

MovieLabs Best Practices for Mapping BT.2100 PQ to HLG Using maxRGB

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Introduction

Recommendation ITU-R BT.2100 [BT2100] defines two systems for high dynamic range video, Perceptual Quantization (PQ) and Hybrid Log-Gamma (HLG). With two systems in use, content often needs to be converted from one system to the other.

For the best consumer experience of the creative intent, content providers recommend that content be distributed and viewed using the display system for which it was created. Generally, our film and TV studios master HDR in PQ. When necessary for distribution channels, an HLG version can be created from that version, subject to approval of the content provider. In some cases, the content provider may want to perform the conversion and provide an HLG distribution master. But frequently, the content provider may permit distributors to perform the conversion using an approved method.

This document outlines a MovieLabs recommendation for how this mapping may be performed for distribution of PQ mastered content in HLG. No conversion method will be optimal for all content, but the method documented here works adequately for a wide range of content.

Background

Report ITU-R BT.2390-9 [BT2390] documents a set of approaches to conversions between PQ and HLG.

The process for converting PQ content to HLG typically involves two steps as described in Section 6 of BT.2390-9. First, for PQ content mastered on a display with a peak luminance of over 1,000 cd/m², the content is mapped to a 1,000 cd/m² display. And second, the signal is then converted from the PQ system to HLG.

For the tone mapping of PQ content exceeding 1,000 cd/m² to 1,000 cd/m² PQ, static or dynamic methods may be used. When static tone mapping is used, we propose the use of the maxRGB method documented in [BUR2020] since we have found that for most our content it performs better than the other static methods listed in Annex 5 of BT.2408-4. Other static tone mapping methods or LUTs may yield equivalent or better results.

The second step of performing the display-referred conversion from PQ to HLG is purely mathematical. However, there is an issue that highly saturated colors in a 1,000 cd/m² PQ signal may extend beyond the color volume of a 1,000 cd/m² HLG signal. One

approach to transmitting those colors in an otherwise narrow range HLG signal is to allow the use of undershoots and overshoots, which are also used to encode “super-whites,” as discussed in Section 6.1 of BT.2390-9 and Section 6.5 of BT.2480-4. For systems capable of handling such signals, their use provides an alternative to clipping or performing additional color remapping.

Tone mapping to create a 1,000 cd/m² PQ master

If a piece of PQ HDR content does not have peaks outside the 1,000 cd/m² color volume, then the process of tone mapping to 1,000 cd/m² is unnecessary and should be avoided as it may lead to unnecessary image modification and therefore degraded image quality. We note that for various technical and/or creative reasons, PQ content may have peaks existing up to 10,000 cd/m² (the upper limit of the PQ HDR format), 4,000 cd/m² (a common mastering display target) or some other value between 100 and 10,000 cd/m². Therefore, it is important that any method handle those pixels well.

Dynamic tone mapping

Content may have dynamic HDR metadata available (e.g., SMPTE ST 2094) that can be used to perform shot-based or scene-based tone mapping to a target 1,000 cd/m² color volume. This is an alternative approach to using a static mapping.

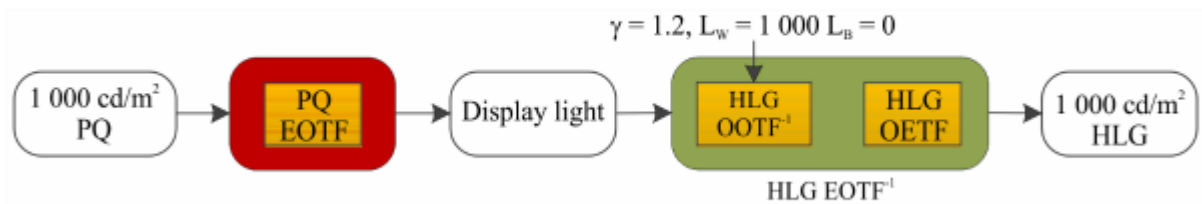
Static tone mapping

When tone mapping is required, BT.2408-4 provides guidance in Section 3.1.1 and in Annex 5 on performing tone mapping using a static EETF. While the use case presented there is mapping to a display with limited luminance range, the technique can also be used to transform masters. Annex 5 lists five notable EETF options. Three of these perform well at preserving hue, but not at limiting the peak values for unclipped display on a 1,000 cd/m² display. A fourth performs well on this limit, but not at preserving hue. Given the importance of hue preservation, a fifth method, maxRGB, was added when the section on EETFs moved from BT.2390-8 (2020) to BT.2408-4 in the March 2021 updates to those documents. This use of maxRGB is documented in [BUR2020], and the math is detailed in Appendix A of this document.

