

# From Scene to Display: A Quantitative Analysis of Real-World Color Gamut

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## Abstract

*This study examines the extent to which displays with ultra-wide color gamut can accurately reproduce the colors of real-world scenes. We further identify the specific colors that may present challenges for such displays. The results suggest the ultra-wide color gamut of QD-OLEDs enables accurate reproduction of a large and significant portion of the colors we encounter in real life, without needing the full gamut of BT.2020.*

## Keywords

Wide color gamut, OLED, QD-OLED, Real-world colors, Spectral image

## 1. Objective and Background

Display technology has seen significant advancements that contribute to expanding the color gamut. A wide color gamut (WCG), referring to a gamut larger than sRGB<sup>1</sup> enables a display to reproduce a wider range of colors, close to what the human eye can perceive. This is why consumers and professionals often associate wider color gamut with superior visual quality.

The P3 color space<sup>2</sup>, also referred to as DCI-P3, is a prominent standard used to evaluate wide color gamuts in consumer displays. Video Electronics Standards Association (VESA) DisplayHDR<sup>3</sup> also adopted the P3 color space for color certification eight years ago<sup>4</sup>, certifying HDR displays based on the intersection of a display's color gamut and P3. However, VESA gives no credit for color rendering that exceeds the P3 boundaries. The P3 color gamut, however, does not represent the entire range of colors that can be reproduced by modern OLED displays. In fact, the color gamut of modern HDR televisions, monitors or mobile displays exceeds DCI-P3 by a significant measure. These displays, which we refer to as ultra-wide color gamut (ultra-WCG, referring to a gamut larger than DCI-P3) utilize advanced technologies like quantum-dot (color-conversion technology), or OLED (self-emissive displays), or both (such as QD-OLED).

The International Telecommunications Union, recommended

BT.2020<sup>5</sup> as future television and laser cinema projectors in 2015. Further, BT.2020 is the standard color container for HDR transmission<sup>6</sup>. However, as of today, BT.2020 is not widely available on consumer displays and it's not expected that they will achieve full BT.2020 coverage anytime soon. However, some high-end TVs and monitors with "ultra-wide" color gamuts are getting close to covering BT.2020, particularly in the areas that standard color gamuts are falling short (e.g. highly saturated red, green or cyan). We employed an ultra-wide color gamut, QD-OLED TV as a test vehicle in this study

The benefits of a wide color gamut display come from the combination of the display panel, which should be capable of producing a wider range of colors, and the content that is displayed on it. Many real-world scenes typically involve vibrant and saturated colors, such as sunsets and sunrises, tropical landscapes, vibrant flowers, fireworks, or underwater scenes. These scenes may experience color clipping when reproduced on displays with standard color gamut like sRGB or DCI-P3. Figure 1 compares the color vibrancy of SDR content while it is displayed on a Samsung QD-OLED TV (S95B) with ultra-WCG, a display with DCI-P3 color gamut, and a display with sRGB color gamut. As shown, wider color gamuts can reproduce a broader range of colors, especially vibrant and saturated colors of the natural scene.

