places in the equations above to maintain the similarity with the numerical form in equations (16) to (19) below.

4 Numerically exact matrices for converting between ITU-R BT.601 and BT.709

The conversion matrices are provided in exact numerical form for converting between the ITU-R BT.601 and ITU-R BT.709 luma/chroma equation sets in equations (14) and (15), respectively.

$$E'_{Y\,601} = 0.299 \cdot E'_R + 0.587 \cdot E'_G + 0.114 \cdot E'_B \quad (14)$$

$$E'_{Y\,709} = 0.2126 \cdot E'_R + 0.7152 \cdot E'_G + 0.0722 \cdot E'_B \quad (15)$$

This exact form of expression can then be used to derive a matrix of whatever lesser precision is needed for a given application. Even though the luma coefficients may be provided to only 3 or 4 significant figures of precision, having higher precision in the other rows of the matrix can be useful for ensuring higher overall accuracy and better generational fidelity.

4.1 Analog

$[AMTX]_{709\ to\ 601}$ =

$$= \begin{bmatrix} 1 & \left(0.114 - \frac{0.587 \times 0.0722}{0.7152}\right) \times 1.8556 & \left(0.299 - \frac{0.587 \times 0.2126}{0.7152}\right) \times 1.5748 \\ 0 & \left(\frac{0.587 \times 0.0722}{0.7152 \times 1.772} + 0.5\right) \times 1.8556 & \left(\frac{0.587 \times 0.2126}{0.7152} - 0.299\right) \times \frac{1.5748}{1.772} \\ 0 & \left(\frac{0.587 \times 0.0722}{0.7152} - 0.114\right) \times \frac{1.8556}{1.402} & \left(\frac{0.587 \times 0.2126}{0.7152 \times 1.402} + 0.5\right) \times 1.5748 \end{bmatrix} \quad (16)$$

$[AMTX]_{601\ to\ 709}$ =

$$\begin{bmatrix} 1 & \left(0.0722 - \frac{0.7152 \times 0.114}{0.587}\right) \times 1.772 & \left(0.2126 - \frac{0.7152 \times 0.299}{0.587}\right) \times 1.402 \\ 0 & \left(\frac{0.7152 \times 0.114}{0.587 \times 1.8556} + 0.5\right) \times 1.772 & \left(\frac{0.7152 \times 0.299}{0.587} - 0.2126\right) \times \frac{1.402}{1.8556} \\ 0 & \left(\frac{0.7152 \times 0.114}{0.587} - 0.0722\right) \times \frac{1.772}{1.5748} & \left(\frac{0.7152 \times 0.299}{0.587 \times 1.5748} + 0.5\right) \times 1.402 \end{bmatrix} \quad (17)$$

4.2 Digital

$[DMTX]_{709\ to\ 601}$ =

$$= \begin{bmatrix} 1 & \left(0.114 - \frac{0.587 \times 0.0722}{0.7152}\right) \times 1.8556 \times \frac{219}{224} & \left(0.299 - \frac{0.587 \times 0.2126}{0.7152}\right) \times 1.5748 \times \frac{219}{224} \\ 0 & \left(\frac{0.587 \times 0.0722}{0.7152 \times 1.772} + 0.5\right) \times 1.8556 & \left(\frac{0.587 \times 0.2126}{0.7152} - 0.299\right) \times \frac{1.5748}{1.772} \\ 0 & \left(\frac{0.587 \times 0.0722}{0.7152} - 0.114\right) \times \frac{1.8556}{1.402} & \left(\frac{0.587 \times 0.2126}{0.7152 \times 1.402} + 0.5\right) \times 1.5748 \end{bmatrix} \quad (18)$$

$[DMTX]_{601\ to\ 709}$ =

$$= \begin{bmatrix} 1 & \left(0.0722 - \frac{0.7152 \times 0.114}{0.587}\right) \times 1.772 \times \frac{219}{224} & \left(0.2126 - \frac{0.7152 \times 0.299}{0.587}\right) \times 1.402 \times \frac{219}{224} \\ 0 & \left(\frac{0.7152 \times 0.114}{0.587 \times 1.8556} + 0.5\right) \times 1.772 & \left(\frac{0.7152 \times 0.299}{0.587} - 0.2126\right) \times \frac{1.402}{1.8556} \\ 0 & \left(\frac{0.7152 \times 0.114}{0.587} - 0.0722\right) \times \frac{1.772}{1.5748} & \left(\frac{0.7152 \times 0.299}{0.587 \times 1.5748} + 0.5\right) \times 1.402 \end{bmatrix} \quad (19)$$

5 Transform matrices calculated to eight decimal places

For convenience, the matrices are provided below in numerical form to a precision of eight decimal places using ordinary rounding. An implementer may take these values and reduce the precision to that which is desired for a given application. If the application has a critical accuracy requirement, such as generational fidelity, rounding to the lower precision may be carried out as described in clause 6.

