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# Abstract

Some observations relating to the ICtCp colour representation, using appropriately created test patterns and sequences, are presented in this document. The test patterns try to exercise a dynamic range from 0 to 10000cd/m2 as well as the entire range of BT.2020 colours, unlike more limited tests that have been conducted in the past using natural content. Such tests may help us to potentially uncover some of the limitations, if any, of this colour representation.

# Introduction

In [1][2] the ICtCp colour representation was presented as an alternative to the commonly used Y’CbCr [3][4][5]representation for the encoding of colour signals. It was suggested that this representation, in combination with the ST 2084 (PQ) transfer function [9], has several better properties than Y’CbCr, such as reduced chroma leakage due to improved Intensity/Luminance correlation, better colour quantization, exhibits hue linearity and uniformity, and has better behavior when performing colour subsampling and blending. Given these properties, it has been claimed that this representation would make it more suitable for use in several video coding applications [7][8].

Some observations about this colour representation are presented in this contribution that suggest that there might be some limitations in its usage and that more careful investigation of its properties should be considered. Our investigation seems to point out that there might be some limitations when looking into content that are limited to one or two primary colours. These issues seem to be an outcome of not only the use of a 4:2:0 representation but also of the limited precision (i.e. 10 bits) that is desired for the applications in mind.

Further analysis of these potential issues is presented in the subsequent sections

# Luminance in the Y’CbCr and ICtCp representations

Almost all modern video coding systems use the Y’CbCr non-constant luminance (NCL) colour representation as a mechanism for de-correlating RGB video data prior to compression. The process first involves applying a perceptually optimized transfer function directly on the RGB linear data, e.g. the power law gamma transfer function specified in [4][5] or the ST.2084 (PQ) transfer function [3][9], followed by a matrix conversion that tries to de-correlate the three colour components, so as to maximize the effect of any subsequent compression. Additional benefits could be achieved by subsampling some of the resulting colour components, i.e. the two chroma components, to a lower resolution. The decorrelation process essentially results in three components, the primary luma Y’ component that tries to resemble the luminance component in the XYZ representation (CIE 1931), and the two chroma components Cb and Cr that try to capture mostly the colour characteristics. The process has been used rather effectively for SDR video applications, even though there have been serious concerns about “chroma leakage” [10][11] that may occur in the signal due to some of the errors introduced especially due to down and up-sampling in the chroma components. This can be better understood by looking at the luma/luminance plot of Figure 1. The same luma value may correspond to a rather large range of luminance values depending on colour/chroma values. If, for any reason the colour/chroma information is changed, e.g. due to chroma down-sampling/upsampling, that may result in a significant and potentially objectionable change in luminance.

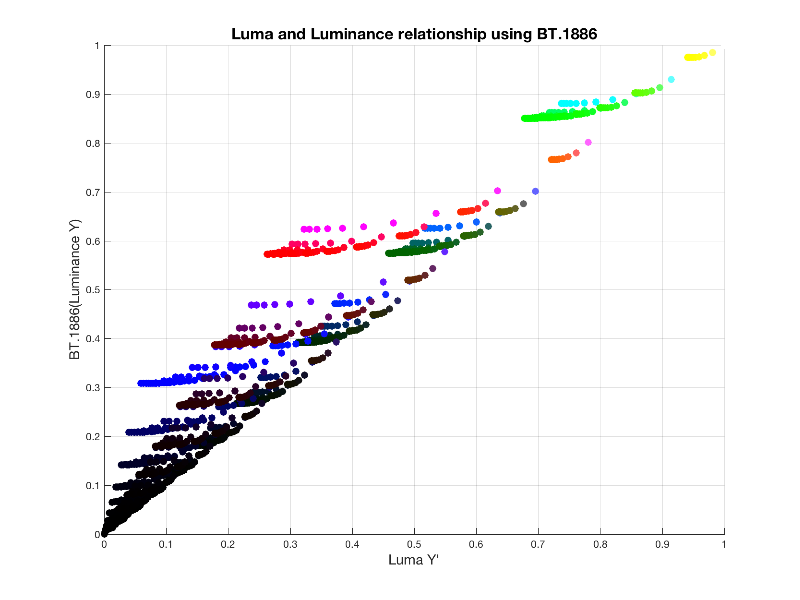


Figure . Luma/Luminance relationship using the inverse of BT.1886 (SDR content)

Unfortunately this issue becomes even more emphasized in HDR material and when using the Y’CbCr NCL representation with the ST 2084 transfer function [9]. The same value of luma may correspond to a much larger range of luminance values as can be seen in Figure 2. This problem, mainly when it comes to chroma leakage due to down/up-sampling, is somewhat addressed in [11], where a closed loop conversion is used to select the luma value that would result in a value closest to the original luminance value, given however chroma leakage. An extension is also presented in **Error! Reference source not found.** where it is recommended performing encoding of such images while considering the final reconstructed image in the 4:4:4 RGB domain instead of using decisions based on the 4:2:0 Y’CbCr representation.