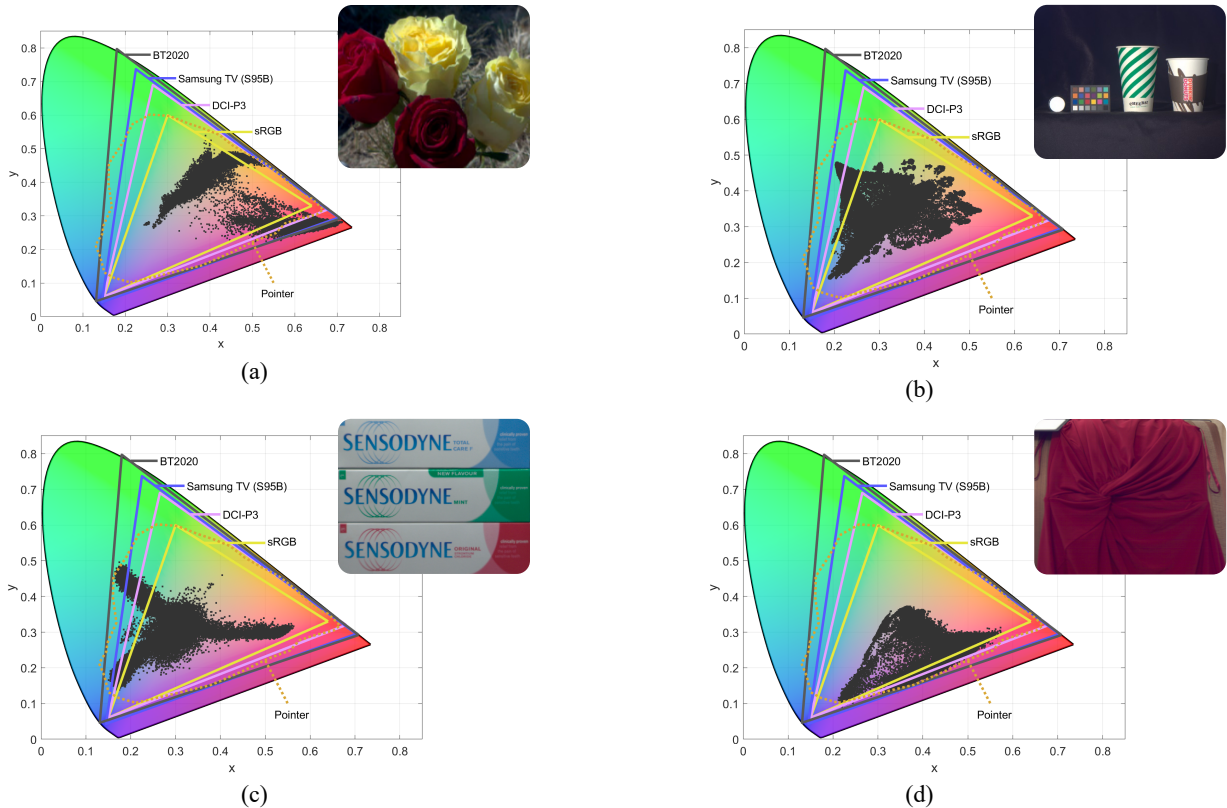
In this paper, we focus on real-world scenes and quantitatively analyze a large number of spectral images captured from a diverse range of natural and man-made scenes to determine:

- Which colors cannot be reproduced on displays with sRGB/DCI-P3 color gamut,
- How accurately OLED displays with ultra-WCG can reproduce these colors, and
- Which colors still remain unproducible on OLED displays.

The findings will benefit both panel design and manufacturing as well as display standardization.



Figure 1. RGB Rendering of a natural scene across three different color gamuts



**Figure 2.** Selected images with highest percentage of pixels (grey dots) falling outside the DCI-P3 color gamut. Depicted are reference polygons for sRGB, DCI-P3, the test unit, BT.2020 and Pointer's gamut.

## 2. Results and Discussion

To analyze the color gamut of real-world colors and determine the extent to which different standard color gamuts (i.e. sRGB, DCI-P3, and BT.2020) and the gamut achievable by Samsung QD-OLED can reproduce it, a large number of spectra of real-world scenes were collected from six different spectral image databases, including CAVE<sup>7</sup>, UEA<sup>8</sup>, KAUS<sup>9</sup>, KAIST<sup>10</sup>, Foster<sup>11</sup>, and ARA D-1K<sup>12</sup>.

