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(01/2019)

Objective metric for the assessment of the potential visibility of colour differences in television

BT Series

Broadcasting service (television)

International Telecommunication Union

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RECOMMENDATION ITU-R BT.2124-0

Objective metric for the assessment of the potential visibility of colour differences in television

(2019)

Scope

This Recommendation defines an objective colour difference metric that is suitable for use in assessing the potential visibility of small colour differences in television images and signals. To do this, it presumes a state of viewer adaptation that is most sensitive for the colour being evaluated. Applications include, but are not limited to, display calibration, camera and display characterization, and objective assessment of differences introduced by signal processing techniques.

Keywords

Calibration, metric, measurement, colour, HDR, HDR-TV, IC_TC_P

The ITU Radiocommunication Assembly,

considering

a) that colour fidelity is an important parameter of television systems and equipment;

b) that subjective evaluations of colour fidelity are complex and time consuming;

c) that an objective measure, or metric, of small colour differences that correspond to subjective perception would facilitate evaluation of television systems and equipment;

d) that existing colour difference metrics assume a state of viewer adaptation (e.g. white point, illumination level, viewing environment etc.);

e) that with television the state of viewer adaptation is variable and often not known;

f) that it is desirable to have a metric that indicates the potential perceptibility of colour differences,

recommends

that a colour difference metric, ΔE_{ITP}, for the assessment of the potential visibility of colour differences in television images and signals, should be calculated as described in Annex 1.

Annex 1
(normative)

Objective colour difference metric ΔE_{ITP}

1 Introduction

The ΔE_{ITP} metric defined in this Recommendation provides an objective assessment of whether the difference between two colours may be visible. For convenience, ΔE_{ITP} is scaled so that a value of 1 indicates the potential of a just noticeable colour difference. To ensure that this metric will not under-predict colour differences, ΔE_{ITP} presumes the most sensitive state of adaptation. Although this means that the ΔE_{ITP} metric will not under-predict perceived colour differences, it may over-predict them.

The ΔE_{ITP} colour difference metric is derived from display referenced IC_TC_P. The definition of IC_TC_P is given normatively in Table 7 of Recommendation ITU-R BT.2100, and is reproduced in this Recommendation for convenience. For other signal representations, including XYZ, refer to informative Annex 2 for conversion to RGB. An alternative metric for scene-referred relative signals is given in informative Annex 3. An example of use in display calibration and characterization is given in informative Annex 4.

2 Calculation of ΔE_{ITP}

Step 1: Convert display-referred linear R, G, B (in accordance with Table 10 of Recommendation ITU-R BT.2100) to linear L, M, S (in accordance with Table 7 of Recommendation ITU-R BT.2100):

$$L = (1688R + 2146G + 262B)/4096$$

$$M = (683R + 2951G + 462B)/4096$$

$$S = (99R + 309G + 3688B)/4096$$

Step 2: Convert linear L, M, S to non-linear L', M', S' by applying the PQ non-linearity defined in Table 4 of Recommendation ITU-R BT.2100:

$$\{L', M', S'\} = EOTF^{-1}(F)$$

where:

$$F = \{L, M, S\}$$

$$EOTF^{-1}(F) = \left(\frac{c_1 + c_2 Y^{m_1}}{1 + c_3 Y^{m_1}}\right)^{m_2}$$

$$Y = F / 10000$$

$$m_1 = 2610/16384 = 0.1593017578125$$

$$m_2 = 2523/4096 \times 128 = 78.84375$$

$$c_1 = 3424/4096 = 0.8359375 = c_3 - c_2 + 1$$

$$c_2 = 2413/4096 \times 32 = 18.8515625$$

$$c_3 = 2392/4096 \times 32 = 18.6875.$$

Step 3: Convert non-linear L', M', S' to I, C_T, C_P as defined in Table 7 of Recommendation ITU-R BT.2100:

$$I = 0.5L' + 0.5M'$$

C_T = $(6610L' - 13613M' + 7003S')/4096$

C_P = $(17933L' - 17390M' - 543S')/4096$

Step 4: Scale IC_TC_P to create ITP:

$I = I$

$T = 0.5 \times C_T$

$P = C_P$

Step 5: Calculate ΔE_{ITP}:

$$\Delta E_{ITP} = 720 \times \sqrt{(I_1 - I_2)^2 + (T_1 - T_2)^2 + (P_1 - P_2)^2}$$

where I, T, and P are a scaled version of colour components for a television signal expressed in the PQ system defined in Table 7 of Recommendation ITU-R BT.2100; subscripts 1, and 2, indicate two signals to be compared; a value of 1 is equivalent to a just noticeable difference when viewed in the most critical adaptation state.

