

2D Representation of Display Color Gamut

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Abstract

Display gamuts usually render complex shapes in a uniform color space, requiring observers to change views to comprehend a 3D plot. We propose a 2D representation of a display color gamut, named “gamut rings,” where the area within an arbitrary luminance and hue angle range corresponds to gamut volume.

Keywords

High dynamic range; wide color gamut; color volume; display gamut size

1. Introduction

For UHD TV, wide-gamut system colorimetry was standardized as a part of Recommendation ITU-R BT.2020 (Rec. 2020). The Rec. 2020 red, green, and blue (RGB) primary set was designed to encompass major standard color spaces, including Recommendation ITU-R BT.709 (Rec. 709) for HDTV, and most object colors [1]. Figure 1 shows the Rec. 2020 and Rec. 709 RGB primary sets by the International Commission on Illumination (CIE) 1931 xy and CIE 1976 $u'v'$ chromaticity diagrams. The Rec. 2020 RGB triangles in the two diagrams are each divided into cyan, magenta, and yellow (CMY) regions, where straight borderlines connect the RGB chromaticity points with the reference white point (D65). It is observed that the $u'v'$ magenta area is relatively large and the $u'v'$ yellow area is relatively small.

Presently, many displays with Rec. 2020 RGB inputs are commercially available. However, their inherent gamut sizes vary. Current wide-gamut displays apply color transformations to input signals to make their colorimetries correct for specific display devices, and they are capable of at least partially producing the Rec. 2020 gamut. Consequently, the gamut size measurement is important.

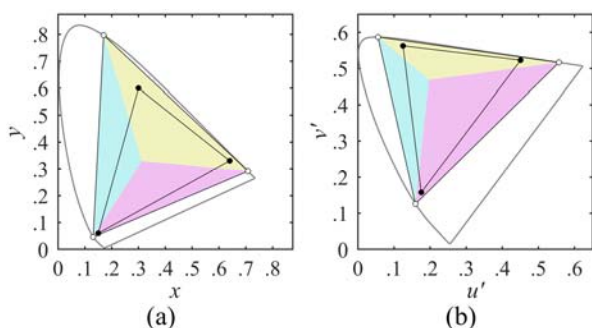


Figure 1. Rec. 2020 and Rec. 709 RGB primary sets. (a) CIE 1931 xy and (b) CIE 1976 $u'v'$ chromaticity diagrams.

A practical metric used in the display industry involves comparing the RGB triangle area of a display to that of a standard color space in a chromaticity diagram. To measure the relative gamut sizes of wide-gamut displays, it is proposed that the xy diagram can be used as a practical metric rather than the

nominally perceptually uniform $u'v'$ diagram because of the high correlations between the Rec. 2020 gamut area-coverage ratios in the xy diagram and the volume-coverage ratios in color appearance spaces [2]. The $u'v'$ perceptual uniformity is valid only when the luminance is constant, and display gamut sizes are overestimated in the $u'v'$ magenta region and underestimated in the $u'v'$ yellow region [3].

High-dynamic-range (HDR) image parameters that were determined by utilizing the perceptual quantization (PQ) and hybrid log-gamma methods with the Rec. 2020 RGB primary set were specified in 2016 in Rec. ITU-R BT.2100. HDR provides viewers with an enhanced visual experience by generating images that appear correct on brighter displays, displaying much brighter highlights and greater detail in dark areas. Therefore, color reproduction over white is the essence of HDR, and setting the white level properly according to the display’s peak luminance is key to HDR content creation.

HDR displays pose new challenges to the field of display metrology [4,5]. For example, a possible method of achieving HDR displays involves adding a white subpixel to the traditional RGB subpixels (i.e., WRGB) to boost the light output, thereby increasing the brightness without increasing the gamut. However, the RGB triangle area in a chromaticity diagram does not manifest such a volumetric difference [6]. Thus, single-valued color gamut volume (or what some are just calling “color volume”) metrics are being addressed to describe the ranges of both the colors and luminance levels that displays can reproduce.

