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Implementation Guidelines for HLG Format Conversion LUTs

Part of the HDR-TV series. Last updated April 2020.

These notes should be read in conjunction with the "Release Notes for HLG Format Conversion LUTs" (currently version 1.4) and the "Guidance on Format Conversion in HLG Production".

Introduction

To facilitate the introduction of ITU-R Recommendation BT.2100 Hybrid Log-Gamma (HLG) production, BBC R&D are licensing a package of look-up tables (LUTs) that implement a range of key format conversions.

The conversions are available as 33-cube 3D-LUTs, with some critical conversions also available as 65-cube LUTs. They comprise:

- Display-light conversions, which preserve the colour and appearance of content after conversion:
  - BT.2100 Perceptual Quantization (PQ) 1000 cd/m^2 nominal peak-luminance signals to BT.2100 HLG
  - BT.2100 PQ 4000 cd/m^2 nominal peak-luminance signals to BT.2100 HLG
  - BT.2100 HLG to BT.2100 PQ 1000 cd/m^2 nominal peak-luminance
  - BT.709 (SDR) to BT.2100 HLG "direct-mapping", preserving the appearance of SDR
  - BT.709 (SDR) to BT.2100 HLG "up-mapping", slightly increasing the contrast of the SDR image to better-match the appearance of "native" HDR content
  - BT.2100 HLG to BT.709 "down-mapping", preserving the "look" of the HDR content (colour, lowlights and mid-tones) when converting material to SDR
  - PQ P3D65 1000 cd/m^2 nominal peak-luminance to BT.2100 HLG
  - BT.2100 HLG to PQ P3D65 1000 cd/m^2 nominal peak-luminance
  - BT.2100 HLG to PQ 110 cd/m^2 nominal peak-luminance X′Y′Z′ (HDR movie)

- Scene-light conversions, which should be used for colour-matching cameras in live production:
  - BT.709 (SDR) to BT.2100 HLG "direct-mapping", for colour-matching SDR and HLG cameras

    - BT.709 (SDR) to BT.2100 HLG "up-mapping", for colour-matching SDR and HLG cameras but with a small highlights "boost" to complement the visual characteristics of HDR cameras
    - BT.2100 HLG to BT.709 (SDR) "down-mapping" to match the colour and "look" of downstream SDR cameras
    - Sony S-Log3 and S-Log3 SR Live (BT.2020 colour) to BT.2100 HLG, thereby matching the colour and "look" of BT.2100 HLG cameras

- Test LUTs to verify the correct operation of LUT hardware.

More details on the different types of conversion can be found in ITU-R Report BT.2408, Section 5 ("Inclusion of standard dynamic range content"). Additional conversions may be added in the future.

Both the accompanying "Guidance on Format Conversion in HLG Production", and Section 7 of ITU-R report BT.2408, provide examples of how the different types of conversion can be used in practice.

As part of the LUT package, we also offer (on request) a 65-cube 3D-LUT for loading into a Dolby PRM-4200/4220 display. This adds support for BT.2100 HLG.

LUT Details

Each LUT is described in detail in Annex 1 of the release notes. The Annex includes tables of the expected output values for SMPTE RP 219 BT.709 colour bars, BT.2111 HDR colour bars and the new EBU Tech 3373 HLG HDR colour bars . The EBU colour bars, with their embedded 75% BT.709 equivalent bars, are designed to be more robust to HDR/SDR format-conversion than the BT.2111 colour bars.

Included are three types of LUT, which scale the input and output video signals in different ways to support different applications. LUT inputs are normalised to span either:

- The **nominal** signal range, from black to nominal peak-white (0% to 100% signal), or
- The full 10-/12-bit signal range with **headroom** above and below a narrow-range signal, or,
- In the case of S-Log3, the full 10-/12-bit signal range with **footroom** below the nominal signal range.

LUT outputs are always in the range 0.0 to 1.0, but with the output normalisation across either:

- The **nominal** signal range, from black to nominal peak-white (0% to 100% signal), or

- The full 10-/12-bit signal range with **headroom** above and below a narrow-range signal.

The terms in **bold** are used to describe the LUT input and output normalisation detailed in Annex 1. The LUT filenames themselves follow the older (and more ambiguous) convention established in previous releases, and have not been changed in this release.

The different types of LUTs are illustrated on the pages that follow.