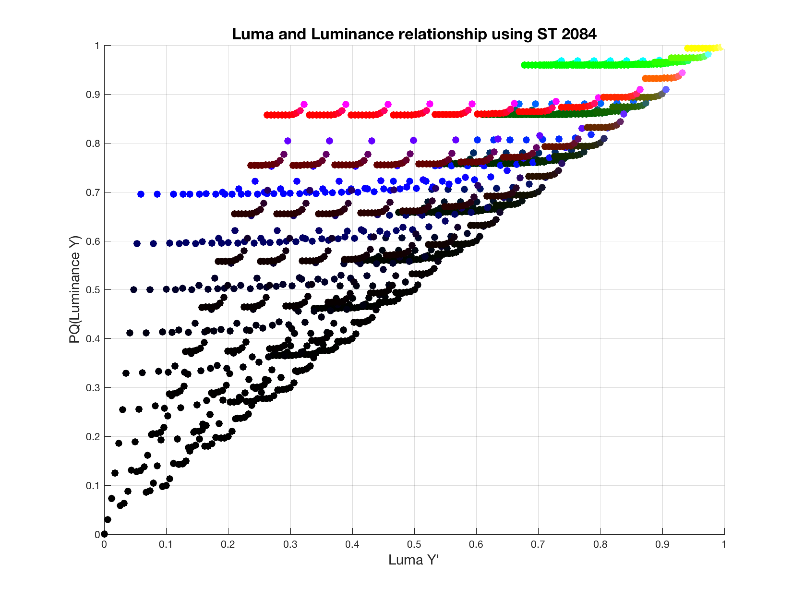


Figure . Luma/Luminance relationship using PQ

On the other hand the ICtCp representation [1][2] takes a different approach. The RGB components are first converted in a different colour space that closely resembles, but is not exactly identical to, the LMS space specified in the Hunt and RLAB color appearance models. The current conversion in [3] is specified in relationship to the RGB BT.2020 colour space using the following conversion:

which is also equivalent to the following conversion from XYZ (CIE 1931):

This conversion is then followed by application of the ST.2084 transfer function on the LMS components and an additional 3x3 matrix conversion to the ICtCp representation as follows:

A close examination of the above equations suggests that the I component has now a much closer relationship with luminance Y, especially given the relationships of L and M in LMS and Y in XYZ CIE 1931. This is also shown in Figure 3, which suggests, and as the original proponents of ICtCp have claimed, that chroma leakage in ICtCp versus Y’CbCr would be smaller. However, it also shows that chroma leakage is not completely eliminated and may still occur and impact some aspects of the signal, i.e. colour negatively. One may argue, for example that if luminance was the most important aspect of the signal, then a constant luminance representation, similar to the one specified in [5], would be more sensible.

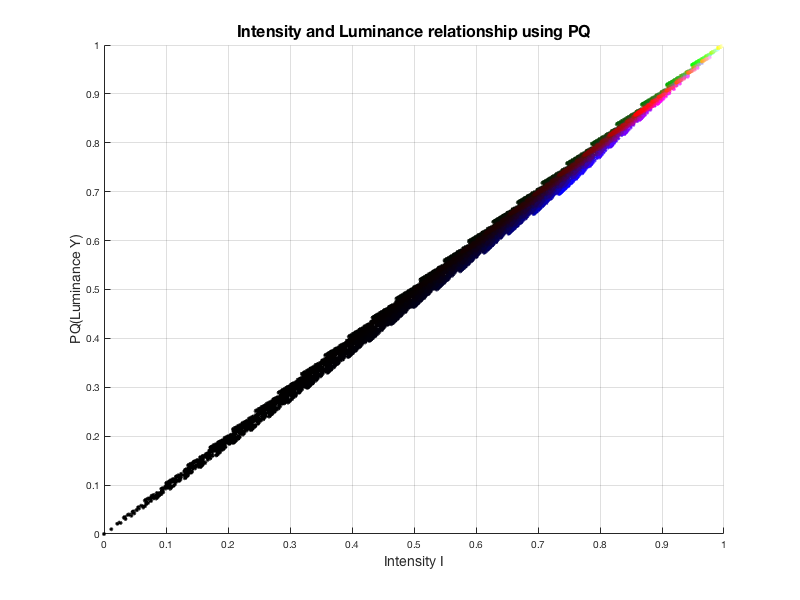


Figure . Intensity/Luminance relationship using PQ

# BT.2020 colours in the Y’CbCr and ICtCp representations

Instead, of considerable concern is in fact the distribution of BT.2020 colours in the ICtCp colour space. This is shown in Figure 4, where we are plotting a subset of the colour values in ITU-R BT.2020 onto the CtCp and CbCr planes. Of particular concern is the behavior on the bottom part of the CtCp plot, which corresponds mostly to the green/blue range of values. The fact that Ct and Cp exhibit a concave relationship in that region seems to point out that there could be potentially issues when performing processing with values in such regions, e.g. when filtering and downsampling two values that might be on or near the edges of this region. These values, unless some intelligent processing is considered, could potentially result in out of range values. Out of range values, could result in severe visual issues if not handled properly. This issue does not appear to exist in the CbCr case since the Cb and Cr values have a linear relationship in the boundaries (thus basic filtering would result in always in range values). This behavior seems to require more thorough analysis and evidence that no issues may arise in this region.

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| --- | --- |
|  |  |
| (a) | (b) |

Figure . BT.2020 colour values on the (a) CtCp and (b) CbCr planes

# 10 bit Quantization and ICtCp using BT.2020 colours

ICtCp claims to be able to cover all BT.2020 colours. We have performed a simple experiment where we evaluated all possible ICtCp colour value combinations in a 10-bit narrow range and tried to see which RGB values could be recreated. It should be noted that naïve clipping, applied in the RGB space is considered. The same process is also applied to the Y’CbCr NCL representation. Figure 5 shows these relationships.