To scientifically quantify color volume in perceptually meaningful ways, a 3D uniform color space based on a color appearance model is required. A color appearance model is any model that includes predictors of at least the relative color appearance attributes of lightness, chroma, and hue. For a model to include reasonable predictors of these attributes, it should include some type of chromatic adaptation transform [7]. Given the above definition, the CIE 1976 (L^* , a^* , b^*) color space (CIELAB) can be considered a color appearance model with a primitive chromatic adaptation transform. Unfortunately, no standardized color appearance models are suitable for HDR/wide color gamut (WCG) displays. However, limited experiments indicate that CIELAB remains approximately perceptually uniform above diffuse white up to L^* of ~ 200 [8].

Masaoka [9] used an extended CIELAB color space to compute the color volume of HDR RGB/WRGB displays and found that color volume is mostly proportional to i) the xy chromaticity area, ii) display peak luminance, and iii) the ratio of the Color Light Output [10] to the White Light Output. Additionally, he stressed the necessity of evaluating HDR/WCG display gamut shapes,

rather than single-valued color volumes. This is particularly important when a display uses a look-up table or more than three primaries, in which case the gamut cannot be uniquely determined and may have a complex shape. It requires changing the angle of view from which an observer sees the 3D plot to grasp the shape.

We propose a theoretical 2D representation of display color gamut, named “gamut rings,” where the area within an arbitrary luminance and hue angle range corresponds to gamut volume.

2. Methods

Extended CIELAB Color Space: The CIELAB color space is expressed by the following coordinates along three orthogonal axes of lightness L^* and color-opponent dimensions (a^* , b^*), or cylindrical coordinates of lightness L^* , chroma C^* , and hue angle h in degrees. For the extended CIELAB color appearance space, the same equations are used for tristimulus values greater than those of the D65 reference white at a luminance of 200 cd/m^2 ($L^* = 100.0$) based on the ITU-R Report for operational practices in HDR television production [11].

Color Volume Computation: To estimate a display gamut, gamut boundary polygons in the xyY color space are first obtained at absolute luminance levels corresponding to lightness values L^* from 0.5 to the maximum lightness value in intervals of 1. To obtain the constant- L^* loci in the extended CIELAB space, 1,000 points between each pair of adjacent xy vertices are interpolated in advance for each polygon, and then, they are converted into a^*b^* coordinates. The sum of the areas of the loci approximates the volume. Figure 2 shows the Rec. 2020 gamut computed with this method in the $L^*a^*b^*$ color space. The gamut consists of 100 slices at L^* of 0.5, 1.5, ... 99.5 colored with a 10-interval grayscale. When the display gamut is determined experimentally, care must be taken to sample an adequate number of colors to achieve the desired accuracy for the area within the gamut rings.

Gamut Ring Transform: The loci forming the display gamut boundaries are then transformed into gamut rings. First, the area of each constant- L^* locus in a hue angle ranging from $h - 0.5^\circ$ to $h + 0.5^\circ$, $A(L^*, h)$, is obtained, where h ranges from 0° to 359° at intervals of 1° . The a^*b^* coordinates of the locus at hue angles of $h \pm 0.5^\circ$ are obtained by linear interpolation. The equivalent chroma value, $C^*(L^*, h)$, is obtained as:

$$C^*(L^*, h) = (360 A(L^*, h)/\pi)^{0.5}.$$

The root sum square of the equivalent chroma values, at each hue angle in the lightness range from 0 to L^* , $C^*_{\text{RSS}}(L^*, h)$, is then obtained as follows:

$$C^*_{\text{RSS}}(L^*, h) = (\sum_{l=1}^{L^*} C^*(l - 0.5, h)^2)^{0.5}.$$

The $(a^*_{\text{RSS}}, b^*_{\text{RSS}})_{L^*,h}$ coordinates of C^*_{RSS} at a hue angle h in the lightness range from 0 to L^* are defined as:

$$(a^*_{\text{RSS}}, b^*_{\text{RSS}})_{L^*,h} = (C^*_{\text{RSS}}(L^*, h) \cos(h), C^*_{\text{RSS}}(L^*, h) \sin(h)).$$

The outer gamut ring area is equivalent to the sum of the areas of the loci, approximating the gamut volume.