- **Type I** LUTs, illustrated in Figure 1 below, are intended for software applications and older hardware-LUT devices that operate over the nominal signal range. They do not process "sub-black"[1] and "super-white" signals.

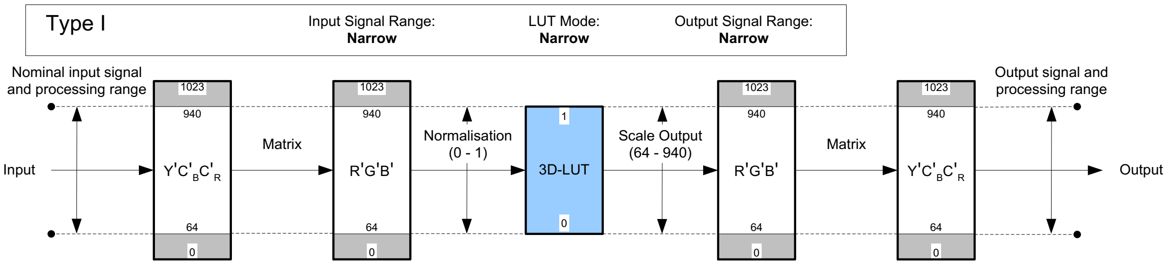

Figure 1- Type I signal-scaling, primarily intended for software-based LUT applications

The LUT file itself is represented by the blue block labelled "3D-LUT".

- Type I LUTs accept **nominal**-range R'G'B' input signals. They do not process sub-blacks or super-whites.
  - Minimum input-value = Black

    := 0.0 % signal
  - Maximum input-value = Nominal peak-white

    := 100% signal

- Type I LUTs produce **nominal**-range R'G'B' output signals, normalised 0.0 to 1.0. They cannot reproduce sub-blacks and super-whites. Thus,

[1] signals below the black level (BT.709 10-bit code value 64)

- ○ Minimum output-value = Black = 0.0

  := 0.0 % signal

- ○ Maximum output-value = Nominal peak-white = 1.0

  := 100% signal

- Type II LUTs are intended for SDI input signals that require full-range processing – examples include Sony's S-Log3, and some types of PQ signals. Both input and output operate over the entire 10-/12-bit SDI signal range. This is illustrated in Figure 2 below:

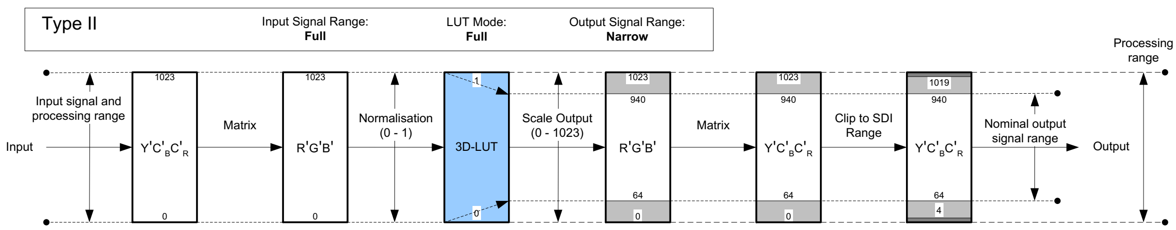

Figure 2 - Type II signal-scaling, intended for full-range input signals (e.g. some PQ variants)

The LUT file itself is represented by the blue block labelled "3D-LUT". Thus, as per BT.2100, where signals are normalised over the range 0.0 to 1.0, the minimum input/output values of the LUT (0.0) map to 10-bit code value 0; the maximum input/output values of the LUT (1.0) map to 10-bit code value 1023. So,

- For PQ input signals: Type II LUTs are designed for **nominal**-range R'G'B' input signals that span the full 10/12-bit signal range. They do not process sub-blacks or super-whites.

  - ○ Minimum input-value = Black

    := 0.0 % signal

  - ○ Maximum input-value = Nominal peak-white

    := 100% signal

So, if converting from a Y′C′$_B$C′$_R$ input to the R′G′B′ LUT input, the full-range C′$_B$C′$_R$ colour matrix scaling should be used (see Table 9 BT.2100).