Conversion of 1,000 cd/m² PQ master to HLG using overshoots and undershoots

The display-referred conversion of PQ to HLG is described in Section 6.2 of BT.2408-4. The conversion process is designed to take in a 1,000 cd/m² PQ signal and produce a 1,000 cd/m² HLG signal, and is shown in BT.2408-4 Figure 14 reproduced below:

FIGURE 28
Conversion from PQ to HLG at a common peak luminance of 1 000 cd/m²



Report BT.2390-28

If starting with 1,000 cd/m² PQ master, no additional tone mapping steps are required before conversion to HLG. However, there is an issue that highly saturated colors in a 1,000 cd/m² PQ signal may extend beyond the color volume of the typical HLG signal.

But if an HLG signal encoded as narrow range allows values in the extended-range, e.g., 4 to 1019 for 10-bit, then the full 1,000 cd/m² PQ color volume can be transmitted. The table below shows the values for the corners of the 1,000 cd/m² PQ color volume with BT.2100 primaries.

	Narrow range HLG with undershoots and overshoots								
	Linear values in BT.2100 (cd/m ²)			10-bit RGB code values			10-bit Y'C _B C _R code values		
	Rd	Gd	Bd	CV_R	CV_G	CV_B	CV_Y	CV_Cb	CV_Cr
Black BT.2100	0	0	0	64	64	64	64	512	512
Red BT.2100	1000	0	0	976	64	64	303	382	978
Green BT.2100	0	1000	0	64	950	64	665	185	95
Blue BT.2100	0	0	1000	64	64	1015	120	998	473
Yellow BT.2100	1000	1000	0	942	942	64	890	63	548
Cyan BT.2100	0	1000	1000	64	948	948	716	638	60
Magenta BT.2100	1000	0	1000	970	64	970	356	846	938
White BT.2100	1000	1000	1000	940	940	940	940	512	512

The math for this PQ to HLG conversion process is detailed in Appendix B.

We note that BT.2100-2 states in Note 9a that “narrow range signals may extend below black (sub-blacks) and exceed the nominal peak values (super-whites)” and in Note 5h that non-linear HLG signals are expected to exceed the 0.0 to 1.0 range in production and “should not be clipped during production and exchange.” Nevertheless, there is no guarantee that some transmission systems or displays won’t clip to the narrow range.

Appendix A Static Tone Mapping to 1,000 cd/m² using maxRGB

A.1 Step 1 – Inverse quantization

Invert the quantization equations in BT.2100-2 Table 9 (i.e., solve for E' given code value D).

A.1.1 For a narrow range PQ Master

If the PQ master is narrow range (aka “legal range,” “head range,” or “video range”), then invert the narrow range equation:

$$D = \text{Round}[(219 E' + 16) \times 2^{n-8}]$$

where:

D: code value

E': non-linear video signal

n: bit depth of code value *D*

Round(): as defined in BT.2100-2 Table 9.

Then, solve for E' given code value D:

$$E' = (D - 16 \times 2^{n-8}) / (219 \times 2^{n-8})$$

if *n* = 10:

$$E' = (D - 64) / 876$$

if *n* = 12:

$$E' = (D - 256) / 3504$$

if *n* = 16:

$$E' = (D - 4096) / 56064.$$

A.1.2 For a full range PQ master

If the PQ master is full range, then invert the full range equation:

$$D = \text{Round}[(2^n - 1) E']$$

where:

D: code value

E': non-linear video signal

n: bit depth of code value *D*.

Then, solve for E' given code value D:

$$E' = D / (2^n - 1)$$

Best Practices for Mapping BT.2100 PQ to HLG using maxRGB

if $n = 10$:

$$E' = D/1023$$

if $n = 12$:

$$E' = D/4095$$

if $n = 16$:

$$E' = D/65535.$$

A.2 Step 2 – Set parameters for tone mapping equation (EETF)

The tone mapping curve (EETF in BT.2408-4) that maps input values to output values is parameterized by values L_B , L_W , L_{min} and L_{max} . For this conversion, in which the shadow region and black level will be unchanged, set:

$$L_{min} = L_B = 0$$

L_{max} is the output target. Since a 1,000 cd/m² master is the target of this conversion, set:

$$L_{max} = 1,000.$$

L_W should be set to the maximum level of the input signal.