3. Simulation Results

Standard Gamuts: Figure 3 shows the Rec. 2020 and Rec. 709 gamuts in the $(a^*_{\text{RSS}}, b^*_{\text{RSS}})$ diagram with the gamut rings for L^* of 10, 20, ... 100, with the same 10-interval grayscale of Figure 2. It is intuitively found that the blue region has a low luminance range, whereas the yellow region has a wide luminance range.

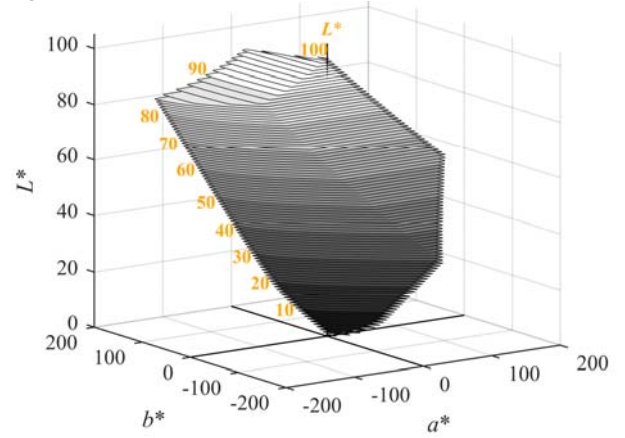


Figure 2. Rec. 2020 gamut consisting of 100 constant- L^* slices in the CIELAB color space.

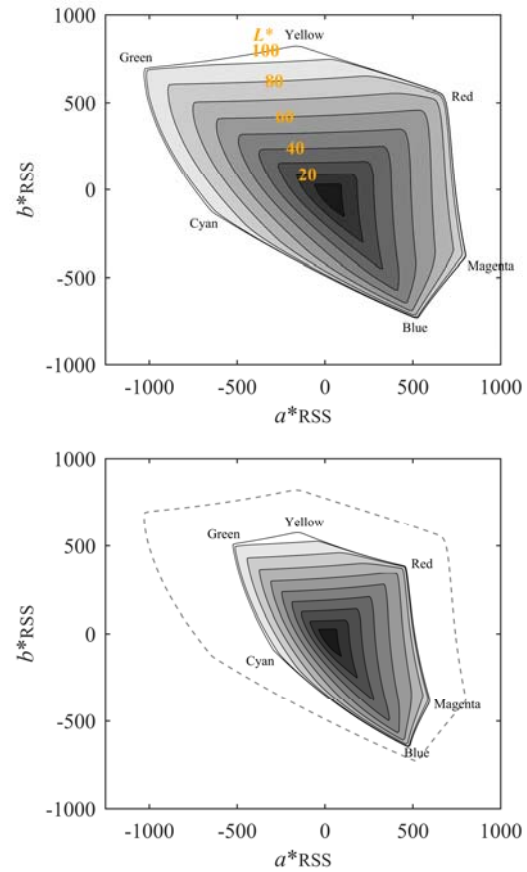


Figure 3. Rec. 2020 (top) and Rec. 709 (bottom) gamut rings. The dotted locus (bottom) shows the outer Rec. 2020 gamut ring.

HDR Displays: Figure 4 shows the loci of the gamuts of Rec. 2020 displays with peak luminances of 200, 500, and 1,000 cd/m^2 . The 3D gamut shapes look similar. Figure 5 shows the gamut with a peak luminance of 1,000 cd/m^2 in the $(a^*_{\text{RSS}}, b^*_{\text{RSS}})$ diagram. The areas having L^* more than 100 are highlighted in yellow. The color volume is almost proportional to the peak luminance because the scale of a display gamut solid in the CIELAB space is mostly proportional to the cube root of the tristimulus values [9].

HDR WRGB Displays: Figure 6 depicts the loci of the gamuts of Rec. 2020 displays with the Color Light Output to White Light Output (CLO/WLO) ratios of 0.2, 0.5, and 1, and a peak luminance of 1,000 cd/m^2 . Figure 7 shows the gamuts with CLO/WLO ratios of 0.2 and 0.5 in the $(a^*_{\text{RSS}}, b^*_{\text{RSS}})$ diagram. The volume is almost proportional to CLO/WLO in the practical range [9]; however, the gamut has less chroma especially in the highlights, as CLO/WLO decreases.