5.1 Analog (to eight decimal places)

$$\text{AMTX}_{709\ \text{to}\ 601} = \begin{bmatrix} 1 & 0.10157905 & 0.19607625 \\ 0 & 0.98985381 & -0.11065251 \\ 0 & -0.07245296 & 0.98339782 \end{bmatrix} \quad (20)$$

$$\text{AMTX}_{601\ \text{to}\ 709} = \begin{bmatrix} 1 & -0.11818787 & -0.21268507 \\ 0 & 1.01863972 & 0.11461795 \\ 0 & 0.07504945 & 1.02532707 \end{bmatrix} \quad (21)$$

5.2 Digital (to eight decimal places)

$$\text{DMTX}_{709\ \text{to}\ 601} = \begin{bmatrix} 1 & 0.09931166 & 0.19169955 \\ 0 & 0.98985381 & -0.11065251 \\ 0 & -0.07245296 & 0.98339782 \end{bmatrix} \quad (22)$$

$$\text{DMTX}_{601\ \text{to}\ 709} = \begin{bmatrix} 1 & -0.11554975 & -0.20793764 \\ 0 & 1.01863972 & 0.11461795 \\ 0 & 0.07504945 & 1.02532707 \end{bmatrix} \quad (23)$$

6 Rounding of matrix coefficients

For a given precision requirement, ordinary rounding is not always the best way to obtain accurate values. One reason is that the rounded value of a sum of three real numbers is not always equal to the sum of the individually rounded numbers. Consequently, the unity normalization of the Y-row sum, or zero normalizations in the color-difference row sums, might be thrown off by a count in either direction. A simple method of accomplishing the rounding is to first do ordinary rounding; then, if a desired row normalization is not correct, nudge the matrix element that is nearest to its corresponding real value either up or down to accomplish the desired normalization.

A more comprehensive method is presented in ITU-R BT.1361, annex 2, wherein a least-squares optimization method is applied to each row to determine an optimal set of coefficients. Also, part of the ITU-R BT.1361 procedure is a means whereby the optimization can be performed over a subregion of the R′G′B′ space.

NOTES

1 ITU-R BT.601 has no specification of primaries or transfer characteristics. It specifies only the third coding-matrix part of the colorimetric characteristics. The ITU-R BT.601 coding matrix is based on the color primaries and the reference white of the NTSC (1953) specification which is practically no longer used. The equation is also used in SMPTE 170M, EBU 625 standards, and the 1250/50 (1152 active lines) specification of ITU-R BT.709, ITU-R BT.1358, and ANSI/SMPTE 293M.

2 In ITU-R BT.709, which includes the 1920 × 1080 common image format (HD-CIF), the unified colorimetric parameters are specified for HD-CIF regardless of 1125/60 and 1250/50. These unified colorimetric parameters are identical with those specified for 1125/60 and those described in ITU-R BT.1361. The equation is also used in SMPTE 274M, ANSI/SMPTE 295M, and ANSI/SMPTE 296M.

Annex A (Informative)
Luma equations used by some television scanning standards

Table A.1 gives luma equations used by some television scanning standards.

Table A.1 – Luma equations

Television	Luma equation		
Scanning standard	ITU-R BT.601	ITU-R BT.709	Other
SMPTE 170M NTSC	X		
EBU 625 PAL, SECAM	X		
ANSI/SMPTE 293M 525 / 720 × 483 / 59.94 / 1:1	X		
SMPTE 274M 1125 / 1920 × 1080 / multiple rates / 1:1, 2:1		X	
ANSI/SMPTE 295M 1250 / 1920 × 1080 / 50 / 1:1, 2:1		X	
ANSI/SMPTE 296M 750 / 1280 × 720 / multiple rates / 1:1		X	
SMPTE 240M 1125 / 1920 × 1035 / 60, 59.94 / 2:1			SMPTE 240M (see note)
NOTE – ANSI/SMPTE 240M uses a luma equation that is similar to ITU-R BT.709 but is not exactly the same. In many applications, the differences may be small enough to ignore, but these differences could become significant in critical applications.			

Annex B (informative)
Bibliography

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ITU-R BT.601-5 (10/95), Studio Encoding Parameters of Digital Television for Standard 4:3 and Wide-Screen 16:9 Aspect Ratios

ITU-R BT.709-3 (02/98), Parameter Values for the HDTV Standards for Production and International Programme Exchange

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