- For S-Log3 input signals, Type II LUTs are designed for a full 10-/12-bit R'G'B' input signal range, with **footroom**. They process S-Log3 sub-blacks. Super-whites are not specified for S-Log3. If normalised in the range 0.0 to 1.0 (as above),
  - Minimum input-value = 0.0
  - Black = 95/1023 = 0.0929
  - Maximum input-value = Nominal peak-white = 1.0
- As Type II LUTs produce narrow-range R'G'B' output signals, that sit within a full 10/12-bit signal-range container (normalised 0.0 to 1.0), they have the **headroom** to accommodate sub-blacks and super-whites. Thus,
  - Black = 64/1023 = 0.0626
  - Nominal peak-white = 940/1023 = 0.9189
  - Minimum output value = 0

    := (0-64)/(940-64) = -7.31% signal

  - Maximum output value = 1.0

    := (1023-64)/(940-64) = 109.47% signal

Type II "full-range mode" LUTs are used to convert full-range PQ and S-Log3 signals to HLG. To facilitate this, full-range Type II versions of the PQ1000, PQ4000, S-Log3 (100%) and S-Log3 (200%) conversion LUTs are provided.

To improve interoperability, maintain signal-fidelity and reduce the likelihood of errors in production, we recommend only using narrow-range signals with HLG (see Table 9 BT.2100). When a hardware-LUT device is operated in "full-range mode", the HLG output-signal is - as a result - offset and scaled, so that it lies within the "narrow" signal range (64 to 940; 10-bits) of a full signal-range container. Thus, if converting from the R′G′B′ LUT output to Y′C′$_B$C′$_R$, the narrow-range C′$_B$C′$_R$ colour matrix scaling should be used (see Table 9 BT.2100).

- **Type III** LUTs are intended for LUT devices that process narrow-range video signals, but operate over the full 10-bit signal range (0 to 1023). These are illustrated in Figure 3. Type III LUTs offer the **headroom** to process the sub-blacks and super-whites, which are found in test patterns (such as the ITU-R BT.814 HDR PLUGE and ITU-R BT.2111 HDR colour bars, and often encountered during live production. They are most suitable for broadcast TV applications. Type III LUTs may also offer better signal-fidelity than the equivalent Type I LUTs, as 3D-LUT interpolation errors are usually greatest at the signal extremities. With Type III LUTs the greatest interpolation errors will therefore occur in the sub-black and super-white regions, where signal distortions are usually less significant.

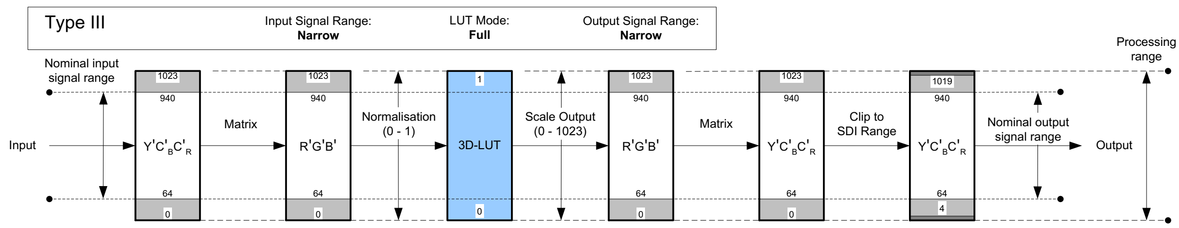

Figure 3 - Type III signal-scaling, primarily intended for hardware-based LUT applications

The LUT file itself is represented by the blue block labelled "3D-LUT". As with Type II LUTs, the input and output signals of the LUT are normalised over the range 0.0 to 1.0. The minimum input/output values of the LUT (0.0) map to 10-bit code value 0; the maximum input/output values of the LUT (1.0) map to 10-bit code value 1023. Thus,

- Type III LUTs are designed for narrow-range R'G'B' input signals that sit within a full 10/12-bit signal-range container, providing the **headroom** to process sub-black and super-white signals. If normalised in the range 0.0 to 1.0,
    - Black = 64/1023 = 0.0626
    - Nominal peak-white = 940/1023 = 0.9189
    - Minimum input-value = 0

      := (0-64)/(940-64) = -7.31% signal

    - Maximum input-value = 1.0

      := (1023-64)/(940-64) = 109.47% signal

  So, if converting from a $Y'C'_BC'_R$ input to the $R'G'B'$ LUT input, the narrow-range $C'_BC'_R$ colour matrix scaling should be used (see Table 9 BT.2100).