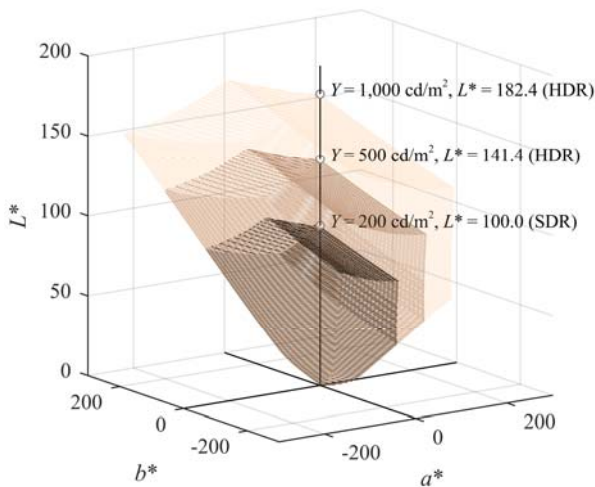


Figure 4. Loci of the gamut boundary of SDR/HDR Rec. 2020 RGB displays with peak luminances of 200 cd/m^2 , 500 cd/m^2 , and 1,000 cd/m^2 in the CIELAB color space.

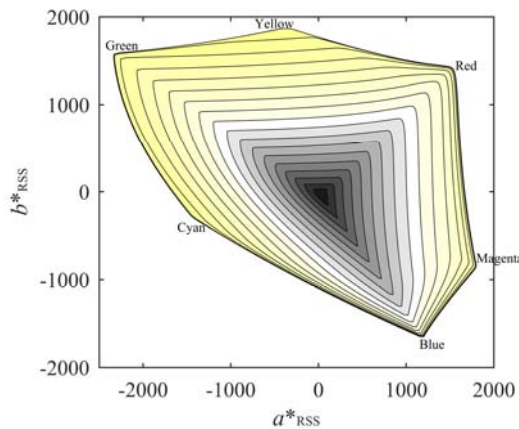


Figure 5. Gamut rings of an HDR Rec. 2020 RGB display with a peak luminance of 1,000 cd/m^2 .

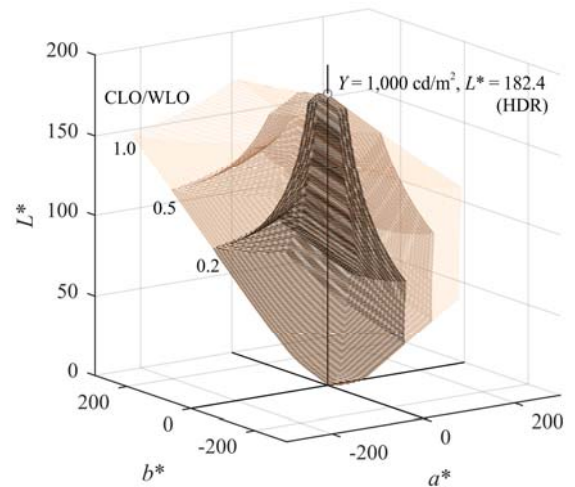


Figure 6. Loci of the gamut boundary of HDR Rec. 2020 WRGB displays with a peak luminance of 1,000 cd/m^2 with CLO/WLO ratios of 0.2, 0.5, and 1.

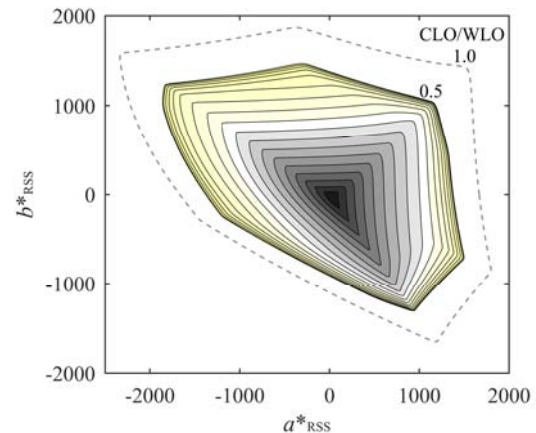
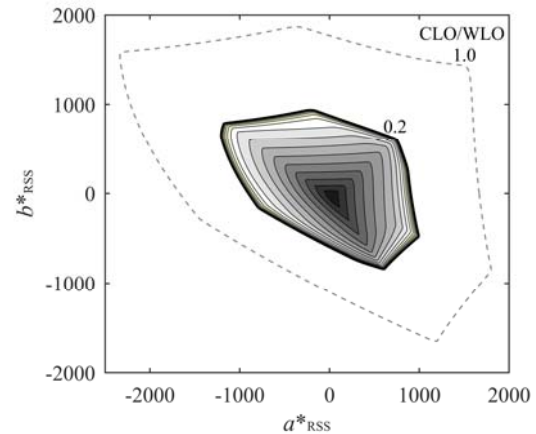