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| --- | --- |
|  |  |
| (a) | (b) |

Figure . 10 bit narrow range ICtCp (a) and Y’CbCr (b) representations mapped the BT.2020 RGB space

These plots seem to suggest that although Y’CbCr seems to have a much more broad coverage within the entire range of BT.2020 colours, the ICtCp representation appears to be more sparse in some areas. This can be better seen in a projection of the plot on only two axes, e.g. Red and Green (Figure 6).

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| --- | --- |
|  |  |
| (a) | (b) |

Figure . 10 bit narrow range ICtCp (a) and Y’CbCr (b) representations   
mapped on the BT.2020 Red/Green plane

In particular, it can be observed from Figure 6a that the allocation of codewords in the ICtCp space to cover colour values that may “lack” one or two colours, and with the remaining values being primarily above the value of 1cd/m2 appear to be quite sparse. A pure red or pure green signal, for example, may end up being poorly quantized if it is within a particular range of values.

Given this observation, we then performed the following experiment. Assuming a pure primary signal, e.g. Red, Green, or Blue, in BT.2020 ranging from a value of 0 up to 10000 cd/m2, what errors would be introduced if we convert these signals to the ICtCp space and back? These errors are shown in Figure 7, Figure 8, and Figure 9 for red, green, and blue colours respectively. These errors were generated assuming that the original input used R, G, B BT.2020 data as input that were previously encoded using the PQ transfer function but in a 12-bit SDI range (as per some of our anchor sequences). The assumption is that such format will be used as the interchange file format for many applications.

It can be seen from these figures that considerable quantization errors are introduced in not only the original colours, that were originally the only ones present in the samples, but also to the other two components. Even though some error is also introduced in Y’CbCr space, given that this space is basically a linear transformation of the R’G’B’ space, the errors are considerably smaller if not negligible (Figure 10, Figure 11, and Figure 12). Essentially pure colours, after ICtCp conversion are likely not to be considered pure any more. Of considerable concern here is also what happens due 4:2:0 conversion, especially if the colour “contamination” in ICtCp space leaks into other colours. More investigation on this topic will be presented in the subsequent section.

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|  |
| (a) |
|  |
| (b) |
|  |
| (c) |

Figure . Errors introduced in RGB on a pure red signal due to the 10 bit narrow ICtCp representation

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|  |
| (a) |
|  |
| (b) |
|  |
| (c) |

Figure . Errors introduced in RGB on a pure green signal due to the 10 bit narrow ICtCp representation

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|  |
| (a) |
|  |
| (b) |
|  |
| (c) |

Figure . Errors introduced in RGB on a pure blue signal due to the 10 bit narrow ICtCp representation

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| (a) |
|  |
| (b) |
|  |
| (c) |

Figure . Errors introduced in RGB on a pure red signal due to the 10 bit narrow Y’CbCr representation

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| --- |
|  |
| (a) |
|  |
| (b) |
|  |
| (c) |

Figure . Errors introduced in RGB on a pure green signal due to the 10 bit narrow Y’CbCr representation

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| --- |
|  |
| (a) |
|  |
| (b) |
|  |
| (c) |

Figure . Errors introduced in RGB on a pure blue signal due to the 10 bit narrow Y’CbCr representation

# Test patterns: Evaluation of Different Colour Representations

Given our initial observations we created several test patterns that we felt could potentially show some of the issues that the ICtCp colour space using the 10 bit narrow range might have. It is in fact possible that these patterns might not show the worse possible artifacts that this space could introduce and we would encourage further investigation on this topic. On the other hand, these patterns might also not be so relevant for some applications and thus our observations might not be applicable or of any consequence.

Figure 14 shows some of the test patterns that we created for our evaluation. Interestingly enough, most of these patterns involve simple color ramps, as well as combinations of different colors, including hue wheels, allowing us to evaluate the behavior of a particular colour representation across the entire colour range of BT.2020 colours. These patterns are saved in EXR files and the values in them are linear light values that go from a value of 0 to 1. The value of 1 can be easily assigned to represent any brightness value, e.g. 1 could be mapped to 100, 1000, or to 10000 if desirable [14]. These patterns will be made available to the MPEG community for further testing if desired. Additional patterns were created by combining some of these patterns. Image resolutions of both 1920x1080 and 3840x2160 are provided. Of particular interest is a pattern we created by taking the different ramp images, e.g. red, blue, or green, creating a horizontally flipped version of these images, and then columnwise interleaving the two images, i.e.

newImage(2\*i, j) = red\_ramp (2\*i, j)

newImage(2\*i+1, j)=red ramp(1920-2\*i-1,j)

An example of how this pattern looks like for the blue case is shown in Figure 13. On the right side a zoom in section of this pattern is shown. These patterns were especially created to test 4:2:0 conversion issues.

It should be noted that all these images are included in the document using a power law gamma process and with a peak brightness of 100 cd/m2 and BT.709 colour primaries, and these could obviously differ considerably depending on the values that one may wish to represent for display. This visualization is provided only for reference purposes.

