COLOUR-VOLUME LIMITATIONS WITH HLG

Summary

At the nominal hybrid-log gamma (HLG) display peak luminance of 1,000 cd/m^2 (or nits) specified by Recommendation ITU-R BT.2100, the colour volume available for the display of HLG signals is smaller than the 1,000 cd/m^2 BT.2100 red-green-blue (RGB) perceptual quantizer (PQ) colour volume. These differences in colour volume are more pronounced as the peak luminance of the display increases. PQ suffers no such limitations in colour volume.

Details

The down-conversion of BT.2100 RGB PQ images to HLG can result in hue shifts, desaturation, and attenuation of bright saturated colours. These errors occur because the displayable colour volume for HLG is smaller than the BT.2100 PQ colour volume; thus, clipping can occur.

It is easy to illustrate this reduction in colour volume using the equations for luminance in both the display and scene domains along with the electro-optical transfer function (EOTF) for HLG:

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

$$Y_S = 0.2627R_S + 0.6780G_S + 0.0593B_S$$

$$R_D = \alpha Y_S^{\gamma - 1} R_S + \beta$$

$$G_D = \alpha Y_S^{\gamma - 1} G_S + \beta$$

$$B_D = \alpha Y_S^{\gamma - 1} B_S + \beta$$

The following table summarizes what happens for the basic colours (white, pure red, pure green, and pure blue). For a 1,000 cd/m^2 BT.2100 PQ display, the maximum luminance of each of these colours is calculated using Y_D and is shown in the second column of the table. For HLG, we can simplify the EOTF by normalizing scene colours between [0,1] and setting beta (black level) to zero:

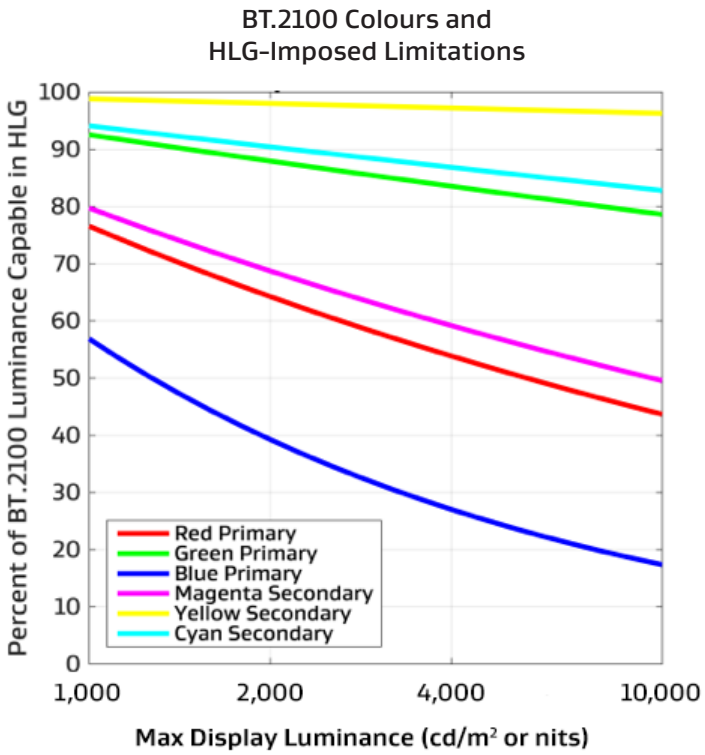
$$R_D = 1{,}000 Y_S^{\gamma - 1} R_S \text{ , etc.}$$

This determines { R_D , G_D , B_D }, and the resulting luminance is calculated using Y_D. The luminance achievable with HLG is tabulated in the third column.

Colour	BT.2100 PQ Y cd/m^2	BT.2100 HLG Y cd/m^2
{1,1,1} // Peak white	**1,000.0**	**1,000.0**
{1,0,0} // Maximum red	**262.7**	**201.1**
{0,1,0} // Maximum green	**678.0**	**627.3**
{0,0,1} // Maximum blue	**59.3**	**33.7**

This is a rather surprising result; there is a significant limitation to the colour volume achievable by HLG. This occurs because for HLG the opto-optical transfer function (OOTF) is (1) applied in the display, and (2) is applied to luminance rather than to the RGB colour channels. Because HLG increases display gamma with display brightness, this effect increases for displays over 1,000 cd/m^2 as shown in the following graph. As you can see, on a 10,000 nit HLG display, saturated blue is limited to 17 percent of the 563 cd/m^2 of blue present in a 10,000 cd/m^2 white, or 103 cd/m^2. A PQ display can show the full 563 cd/m^2 for saturated blue.

A further visual depiction of the HLG limitations is shown below. The full PQ colour volume (shown in green) is determined by its peak luminance (10,000 cd/m^2) and the chromaticity of the BT.2100 primaries. The HLG colour volume (shown in red) is presented for the same display luminance of 10,000 cd/m^2 (of white). Points inside the HLG colour volume are identical to the corresponding points in the PQ colour volume (indicated by the green dots with smaller red dots inside). If PQ is down-converted to HLG, and clipping to legal signal values occurs, points that are inside the PQ colour volume but outside the HLG colour volume are clipped to the HLG colour volume boundary following the path shown by the black lines. The black lines are not vertical, which means that along with attenuation, these colours also undergo hue shifts and desaturation. The HLG signal simply cannot represent all the bright saturated colours that a BT.2100 PQ display could reproduce, and unless sophisticated 3D colour volume mapping is done in the down-conversion from PQ to HLG, bright saturated objects in the PQ image may suffer noticeable hue shifts along with desaturation in the down-conversion. While this figure illustrates the situation at 10,000 cd/m^2 (the most extreme case) the HLG colour volume limitation does occur for an HLG display at any brightness (as shown in the plot above). There are no such limitations in converting HLG signals into PQ as the PQ container is larger than the HLG container.



The colour volumes shown in the graph of the RGB displayable colour volumes apply to PQ and HLG signals in the $Y'C'_BC'_R$ or IC_TC_P domains as well as the RGB domain. If the $Y'C'_BC'_R$ signal represents PQ, then the colour volume is as indicated by the outlined green solid. If the $Y'C'_BC'_R$ signal represents HLG, then the colour volume, when reproduced on a 10,000 cd/m^2 display, is shown by the outlined red solid. In order for an HLG $Y'C'_BC'_R$ signal to fill the PQ colour volume, C'_B and C'_R would need to take on values that exceed the allowed [-0.5, 0.5] signal range.