Figure 7. Gamut rings of HDR Rec. 2020 WRGB displays with a peak luminance of 1,000 cd/m^2 with CLO/WLO ratios of 0.2 (top) and 0.5 (bottom). The dotted loci show the outer rings with CLO/WLO ratio of 1.

4. Discussion

The proposed gamut rings make it possible to intuitively and quantitatively comprehend the color volume without rendering complex 3D shapes in a uniform color space. However, the color appearance model used has accuracy limitations. It is fundamentally important to develop new color appearance models to predict the attributes of both highlighted and very dark colors. Although analysis using the extended CIELAB model would be reasonable, additional testing is necessary to collect more HDR visual data [8]. Currently, the ICtCp color space standardized in Rec. 2100 has been proposed to determine the color volume metric [12] with intensity component I with PQ. In the ICtCp space, no white point is defined. Instead, based on the assumption that a viewer can adapt to any luminance level, an optimized nonlinear function is developed for the PQ signal, which can operate over a wide range of luminance levels and colors without any visible quantization artifacts. Although a viewer can adapt to a local luminance on a display to some extent and the adaptation status fluctuates, the adaptation level should be limited to a much smaller range than that of the display black luminance to the peak luminance, if real viewing conditions are considered. Otherwise, the color volume will be overestimated [5].

For practical gamut measurement of well-behaved RGB displays, whose gamuts are usually uniquely determined based on the chromaticities of the RGB primaries assuming a perfect additive color mixing, a combination of conventional display metrics based on basic colorimetry is useful [9]. In terms of the gamut in the CMY regions (Figure 1), the xy diagram is still suggestive of the color volume [3]. Figure 8 shows the outer gamut rings of SDR Rec. 2020 and Rec. 709 RGB displays. The Rec. 2020 ring is divided into CMY regions, where the angles of the straight borderlines correspond to the CIELAB hue angles of the full-on Rec. 2020 RGB. The area ratio of the CMY regions of the Rec. 2020 gamut ring is closer to the CMY chromaticity area ratio in the xy diagram (Figure 1a) than that in the $u'v'$ diagram (Figure 1b), supporting the validity of the xy chromaticity area metric. However, a general method is needed to first determine if the display exhibits additive mixing.

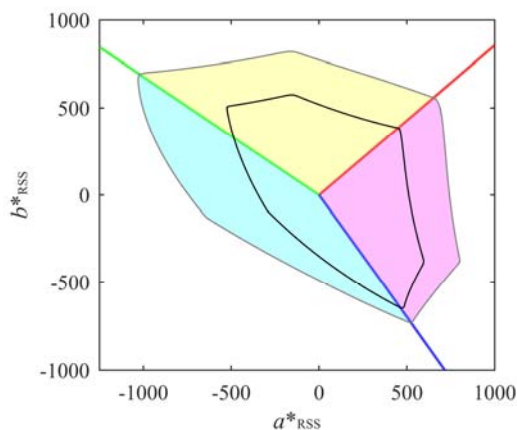


Figure 8. Outer gamut rings for SDR Rec. 2020 and Rec. 709 RGB displays.

5. Conclusion

In the proposed 2D plot of gamut rings, the areal dimension corresponds to the volume within an arbitrary luminance and hue range, enabling an intuitive approach to grasping the color volume of a complex shape in a quantitative manner. For practical gamut measurement of well-behaved RGB displays, a combination of conventional display metrics based on basic colorimetry is useful. Further study is necessary to develop a new color appearance model to evaluate HDR/WCG display gamut shapes, rather than just volumes.

6. References

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