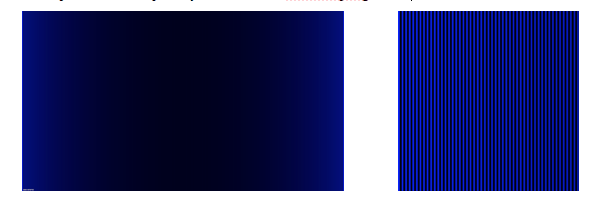


Figure . Interleaved ramp pattern. On the right, a scaled segment of this pattern is shown

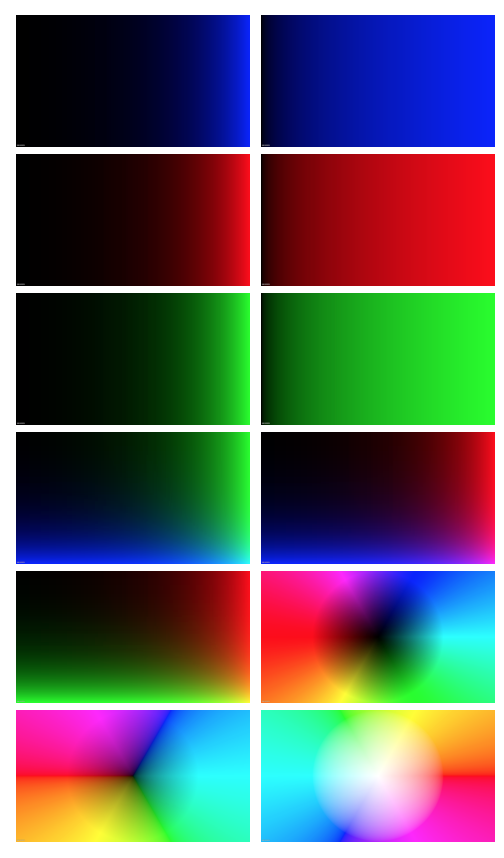


Figure . Subset of the test patterns created for this evaluation

## Conversion results using HDRTools [14]

We have evaluated these test patterns by performing the conversion from EXR RGB linear space to different representations, including basically NCL Y’CbCr, ICtCp, and Constant Luminance (CL)[[1]](#footnote-1) YclCbCr 10 bit narrow narrow and back to the original EXR RGB representation. We have evaluated also both 4:4:4 (Table 1) and 4:2:0 (Table 2)conversions. Only 1920x1080 results are included in this document since the higher resolution results were very similar. Some of the patterns, e.g. ramps of the same colour and hue wheels, are processed as sequences and only average results are reported in this document. Results for individual frames are available and can be provided. Values in some metrics that are below a certain threshold (i.e. 30dB) are especially highlighted.

Table : Test Pattern conversion performance of different 4:4:4 10 bit narrow range colour representations