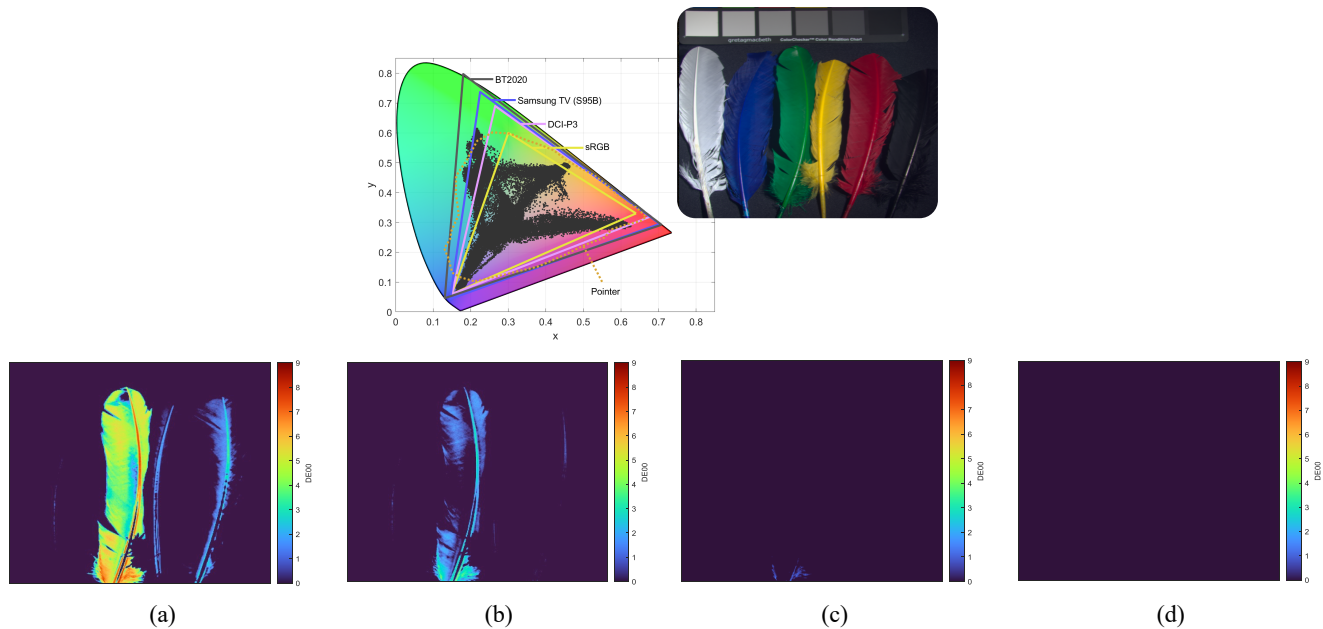
Figure 2 shows some representative images from the utilized datasets, which exhibits the highest percentage of pixels falling outside the DCI-P3 color gamut. In each chromaticity diagram, the Pointer's gamut<sup>13</sup> has been plotted as a comparison reference. According to our analysis, cyan and highly saturated colors in green, red, and orange areas are prominent, and these colors are not representable within the sRGB and DCI-P3 color spaces, and outside of BT.2020 in some cases. Figure 2(a) is a perfect example of natural colors that we encounter in our daily lives. Some flowers like the ones shown in this picture have incredibly saturated colors that easily fall outside the limits of the DCI-P3 or even BT.2020. In everyday life, we frequently capture images of these types of flowers and desire to have accurate and pleasing reproductions of those colors on our screens. Here is a place where an ultra-WCG OLED screen will be handy at the time of a camera capture so that the photographer can compare their photos with the actual scene side-by-side. A Samsung QD-OLED display offers significantly wider color coverage than DCI-P3, resulting in reduced clipped colors in saturated red areas.

Cyan and saturated greens are two challenging colors that displays, especially the ones without ultra-WCG, cannot

accurately reproduce. Cyan is often found in nature (bird feathers, tropical waters, flowers, marine animals, etc.) and man-made objects (clothing, packaging, toys, cars, etc.). Figure 2(b), 2(c) are notable examples of everyday objects containing cyan and saturated green where QD-OLED display can cover a vast range of cyan and green colors, including many pixels that fall outside standard sRGB/DCI-P3 gamuts. However, to achieve more accurate color reproduction, OLED color gamut may need to be optimized further in these areas. Subjective studies are required to confirm if further gamut expansion has a worthwhile return.

Highly saturated and vivid colors are also found frequently in fashion and textiles, particularly in fabrics like velvet and silk. Accurately reproducing these colors on displays is critical for e-commerce. Figure 2(d) clearly illustrates how the sRGB and DCI-P3 gamut are insufficient for accurately reproducing the colors of a purple dress and how a Samsung QD-OLED display with wider gamut in the purple area can overcome this limitation.

Figure 3 illustrates color difference maps for a given image. The maps highlight the color errors (in terms of DE00) between the original image representing the real-world scene versus each simulated reproduction on displays with different color gamut sizes. A clear trend emerges by switching from sRGB or DCI-P3 color gamuts to an ultra-WCG display, the amount of out of gamut pixels significantly reduces, leading to less clipping, lower color errors and ultimately more accurate color reproduction on the screen. As each color map shows, displays with sRGB or even DCI-P3 color gamut struggle to accurately reproduce the green feather, while Samsung QD-OLED display with its ultra-wide color gamut, especially in the green area, is quite successful.