A.2.1 For an unconstrained 10,000 cd/m² master

For an unconstrained master that is really using the full range of PQ, set:

$$L_W = 10,000.$$

A.2.2 For a 4,000 cd/m² master

Alternatively, for a 4,000 cd/m² master that uses the full range of PQ up to 4,000 cd/m², set:

$$L_W = 4,000.$$

A.2.3 Using MaxCLL to set L_W

If the title has a known and reliable MaxCLL metadata item that represents the significant maximum value that exists in a PQ HDR Master, then set:

$$L_W = MaxCLL.$$

If MaxCLL is equal to or less than 1,000 cd/m², no tone mapping should be applied. Different titles often have different MaxCLL values.

A.2.4 Using ST 2086 to set L_W

If the title has a known and reliable SMPTE ST 2086 metadata [ST2086] that represents the Color Volume of the Mastering Display, then the Maximum Luminance field from ST 2086 can be used for L_W . Set:

$$L_W = Maximum\ Display\ Mastering\ Luminance.$$

A.2.5 Preferred selection order for setting L_w

Generally, knowledge of the most reliable source for setting L_w should drive the selection. In the absence of such knowledge, the following precedence can be applied based on availability.

- 1) MaxCLL
- 2) ST 2086 Maximum Luminance
- 3) 4,000 cd/m² (unless the source is known to be unconstrained)
- 4) 10,000 cd/m²

A.3 Step 3 – Apply EETF to $\max(R', G', B')$

$$\begin{aligned} \max RGB'_1 &= \max(R', G', B') \\ \max RGB'_2 &= EETF(\max RGB'_1). \end{aligned}$$

The EETF() computation is described in the steps below, starting with Step 1 of Annex 5 of BT.2408-4.

A.3.1 Normalize based on L_B and L_w

Set:

$$E_1 = \frac{\max RGB'_1 - EOTF_{PQ}^{-1}(L_B)}{EOTF_{PQ}^{-1}(L_w) - EOTF_{PQ}^{-1}(L_B)}$$

Since $L_B = 0$, this simplifies to:

$$E_1 = \max RGB'_1 / EOTF_{PQ}^{-1}(L_w).$$

A.3.1.1 Map the value using the parameterized Hermite spline equation

A.3.1.1.1 Calculate constants that influence the mapping curve

Set:

$$\begin{aligned} \min Lum &= \frac{EOTF_{PQ}^{-1}(L_{min}) - EOTF_{PQ}^{-1}(L_B)}{EOTF_{PQ}^{-1}(L_w) - EOTF_{PQ}^{-1}(L_B)} \\ \max Lum &= \frac{EOTF_{PQ}^{-1}(L_{max}) - EOTF_{PQ}^{-1}(L_B)}{EOTF_{PQ}^{-1}(L_w) - EOTF_{PQ}^{-1}(L_B)} \end{aligned}$$

Since $L_B = 0$ and $L_{min} = 0$, this simplifies to:

$$\begin{aligned} \min Lum &= 0 \\ \max Lum &= EOTF_{PQ}^{-1}(L_{max}) / EOTF_{PQ}^{-1}(L_w). \end{aligned}$$

Performing Step 2 of Annex 5, set:

$$\begin{aligned} KS &= 1.5 \max Lum - 0.5 \\ b &= \min Lum. \end{aligned}$$

Since $\min Lum = 0$, this simplifies to:

$$b = 0.$$

A.3.1.2 Perform the tone mapping

Start to solve for the EETF, performing the first part of Step 3 of Annex 5.

Best Practices for Mapping BT.2100 PQ to HLG using maxRGB

Initialize for $E_1 < KS$:

$$E_2 = E_1.$$

If $E_1 \geq KS$, compute E_2 using the Hermite spline equation:

$$T = T[E_1] = \frac{E_1 - KS}{1 - KS}$$
$$P = P[E_1] = (2T^3 - 3T^2 + 1)KS + (T^3 - 2T^2 + T)(1 - KS) + (-2T^3 + 3T^2)maxLum$$
$$E_2 = P.$$