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  |  | **PSNR** | | | **tPSNR** | | | | | | | | **t-oPSNR** | **DE2000** | |
|  |  | **R** | **G** | **B** | **R** | **G** | **B** | **RGB** | **X** | **Y** | **Z** | **XYZ** | **XYZ** | **DE0100** | **L0100** |
| **Y'CbCr** | blue\_mix | 263.17 | 263.17 | 58.86 | 263.17 | 263.17 | 50.43 | 55.20 | 53.57 | 55.68 | 50.47 | 52.27 | 53.05 | 21.50 | 34.77 |
| blue | 263.17 | 263.17 | 58.86 | 263.17 | 263.17 | 50.43 | 55.20 | 53.57 | 55.68 | 50.47 | 52.27 | 53.05 | 21.50 | 34.77 |
| bluexgreen | 263.17 | 58.82 | 54.46 | 263.17 | 50.11 | 47.28 | 50.02 | 55.48 | 55.04 | 51.27 | 53.38 | 55.62 | 16.99 | 23.83 |
| colorimage | 56.09 | 58.53 | 50.38 | 56.23 | 55.90 | 53.07 | 54.64 | 66.65 | 69.03 | 54.84 | 58.53 | 60.85 | 14.75 | 22.95 |
| cyan | 263.17 | 54.87 | 48.10 | 263.17 | 69.24 | 62.56 | 66.49 | 66.46 | 69.30 | 63.14 | 65.58 | 61.95 | 13.68 | 20.49 |
| green\_mix | 263.17 | 58.90 | 263.17 | 263.17 | 50.43 | 263.17 | 55.20 | 53.87 | 51.07 | 57.28 | 52.97 | 53.75 | 19.40 | 24.18 |
| green | 263.17 | 58.90 | 263.17 | 263.17 | 50.43 | 263.17 | 55.20 | 53.87 | 51.07 | 57.28 | 52.97 | 53.75 | 19.40 | 24.18 |
| magenda | 54.15 | 263.17 | 48.28 | 68.65 | 263.17 | 62.75 | 66.52 | 69.37 | 69.46 | 62.97 | 66.11 | 62.41 | 14.39 | 24.08 |
| red\_mix | 58.90 | 263.17 | 263.17 | 50.45 | 263.17 | 263.17 | 55.22 | 51.20 | 52.76 | 263.17 | 53.61 | 54.41 | 20.22 | 28.30 |
| red | 58.90 | 263.17 | 263.17 | 50.45 | 263.17 | 263.17 | 55.22 | 51.20 | 52.76 | 263.17 | 53.61 | 54.41 | 20.22 | 28.30 |
| redxblue | 58.52 | 263.17 | 54.88 | 49.55 | 263.17 | 47.28 | 49.89 | 55.05 | 56.61 | 47.28 | 50.85 | 51.31 | 17.64 | 27.43 |
| redxgreen | 56.24 | 58.34 | 263.17 | 48.07 | 49.43 | 263.17 | 50.41 | 53.80 | 54.83 | 56.40 | 54.78 | 56.07 | 16.30 | 22.78 |
| yellow | 50.17 | 53.71 | 263.17 | 64.51 | 68.23 | 263.17 | 67.75 | 66.06 | 69.37 | 69.16 | 67.92 | 63.86 | 12.24 | 19.42 |
|  | **151.69** | **152.39** | **150.22** | **151.30** | **151.75** | **150.22** | **56.69** | **57.70** | **58.67** | **88.22** | **56.53** | **56.50** | **17.56** | **25.81** |
| **ICtCp** | blue\_mix | 88.17 | 82.32 | 57.47 | 26.51 | 23.99 | 49.73 | 26.32 | 52.86 | 55.09 | 49.73 | 51.59 | 52.37 | 20.75 | 34.37 |
| blue | 88.17 | 82.32 | 57.47 | 26.51 | 23.99 | 49.73 | 26.32 | 52.86 | 55.09 | 49.73 | 51.59 | 52.37 | 20.75 | 34.37 |
| bluexgreen | 69.67 | 58.66 | 57.27 | 18.46 | 41.30 | 41.77 | 22.78 | 56.13 | 55.05 | 53.35 | 54.57 | 56.73 | 17.86 | 23.82 |
| colorimage | 52.91 | 54.81 | 53.13 | 19.26 | 25.19 | 28.26 | 22.61 | 65.39 | 66.06 | 53.93 | 57.54 | 59.47 | 14.62 | 19.85 |
| cyan | 64.41 | 54.65 | 53.51 | 15.06 | 69.16 | 67.11 | 19.83 | 68.34 | 69.35 | 67.45 | 68.31 | 64.49 | 15.49 | 20.48 |
| green\_mix | 69.95 | 58.66 | 88.36 | 18.62 | 50.40 | 26.39 | 22.52 | 52.46 | 51.12 | 55.60 | 51.88 | 52.48 | 19.10 | 24.20 |
| green | 69.95 | 58.66 | 88.36 | 18.62 | 50.40 | 26.39 | 22.52 | 52.46 | 51.12 | 55.60 | 51.88 | 52.48 | 19.10 | 24.20 |
| magenda | 54.65 | 75.31 | 53.55 | 69.12 | 18.46 | 67.76 | 23.23 | 69.22 | 69.51 | 67.99 | 68.86 | 65.16 | 15.96 | 24.13 |
| red\_mix | 58.83 | 84.26 | 102.62 | 50.34 | 23.38 | 37.04 | 27.32 | 51.10 | 52.74 | 32.81 | 34.27 | 35.86 | 20.14 | 28.35 |
| red | 58.83 | 84.26 | 102.62 | 50.34 | 23.38 | 37.04 | 27.32 | 51.10 | 52.74 | 32.81 | 34.27 | 35.86 | 20.14 | 28.35 |
| redxblue | 58.78 | 80.63 | 57.36 | 43.15 | 21.98 | 46.62 | 25.92 | 54.95 | 56.62 | 45.06 | 49.13 | 52.43 | 18.29 | 27.44 |
| redxgreen | 57.95 | 58.64 | 86.79 | 36.55 | 40.30 | 25.53 | 27.71 | 54.52 | 54.85 | 49.25 | 50.92 | 54.52 | 17.55 | 22.78 |
| yellow | 53.25 | 54.61 | 81.39 | 68.06 | 69.08 | 21.68 | 26.45 | 68.61 | 69.35 | 65.19 | 67.32 | 63.80 | 14.87 | 19.43 |
|  | **65.04** | **68.29** | **72.30** | **35.43** | **37.00** | **40.39** | **24.68** | **57.69** | **58.36** | **52.19** | **53.24** | **53.69** | **18.05** | **25.52** |
| **YclCbCr** | blue\_mix | 263.17 | 76.38 | 50.76 | 263.17 | 21.86 | 46.70 | 26.15 | 49.92 | 52.76 | 46.72 | 48.79 | 49.35 | 17.43 | 32.05 |
| blue | 263.17 | 76.38 | 50.76 | 263.17 | 21.86 | 46.70 | 26.15 | 49.92 | 52.76 | 46.72 | 48.79 | 49.35 | 17.43 | 32.05 |
| bluexgreen | 79.76 | 58.75 | 52.34 | 20.91 | 40.14 | 47.26 | 24.69 | 55.25 | 55.07 | 51.23 | 53.30 | 55.38 | 16.28 | 23.80 |
| colorimage | 51.33 | 54.24 | 49.73 | 19.45 | 19.01 | 53.38 | 20.95 | 64.78 | 66.44 | 50.80 | 54.88 | 57.66 | 12.93 | 20.42 |
| cyan | 74.64 | 54.83 | 46.41 | 16.56 | 69.20 | 61.65 | 21.33 | 66.16 | 69.39 | 62.19 | 64.94 | 61.10 | 12.59 | 20.50 |
| green\_mix | 80.30 | 58.77 | 263.17 | 21.21 | 50.51 | 263.17 | 25.52 | 53.90 | 51.16 | 57.36 | 53.03 | 53.77 | 19.33 | 24.13 |
| green | 80.30 | 58.77 | 263.17 | 21.21 | 50.51 | 263.17 | 25.52 | 53.90 | 51.16 | 57.36 | 53.03 | 53.77 | 19.33 | 24.13 |
| magenda | 49.61 | 63.19 | 49.03 | 64.85 | 16.28 | 63.01 | 21.05 | 65.46 | 66.67 | 63.41 | 64.97 | 61.38 | 13.52 | 22.80 |
| red\_mix | 54.29 | 66.39 | 263.17 | 47.85 | 16.30 | 263.17 | 20.96 | 48.80 | 51.91 | 26.42 | 30.15 | 29.17 | 16.76 | 27.69 |
| red | 54.29 | 66.39 | 263.17 | 47.85 | 16.30 | 263.17 | 20.96 | 48.80 | 51.91 | 26.42 | 30.15 | 29.17 | 16.76 | 27.69 |
| redxblue | 54.14 | 66.56 | 52.28 | 48.03 | 16.96 | 47.26 | 21.48 | 53.11 | 55.49 | 42.73 | 46.89 | 50.62 | 15.46 | 26.51 |
| redxgreen | 54.10 | 57.82 | 263.17 | 40.35 | 33.94 | 263.17 | 37.74 | 53.53 | 54.85 | 43.44 | 46.88 | 51.78 | 15.26 | 22.77 |
| yellow | 54.56 | 54.70 | 263.17 | 68.96 | 69.22 | 263.17 | 70.85 | 69.15 | 69.34 | 70.15 | 69.53 | 65.93 | 16.54 | 19.43 |
|  | **93.36** | **62.55** | **148.49** | **72.58** | **34.01** | **149.61** | **27.95** | **56.36** | **57.61** | **49.61** | **51.18** | **51.42** | **16.12** | **24.92** |