**Figure 3.** Original image, and the corresponding color difference maps, highlighting regions of significant color difference (DE00) between the original and reproduced images on displays with different color gamuts. (a) to (d) columns correspond to sRGB, DCI-P3, Samsung QD-OLED (S95B TV), and BT2020, respectively. Reddish and yellowish colors on the map imply more rendering errors.

### Statistical Analysis of Spectral Image Datasets

**Cave** dataset analysis showed that only eight images (25% of the dataset) can be accurately reproduced on displays with color gamuts as small as sRGB. While nine images (28% of the dataset) exceed DCI-P3 – four out of the nine of them can be accurately displayed on Samsung QD-OLED display. Four of the remaining five images contain more saturated green and cyan that even exceed the QD-OLED gamut but are still within BT.2020.

**UEA** dataset illustrates a very similar trend. Cyan and green are two areas where DCI-P3 is insufficient to render the entire image. Of the 22 images, only 10 can be fully represented by displays with DCI-P3 gamut. QD-OLED TV with a broader gamut in green/cyan areas, enabling the full rendering of 7 additional images that are otherwise unattainable with sRGB or DCI-P3 color gamut.

**KAUST** is a collection of 490 images, encompassing a diverse range of indoor and outdoor scenes. According to our analysis, 68% of images can be fully represented within the sRGB color gamut, while approximately 28% require the DCI-P3 color gamut. Only a very small percentage of images (<5%) exceed DCI-P3, making QD-OLED sufficient for their accurate reproduction.

**KAIST** consists of images of man-made objects, which are mostly colorful and highly saturated. Our analysis indicates that the majority of the dataset demands a display with a wide color gamut, at least as wide as DCI-P3, for accurate representation. However, five images, constitute 16.7% of the KAIST dataset, require a larger color gamut, which can be provided by Samsung QD-OLED displays. In fact, the QD-OLED color gamut effectively covers the cyan and green areas where DCI-P3 falls short. Only two images out of 30 exceed the QD-OLED color gamut, but only in a very small number of pixels, which is unlikely to be noticeable to human observers.

**Foster** dataset, which contains outdoor scenes and nature images,

reveals that approximately 90% of images fall within the sRGB and DCI-P3 color gamuts. However, a small number of images, primarily vibrant flowers, exceed these standard gamuts due to their high saturation. An Example of such images are provided in Figure 2. As seen in the rose picture, deep blood red and saturated yellow are areas where sRGB and DCI-P3 do not cover. However, the QD-OLED gamut, which is as wide as BT.2020 in these regions, can provide adequate coverage.

**ARAD-1K** is currently the most extensive natural hyperspectral image collection. Our analysis indicated that almost 98% of real-world images of ARAD dataset are falling within sRGB and DCI-P3 color gamuts, meaning that only 20 images out of 950 require ultra-WCG for more accurate reproduction.

### 3. Conclusion

The main findings of this research can be outlined as follows:

- A considerable number of everyday colors in nature, such as, blue sky, green plants, fruits, etc., and man-made objects, such as clothing, paper, toys, buildings, vehicles, etc., fall within the boundaries of the sRGB and mostly DCI-P3 color spaces. However, some colors, such as cyan, pure green, or highly saturated reds and yellows, exist outside these gamuts. Displays without ultra-wide color gamut cannot accurately reproduce images containing these colors.
- Our analysis showed that OLED displays, such as a Samsung S95B TV, with an ultra-wide color gamut can reproduce a significant portion of colors we encounter in real life, providing a realistic viewing experience without needing the full gamut of BT.2020. Until BT.2020 is achievable on displays, we won't truly know how much the missing colors will contribute to image quality and whether the difference will be perceived or important to human observers.
- Although a Samsung QD-OLED display offers a wide range of cyan and green colors, accurate reproduction of

all shades of cyan and saturated greens may still be challenging.

- While BT.2020 is the ultimate long-term goal for the standard display gamut, it would be worthwhile to consider adopting the superior color gamut of high-end OLED displays which offer a significant improvement over P3 as a more sophisticated standard.

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