- Type III LUTs produce narrow range R'G'B' output signals, that sit within a full 10/12-bit signal-range container (normalised 0.0 to 1.0), providing the **headroom** to output sub-black and super-white signals. Thus,
    - Black = 64/1023 = 0.0626
    - Nominal peak-white = 940/1023 = 0.9189
    - Minimum output-value = 0

      := (0-64)/(940-64) = -7.31% signal

    - Maximum output-value = 1.0

      := (1023-64)/(940-64) = 109.47% signal

So, if converting from the R′G′B′ LUT output to $Y'C'_BC'_R$, the narrow-range $C'_BC'_R$ colour matrix scaling should be used (see Table 9 BT.2100).

Extending the SDR Colour Gamut

When using a mix of SDR BT.709 cameras and BT.2100 HLG cameras, significantly-better results can be obtained if (i) the signal-clippers on the SDR cameras are relaxed to EBU Technical Recommendation R103 “preferred” signal levels (-5%/+105%) and (ii) the conversion process takes account of the signals in the sub-blacks and super-whites. The sub-black and super-white signals produced by many cameras effectively-increase the dynamic range and colour gamut of the camera. More details can be found in ITU-R report BT.2250.

In order to exploit the extended SDR signal range, the conversion LUT has to operate in “full-range” (or “headroom”) mode, taking account of the black-level offset of the SDR input signals (10-bit code value 64) (LUT Type III). Because of the improved performance, the scene-light BT.709-to-BT.2100 HLG direct-mapping LUT (LUT 4) and up-mapping LUTs (LUT 6-1 and 6-2) are only provided in full-range mode (Type III) versions. It is therefore important to ensure that the correct LUT hardware-variant is used.

Output Signal Clipping

Output signals for Type I LUTs are clipped to the nominal signal range 0 to 1. They do not process sub-black and super-white signals. Most Type III LUTs with SDR BT.709 outputs are clipped within the look-up table to EBU R103 "preferred" signal levels. The exception is the new LUT9, which is designed to complement the up-mapping LUT5, and reduce the round-trip losses with direct-mapping LUT3. The new LUT9 places most of the HDR highlights within the SDR super-white signal range, exceeding the EBU R103 limits. In territories where stricter limits on the SDR signal range are imposed, an additional hardware legaliser may be required.

The remaining Type II and Type III LUTs (with PQ or HLG outputs) are clipped to full-range, to ensure that they pass the ITU-R BT.2111 and EBU Tech 3373 HDR colour bars.

External-processing, illustrated in Figures 2 and 3, is necessary to clip the LUT output to 10-bit SDI range (4 to 1019) in order to avoid EAV/SAV sync-word emulation.

Colour Matrices

Older hardware-based LUT devices assume BT.709 colour when converting between the $Y'C'_BC'_R$ signals carried on SDI interfaces, and the R′G′B′ signals required by the look-up tables. When no option is available to select the correct BT.2020/BT.2100 colour-matrix for HDR signals, a correction can be applied within the look-up table itself as illustrated in Figure 7 (over page). The descriptions in Annex 1 indicate whether a LUT file includes the BT.709 colour-matrix compensation.

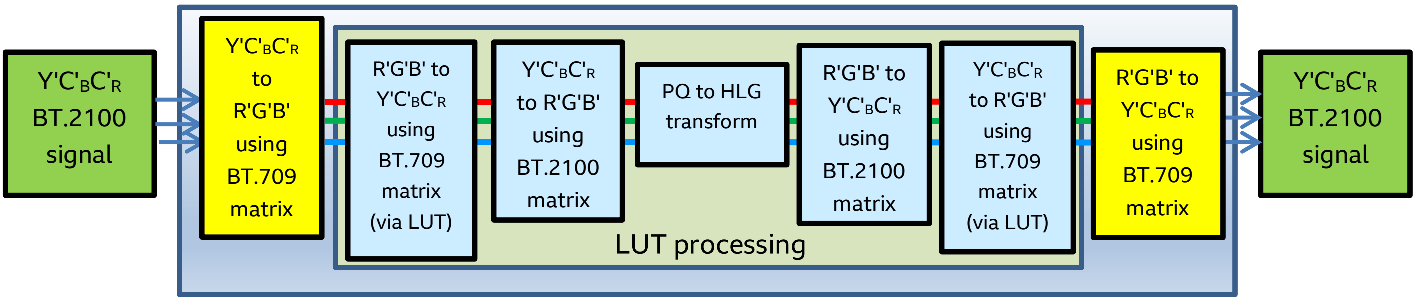

Figure 7 - Example of colour-matrix compensation within a LUT.