Table : Test Pattern conversion performance of different 4:2:0 10 bit narrow range colour representations

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  |  | **PSNR** | | | **tPSNR** | | | | | | | | **t-oPSNR** | **DE2000** | |
|  |  | **R** | **G** | **B** | **R** | **G** | **B** | **RGB** | **X** | **Y** | **Z** | **XYZ** | **XYZ** | **DE0100** | **L0100** |
| **Y'CbCr** | blue\_mix | 53.03 | 51.46 | 23.43 | 19.28 | 19.14 | 19.66 | 19.34 | 21.32 | 22.66 | 19.62 | 20.98 | 23.20 | 4.44 | 22.09 |
| blue | 263.17 | 263.17 | 58.79 | 263.17 | 263.17 | 48.49 | 53.26 | 52.43 | 54.92 | 48.42 | 50.87 | 52.98 | 21.49 | 34.75 |
| bluexgreen | 263.17 | 58.81 | 54.51 | 263.17 | 43.50 | 41.29 | 43.89 | 55.38 | 55.04 | 50.38 | 52.81 | 55.64 | 17.09 | 23.83 |
| colorimage | 55.81 | 58.38 | 49.37 | 46.06 | 44.52 | 44.98 | 45.10 | 65.37 | 68.90 | 48.22 | 52.73 | 60.27 | 14.83 | 22.96 |
| cyan | 263.17 | 54.87 | 48.04 | 263.17 | 69.32 | 62.39 | 66.36 | 66.39 | 69.38 | 62.96 | 65.47 | 61.98 | 13.71 | 20.50 |
| green\_mix | 44.43 | 48.49 | 44.43 | 18.66 | 44.11 | 18.70 | 20.39 | 44.05 | 44.91 | 36.71 | 39.41 | 45.73 | 13.21 | 24.04 |
| green | 263.17 | 58.97 | 263.17 | 263.17 | 50.40 | 263.17 | 55.17 | 53.84 | 51.04 | 57.26 | 52.94 | 53.72 | 19.44 | 24.23 |
| magenda | 54.12 | 263.17 | 48.38 | 68.12 | 263.17 | 61.80 | 65.66 | 69.05 | 69.23 | 61.97 | 65.33 | 62.27 | 14.42 | 24.08 |
| red\_mix | 36.30 | 45.73 | 51.35 | 25.60 | 18.69 | 19.12 | 20.10 | 26.11 | 27.24 | 18.93 | 22.21 | 24.51 | 10.34 | 23.23 |
| red | 58.98 | 263.17 | 263.17 | 50.22 | 263.17 | 263.17 | 54.99 | 50.99 | 52.61 | 263.17 | 53.43 | 54.33 | 20.23 | 28.32 |
| redxblue | 58.53 | 263.17 | 55.01 | 43.50 | 263.17 | 41.31 | 43.90 | 55.04 | 56.60 | 41.18 | 45.55 | 50.81 | 17.69 | 27.43 |
| redxgreen | 56.46 | 58.39 | 263.17 | 43.28 | 41.42 | 263.17 | 43.91 | 53.75 | 54.82 | 51.40 | 51.93 | 55.87 | 16.54 | 22.78 |
| yellow | 50.20 | 53.73 | 263.17 | 64.52 | 68.24 | 263.17 | 67.75 | 66.08 | 69.38 | 69.16 | 67.93 | 63.89 | 12.25 | 19.44 |
|  | **116.96** | **118.58** | **114.31** | **110.15** | **111.69** | **108.49** | **46.14** | **52.29** | **53.59** | **63.80** | **49.35** | **51.17** | **15.05** | **24.44** |
| **ICtCp** | blue\_mix | 46.54 | 41.00 | 21.88 | 12.25 | 12.39 | 31.59 | 13.83 | 35.73 | 39.32 | 31.86 | 34.59 | 34.86 | 4.41 | 21.02 |
| blue | 88.32 | 82.25 | 57.45 | 26.59 | 24.03 | 45.07 | 26.36 | 49.57 | 52.53 | 44.94 | 47.80 | 52.10 | 20.77 | 34.37 |
| bluexgreen | 69.81 | 58.67 | 57.34 | 18.73 | 40.02 | 38.24 | 23.01 | 56.13 | 55.04 | 52.77 | 54.33 | 56.75 | 17.92 | 23.82 |
| colorimage | 52.78 | 54.78 | 53.00 | 19.48 | 25.41 | 28.60 | 22.84 | 65.02 | 65.99 | 47.24 | 51.75 | 59.05 | 14.69 | 19.84 |
| cyan | 64.40 | 54.64 | 53.50 | 15.06 | 68.28 | 66.41 | 19.83 | 65.29 | 69.18 | 66.68 | 66.77 | 64.26 | 15.49 | 20.48 |
| green\_mix | 31.72 | 35.79 | 32.80 | 10.39 | 46.00 | 11.36 | 12.60 | 37.78 | 49.46 | 28.68 | 32.83 | 34.31 | 7.16 | 18.54 |