Perform the next step in solving for the EETF. This lifts the black level and can be skipped in this use case, since $b = 0$, so set:

$$E_3 = E_2.$$

A.3.1.3 Invert the normalization based on L_B and L_W

Perform Step 5 of Annex 5, setting:

$$E_4 = E_3 (EOTF_{PQ}^{-1}(L_W) - EOTF_{PQ}^{-1}(L_B)) + EOTF_{PQ}^{-1}(L_B).$$

Since $L_B = 0$, this simplifies to:

$$E_4 = E_3 EOTF_{PQ}^{-1}(L_W).$$

A.4 Step 4 – Calculate scaling ratio

Initialize:

$$scaling_ratio = 1.0.$$

If $maxRGB'_1 > 0$:

$$scaling_ratio = EOTF_{PQ}(maxRGB'_2) / EOTF_{PQ}(maxRGB'_1).$$

A.5 Step 5 – Compute new R'G'B' values using scaling ratio

Set:

$$R_1 = EOTF_{PQ}(R')$$

$$G_1 = EOTF_{PQ}(G')$$

$$B_1 = EOTF_{PQ}(B')$$

$$R_2 = scaling_ratio R_1$$

$$G_2 = scaling_ratio G_1$$

$$B_2 = scaling_ratio B_1$$

$$R'_2 = EOTF_{PQ}^{-1}(R_2)$$

$$G'_2 = EOTF_{PQ}^{-1}(G_2)$$

$$B'_2 = EOTF_{PQ}^{-1}(B_2).$$

A.6 Step 6 – Quantize new R'G'B' values

The new R'G'B' values can be quantized to integer code values using either full range or narrow range equations.

A.6.1 R'G'B' full range quantization

Follow the equations in BT.2100-2 Table 9 for full range quantization:

$$D = \text{round}(E' \times (2^n - 1))$$

if $n = 10$:

$$D = \text{Round}(1023 E')$$

if $n = 12$:

$$D = \text{Round}(4095 E')$$

if $n = 16$:

$$D = \text{Round}(65535 E')$$

where:

$$\text{round}(x) = \text{sign}(x) \times \text{floor}(|x| + 0.5)$$

$\text{floor}(x)$ = the largest integer less than or equal to x

$$\text{sign}(x) = \begin{cases} 1; & x > 0 \\ 0; & x = 0 \\ -1; & x < 0. \end{cases}$$

A.6.2 R'G'B' Narrow Range Quantization

Follow the equations in BT.2100 Table 9 for Narrow Range quantization of

$$D = \text{Round}((219 E' + 16) \times 2^{n-8})$$

if $n = 10$:

$$D = \text{Round}(876 E' + 64)$$

if $n = 12$:

$$D = \text{Round}(3504 E' + 256)$$

if $n = 16$:

$$D = \text{Round}(56064 E' + 4096).$$

Appendix B Conversion of 1000 cd/m² PQ master to HLG using overshoots and undershoots

The process here utilizes the display-referred conversion shown in Figure 14 of BT.2408-4, which maps to Steps 2 through 4 below.

B.1 Step 1 – Inverse quantization

Invert the quantization equations in BT.2100-2 Table 9 (i.e., solve for E' given code value D)

B.1.1 PQ Master is narrow range

If the PQ Master is narrow range (aka “legal range”, “head range”, or “video range”), then invert the narrow range equation:

$$D = \text{Round}[(219 E' + 16) \times 2^{n-8}]$$

where:

D : code value

E' : non-linear video signal

n : bit depth of code value D .

Solve for E' given code value D :

$$E' = (D - 16 \times 2^{n-8}) / (219 \times 2^{n-8})$$

if $n = 10$:

$$E' = (D - 64) / 876$$

if $n = 12$:

$$E' = (D - 256) / 3504$$

if $n = 16$:

$$E' = (D - 4096) / 56064.$$

B.1.2 PQ master is full range

If the PQ Master is Full Range, then invert the full range equation:

$$D = \text{Round}((2^n - 1)E').$$

Solve for E' given code value D :

$$E' = D / (2^n - 1).$$

if $n = 10$:

$$E' = D / 1023$$

if $n = 12$:

$$E' = D / 4095$$

if $n = 16$:

$$E' = D / 65535.$$

B.2 Step 2 – Apply PQ EOTF

The PQ EOTF is defined in Table 4 of BT.2100-2 as:

$$F_D = 10000 \times \left(\frac{\max \left[\left(E'^{1/m_2} - c_1 \right), 0 \right]}{c_2 - c_3 E'^{1/m_2}} \right)^{1/m_1}$$

where:

E' : non-linear video signal value

$$m_1 = 0.1593017578125$$

$$m_2 = 78.84375$$

$$c_1 = 0.8359375$$

$$c_2 = 18.8515625$$

$$c_3 = 18.6875.$$

B.3 Step 3 – Apply HLG Inverse-OOTF

The HLG Inverse-OOTF is defined in Note 5i of BT.2100-2 [BT.2100] as:

$$R_S = (R_D/\alpha) \times (Y_D/\alpha)^{(1-\gamma)/\gamma}$$

$$G_S = (G_D/\alpha) \times (Y_D/\alpha)^{(1-\gamma)/\gamma}$$

$$B_S = (B_D/\alpha) \times (Y_D/\alpha)^{(1-\gamma)/\gamma}$$

$$Y_D = 0.2627 R_D + 0.6780 G_D + 0.0593 B_D$$

where:

$$\gamma = 1.2$$

$$\alpha = 1000.$$

B.4 Step 4 – Apply HLG OETF with overshoots and undershoots

For scene linear light normalized to the range of 0 to 1, the HLG OETF is defined in Table 5 of BT.2100-2 as:

$$E' = \begin{cases} \sqrt{3E} & 0 \leq E \leq 1/12 \\ a \cdot \ln(12E - b) + c & 1/12 < E \leq 1 \end{cases}$$

where:

$$a = 0.17883277$$

$$b = 1 - 4a = 0.28466892$$

$$c = 0.5 - a \cdot \ln(4a) = 0.55991073$$

$\ln(x)$ is the natural logarithm of x .

In scene linear light, the use of overshoots and undershoots causes value of E to exceed 1.0, with blue causing the largest deviation. Maximum blue from the 1,000 cd/m² P3D65 color volume requires values up to 1.500688. For the BT.2100 primaries, maximum blue uses values up to 1.601367.

B.5 Step 5 – Conversion of non-linear HLG to output integer code values

B.5.1 R'G'B' narrow range quantization

If an R'G'B' signal is the desired output, no additional R'G'B' to Y'C_BC_R conversion is necessary, only quantization to Narrow Range code values.

Best Practices for Mapping BT.2100 PQ to HLG using maxRGB

Follow the equation in BT.2100-2 Table 9 for narrow range quantization of

$$D = \text{Round}((219 E' + 16) \times 2^{n-8})$$

if $n = 10$:

$$D = \text{Round}(876 E' + 64)$$

if $n = 12$:

$$D = \text{Round}(3504 E' + 256)$$

if $n = 16$:

$$D = \text{Round}(56064 E' + 4096).$$

B.5.2 R'G'B' to Y'C_BC_R conversion and Y'C_BC_R narrow range quantization

If a Y'C_BC_R signal is the desired output, the R'G'B' is first converted to Y'C_BC_R followed by Narrow Range Quantization, as described in the steps below:

B.5.2.1 R'G'B' to Y'CB'CR conversion

Perform R'G'B' to Y'C_BC_R conversion as described in Table 6 of BT.2100-2:

$$Y' = 0.2627 R' + 0.6780 G' + 0.0593 B'$$

$$C'_B = (B' - Y')/1.8814$$

$$C'_R = (R' - Y')/1.4746.$$

B.5.2.2 Quantization to Y'C_BC_R narrow range code values

Follow equations in BT.2100 Table 9 for Narrow Range quantization of Y'C_BC_R

$$DY' = \text{Round}[(219 Y' + 16) \times 2^{n-8}]$$

$$DC'_B = \text{Round}[(224 C'_B + 128) \times 2^{n-8}]$$

$$DC'_R = \text{Round}[(224 C'_R + 128) \times 2^{n-8}]$$

if $n = 10$:

$$DY' = \text{Round}(876 Y' + 64)$$

$$DC'_B = \text{Round}(896 C'_B + 512)$$

$$DC'_R = \text{Round}(896 C'_R + 512)$$

if $n = 12$:

$$DY' = \text{Round}(3504 Y' + 256)$$

$$DC'_B = \text{Round}(3584 C'_B + 2048)$$

$$DC'_R = \text{Round}(3584 C'_R + 2048)$$

if $n = 16$:

$$DY' = \text{Round}(56064 Y' + 4096)$$

$$DC'_B = \text{Round}(57344 C'_B + 32768)$$

$$DC'_R = \text{Round}(57344 C'_R + 32768).$$

References

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- [BT2100] ITU-R, Recommendation ITU-R BT.2100-2, "Image parameter values for high dynamic range television for use in production and international programme exchange," July 2018.
- [BT2390] ITU-R, Report BT.2390-9, "High dynamic range television for production and international programme exchange," March 2021.
- [BT2408] ITU-R, Report BT.2408-4, "Operational practices in HDR television production," March 2021.
- [ST2086] SMPTE, ST 2086:2018, "Mastering Display Color Volume Metadata Supporting High Luminance and Wide Color Gamut Images," April 2018.