(This example shows a PQ to HLG conversion)

Software packages that support conversion LUTs, such as colour-grading software, can usually be configured to (i) use the correct BT.2020/BT.2100 colour-primaries, (ii) normalise full-range and narrow-range input signals to a common range for their internal processing, and (iii) only process the nominal signal range (0% to 100%) and clip super-whites and sub-blacks. As a result, only a single Type I LUT (which is the same as the "narrow-mode" hardware LUT, without BT.709 colour-matrix compensation) is necessary for most software applications. Take care, however, when processing YC_BC_R signals with software tools - it is not always possible to configure the LUTs for different colour-systems (which will require different YC_BC_R matrixing).

LUTs for Testing Hardware

In order to test that LUT hardware is correctly configured, or to help determine which type of LUT (Type I, Type II or Type III) should be used with a particular LUT interpolator, we have developed four special test LUTs (13a, 13b, 13c & 13d). These can be used to determine the LUT interpolator's input/output scaling and colour-matrix processing.

Particular care is necessary when configuring LUT interpolator hardware, as the scaling of the C'_B and C'_R colour components is different for full-range and narrow-range BT.2100 signals (see Table 9 of ITU-R BT.2100). All BBC LUTs output narrow-range signals, even when the LUT is operating in full-range mode. The narrow-range $Y'C'_BC'_R$ colour-matrix equations should, therefore, always be used for outputs. LUTs 1c & 1d and 2c & 2d (Type II LUTs) are designed for full-range PQ *input* signals, but narrow-range *output* signals. So full-range matrix equations should, therefore, be used on the input, and narrow-range matrix equations on the output. We have not yet developed a test, loaded with these Type II LUTs, for LUT hardware.

LUTs 13b, 13c & 13d output a fixed RGB triplet for any input value. Tables 2 and 3 (over page) illustrate the expected $Y'C'_BC'_R$ 10-bit code values (decimal) on the SDI output for different combinations of colour-matrix and LUT mode for each of the test LUTs. By loading these LUT files into the LUT interpolator, and measuring its output, it is possible to determine how the input/output scaling and colour matrixes have been configured. Rounding-errors of +/- 1 LSB (least significant bit) should be expected, as these values are calculated from the fixed-point R′G′B′ LUT output, rather than after any interpolation or 10-bit R′G′B′ processing.

LUT 13a is a “pass-though” LUT. Once the output-side processing is known, the pass-through LUT can be used to confirm complementary processing on the input-side. When both input and output colour-matrices are configured for the same colour-space (BT.709 or BT.2020/BT.2100) and scaling, signals should pass through the LUT hardware almost transparently (with some interpolation errors) when loaded with the pass-through LUT 13a.

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Table 2. Narrow-range mode LUT output on Y′C′BC′R SDI

LUT Filename	LUT Output Values			Type I - Narrow Range LUT Mode (10-bit decimal 64 - 940)					
				BT.2020/BT.2100 Colour			BT.709 Colour		
	R'	G'	B'	Y'	C'b	C'r	Y'	C'b	C'r
13b_static_0-0_0-5_1-0.cube	0.000	0.500	1.000	412	798	269	440	787	267
13c_static_0-4_0-5_0-6.cube	0.400	0.500	0.600	484	569	463	489	567	463
13d_static_0-125_0-5_0-875.cube	0.125	0.500	0.875	435	726	330	455	718	328

Table 3. Full-range mode LUT output on Y′C′BC′R SDI for narrow-range signals

LUT Filename	LUT Output Values			TYPE III - Full Range LUT Mode (10-bit decimal 0 - 1023), Narrow Range Output Signals (10-bit decimal 64 - 940)					
				BT.2020/BT.2100 Colour			BT.709 Colour		
	R'	G'	B'	Y'	C'b	C'r	Y'	C'b	C'r
13b_static_0-0_0-5_1-0.cube	0.000	0.500	1.000	407	846	229	439	833	226
13c_static_0-4_0-5_0-6.cube	0.400	0.500	0.600	490	578	455	497	576	454
13d_static_0-125_0-5_0-875.cube	0.125	0.500	0.875	433	762	300	457	753	297

Licensing Options

Two LUT licences are available. The first is intended for manufacturers wishing to either embed the LUTs within their products, or include the LUTs with their products. The second is intended for broadcasters and production facilities, where the LUTs are to be loaded into existing equipment or software tools.

Please email transfer.rd@bbc.co.uk for details.