| green | 69.95 | 58.68 | 88.34 | 18.64 | 49.86 | 26.44 | 22.54 | 49.72 | 51.06 | 50.02 | 47.76 | 52.20 | 19.11 | 24.21 |
| magenda | 54.66 | 75.30 | 53.56 | 65.66 | 18.47 | 62.79 | 23.24 | 65.98 | 69.23 | 62.88 | 65.29 | 64.91 | 15.97 | 24.14 |
| red\_mix | 27.18 | 36.28 | 40.79 | 39.14 | 11.32 | 11.86 | 13.32 | 40.50 | 46.12 | 11.67 | 16.41 | 15.02 | 5.79 | 24.26 |
| red | 58.82 | 84.22 | 101.79 | 47.68 | 23.38 | 36.37 | 27.30 | 48.68 | 50.78 | 32.55 | 34.23 | 35.82 | 20.14 | 28.35 |
| redxblue | 58.79 | 80.87 | 57.42 | 40.61 | 22.32 | 38.39 | 26.19 | 54.93 | 56.62 | 38.29 | 42.70 | 51.36 | 18.32 | 27.44 |
| redxgreen | 57.99 | 58.66 | 87.04 | 36.39 | 38.29 | 25.90 | 27.97 | 54.50 | 54.85 | 48.40 | 50.19 | 54.53 | 17.64 | 22.78 |
| yellow | 53.24 | 54.61 | 81.40 | 67.97 | 69.05 | 21.71 | 26.48 | 68.53 | 69.36 | 54.35 | 58.83 | 63.27 | 14.87 | 19.43 |
|  | **56.48** | **59.67** | **60.49** | **32.20** | **34.52** | **34.21** | **21.96** | **53.26** | **56.12** | **43.87** | **46.42** | **49.11** | **14.79** | **23.74** |
| **YclCbCr** | blue\_mix | 61.59 | 42.16 | 20.71 | 20.53 | 11.60 | 30.29 | 15.62 | 32.67 | 39.31 | 30.51 | 32.85 | 32.47 | 3.40 | 31.43 |
| blue | 263.17 | 76.36 | 50.76 | 263.17 | 21.91 | 44.39 | 26.18 | 48.43 | 51.41 | 44.30 | 46.92 | 49.15 | 17.45 | 32.07 |
| bluexgreen | 79.76 | 58.76 | 52.51 | 20.91 | 38.64 | 40.47 | 24.69 | 55.26 | 55.05 | 50.19 | 52.66 | 55.47 | 16.46 | 23.80 |
| colorimage | 51.27 | 54.21 | 49.76 | 19.45 | 19.05 | 45.06 | 20.97 | 64.00 | 66.31 | 46.64 | 51.16 | 57.31 | 13.08 | 20.42 |
| cyan | 74.64 | 54.83 | 46.41 | 16.56 | 69.21 | 61.49 | 21.33 | 66.06 | 69.38 | 62.00 | 64.80 | 61.04 | 12.59 | 20.50 |
| green\_mix | 46.74 | 49.83 | 46.42 | 15.01 | 50.27 | 18.78 | 17.92 | 48.09 | 51.15 | 37.87 | 41.62 | 47.44 | 13.64 | 24.13 |
| green | 80.30 | 58.77 | 263.17 | 21.21 | 50.50 | 263.17 | 25.52 | 53.89 | 51.15 | 57.36 | 53.03 | 53.77 | 19.33 | 24.13 |
| magenda | 49.61 | 63.19 | 49.03 | 62.03 | 16.28 | 60.93 | 21.05 | 62.84 | 66.18 | 61.18 | 62.94 | 61.10 | 13.52 | 22.79 |
| red\_mix | 26.85 | 35.24 | 52.17 | 39.31 | 11.02 | 19.38 | 15.09 | 40.31 | 46.13 | 16.81 | 21.53 | 20.72 | 4.99 | 26.29 |
| red | 54.26 | 66.42 | 263.17 | 46.35 | 16.32 | 263.17 | 20.97 | 47.37 | 50.12 | 26.44 | 30.15 | 29.18 | 16.76 | 27.69 |
| redxblue | 54.17 | 66.62 | 52.42 | 42.59 | 17.08 | 40.47 | 21.60 | 53.11 | 55.50 | 40.12 | 44.43 | 50.20 | 15.56 | 26.54 |
| redxgreen | 54.24 | 57.87 | 263.17 | 40.10 | 34.03 | 263.17 | 37.79 | 53.55 | 54.85 | 43.59 | 47.01 | 51.96 | 15.47 | 22.77 |
| yellow | 54.56 | 54.70 | 263.17 | 68.92 | 69.23 | 263.17 | 70.83 | 69.12 | 69.33 | 70.16 | 69.51 | 65.92 | 16.54 | 19.43 |
|  | **73.17** | **56.84** | **113.30** | **52.01** | **32.70** | **108.76** | **26.12** | **53.44** | **55.84** | **45.17** | **47.59** | **48.90** | **13.75** | **24.77** |

Interestingly enough, the NCL Y’CbCr representation, using 4:4:4 sampling, seems to exhibit the best performance given these measurements. Its performance does drop, as expected in the “mixed” sequences that we created, and especially on the blue\_mix and red\_mix sequences. However, visual inspection of these images on both a Sim2 display and a Sony BVMX300 suggested that the results we were seeing on those images were far less objectionable than in the ICtCp case in which more objectionable color shifts were observed. These results for the blue mix are shown in Figure 15 through Figure 18 (it should be noted that these images were compressed and scaled for the purpose of including them in this document)



Figure . Original blue mix frame



Figure . Y’CbCr 4:2:0 10 bit converted



Figure . ICtCp 4:2:0 10 bit converted



Figure . YclCbCr 4:2:0 10 bit converted

We have evaluated all of these images on both a Sim2 and a Sony BVM X300 monitor, which is a professional OLED monitor. Both of these displays have several limitations that should be highlighted since they may have had a considerable impact in our evaluation. Unfortunately, these were the only displays available to us and thus we would encourage other people interested in this area that may have better displays or interfaces to also evaluate our results. More specifically the limitations we encountered with these displays are as follows:

Sim2:

* This is a BT.709 colour gamut limited display. All values outside BT.709 are clipped thus a lot of the colours that we care about and seem to be impacted by these conversions are likely not rendered properly on this display.
* The display uses a 4:2:2 Lu’v’ interface with rather basic processing for the chroma conversion. That also introduces additional distortions in the signal.
* The panel is an 8-bit panel for both the LCD and the backlight LED. Also, only 2202 white LEDs are used, which further impact colour accuracy.
* There are severe homogeneity issues with this display.
* The display is also limited to 4000 cd/m2. Values outside that range are again clipped

Sony BVM X300

* This is a P3 colour gamut limited display. Similar to the Sim2 display, values outside its intended gamut are somehow clipped.
* Our current interface for driving the display is limited to a 4:2:2 Y’CbCr 10-bit interface. This would obviously bias everything towards Y’CbCr. We do plan in the future to upgrade the interface to a 4:4:4 R’G’B’ interface, but that is not possible for us currently
* The display is also limited to ~1000 cd/m2. Some processing seems to be performed when values in the signal exceed this range.

Given the rather considerable limitations of the two displays, these are our observations, which, given especially the interface issues with the Sony BVM X300, should be taken with a grain of salt.

In particular, we think that the Sim2 is an inappropriate display to be used for such tests and especially given the colour gamut of the display. Although some banding was visible especially in the hue color wheels, the display was clipping and thus hiding a considerable amount of colours.

On the other hand, the Sony BVM X300 was a much more interesting and possibly reliable platform to use for our evaluations, regardless of the interface used. We should highlight though that some of the artifacts that we were seeing were likely enhanced by the 4:2:2 Y’CbCr conversion, which itself likely introduces further chroma leakage. Our evaluations need to certainly be repeated with a 4:4:4 RGB display that can also handle a wider colour gamut and brightness.

In particular, on the Sony monitor, we observed much more considerable banding on the signals that were processed using ICtCp than any of the YCbCr signals. The YclCbCr representation also exhibited considerable banding but somewhat less objectionable than ICtCp. Colour shifts were also observed on the special patterns that we created. These artifacts are in fact are also visible if one opens these files on an SDR display and using an SDR player. Again though there are no guarantees that these artifacts are not created by our display’s interface. Regardless, there is an indication that this colour representation should be more carefully examined and may have its own limitations. It should also be noted that this colour representation did not perform any better than the YclCbCr representation either[[2]](#footnote-2) . Banding was especially objectionable in blue values.

# Image Blending

It has been claimed that ICtCp might also have better properties than Y’CbCr also for blending applications. Given some of our observations about colour leakage when dealing with primary colours, we created a blended sequences using the primary colour ramps that we presented in Figure 14. Linear blending was basically performed from the horizontally flipped version of this image to the original image in ICtCp space, using 10% increments. This process was performed in 4:4:4 and no impact of downsampling in the blending process was considered.

Unfortunately, and in our own subjective opinion, we found that the visual result, when looked on the Sony display, was rather objectionable. This creates a concern for us on whether this space is a better space to perform blending, as was claimed, especially when blending may involve graphics/captions that might more likely have the properties of the signals tested.

# Conclusion

In this document we presented some observations and analysis of different colour representations, including the NCL Y’CbCr, ICtCp, and CL YclCbCr representations. Our analysis was done using appropriately created test patterns that try to cover as much as possible of the BT.2020 colour gamut, given our observations that most tests conducted used content with rather limited characteristics. There are some indications that the ICtCp space when used in combination with the 10-bit narrow representation may, in fact, have some limitations. It is also not clear what advantages this may provide versus the Constant Luminance representation, especially if one of the main features of this representation is chroma leakage. In some cases it also appears that the NCL Y’CbCr representation may perform better than ICtCp. Further investigation on the behavior of this representation, that should also include more appropriate methods of visualization, is strongly encouraged.

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# Patent rights declaration

**Apple, Inc. does not have any current or pending patent rights relating to the technology described in this contribution.**

1. We should point out that we have some dislike on the CL representation given the additional non-linearity introduced in the two chroma components at point 0 [5][7][8]. This likely was done to maximize the coverage of the Cb and Cr components, however it introduces an extra non-linearity that could be impacting processing. A potentially better conversion would have been to compute the maximum scaling factor among the scaling factors that are currently used, and use that factor for all values [↑](#footnote-ref-1)
2. There are some indications that higher bitdepth is required for both of these representations. [↑](#footnote-ref-2)