Annex 2
(informative)

Conversion to display-referred linear RGB in accordance with the specifications contained in Recommendation ITU-R BT.2100

This informative Annex describes conversion from several commonly used colour representations to the display-referred linear RGB used in calculating the ΔE_{ITP} colour difference.

Conversion 1: CIE 1931 X, Y, Z to display-referred linear R, G, B

Linear XYZ values are often reported when measuring physical displays using an imaging colorimeter. These can be converted to display-referred RGB following the conversion steps below. The result can then be used as input to step 1 of Annex 1. Note that this operation can be combined with the operation to linear L, M, S in step 1 of Annex 1 for efficient computation.

$R = 1.7167X - 0.3557Y - 0.2534Z$

$G = -0.6667X + 1.6165Y + 0.0158Z$

$B = 0.0176X - 0.0428Y + 0.9421Z$

Conversion 2: Digital IC_TC_P colour representation

The IC_TC_P colour representation can be used for calculating ΔE_{ITP} after undoing the digital range scaling and then proceeding directly to step 4 of Annex 1. The conversion depends on the bit depth and the narrow or full range digital representation, as described in Table 9 of Recommendation ITU-R BT.2100.

Full Range

$I = I_D / (2^n - 1)$

$C_T = (C_{TD} - 2^{n-1}) / (2^n - 1)$

$C_P = (C_{PD} - 2^{n-1}) / (2^n - 1)$

Narrow Range

$I = ((I_D / 2^{n-8}) - 16) / 219$

$C_T = ((C_{TD} / 2^{n-8}) - 128) / 224$

$C_P = ((C_{PD} / 2^{n-8}) - 128) / 224$

where:

n is bit depth

$\{I_D, C_{TD}, C_{PD}\}$ are the digital representations of the IC_TC_P colour representation.

Conversion 3: Digital BT.2100 PQ RGB colour representation to display-referred linear R, G, B

The digital PQ RGB colour representation can be converted to display-referred linear RGB by following the conversion steps below. The conversion depends on the bit depth and the narrow or full range digital representation. The result can then be used as input to step 1 of Annex 1. This follows the process described in Table 4 of Recommendation ITU-R BT.2100.

$$E' = \begin{Bmatrix} E'_D/(2^n - 1) & \mathit{Full\ Range} \\ \left((E'_D/2^{n-8}) - 16\right)/219 & \mathit{Narrow\ Range} \end{Bmatrix}$$

where n is bit depth.

$\{R, G, B\} = EOTF(E')$

where:

$E' = \{R', G', B'\}$ the normalized non-linear signals.

$$EOTF(E') = 10\,000 * \left(\frac{\max\left[E'^{1/m_2} - c_1, 0\right]}{c_2 - c_3 E'^{1/m_2}}\right)^{1/m_1}$$

$m_1 = 2610/16384 = 0.1593017578125$

$m_2 = 2523/4096 \times 128 = 78.84375$

$c_1 = 3424/4096 = 0.8359375 = c_3 - c_2 + 1$

$c_2 = 2413/4096 \times 32 = 18.8515625$

$c_3 = 2392/4096 \times 32 = 18.6875$

Conversion 4: Digital BT.2100 HLG RGB colour representation to display-referred linear R, G, B

The digital HLG RGB colour representation can be converted to display-referred RGB by following the conversion steps below. The conversion depends on the bit depth and the narrow or full range digital representation. The conversion assumes a 1 000 cd/m^2 peak luminance display with user gain set to 1.0 and user black level lift set to 0.0. The result can then be used as input to step 1 of Annex 1. This follows the process described in Table 5 of Recommendation ITU-R BT.2100.

$$E' = \begin{Bmatrix} E'_D/(2^n - 1) & \mathit{Full\ Range} \\ \left((E'_D/2^{n-8}) - 16\right)/219 & \mathit{Narrow\ Range} \end{Bmatrix}$$

where n is bit depth.

$\{R, G, B\} = EOTF(E')$

where:

$E' = \{R', G', B'\}$ the normalized non-linear signals.

$EOTF(E') = OOTF(OETF^{-1}(E'))$

$$OETF^{-1}(x) = \begin{Bmatrix} x^2/3 & 0 \leq x \leq 1/2 \\ \left\{\exp\left((x-c)/a\right)+b)\right\}/12 & 1/2 < x \leq 1 \end{Bmatrix}$$

$$OOTF(x) = L_W . Y_S^{\gamma-1} x$$

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

$\{R_S, G_S, B_S\} = OETF^{-1}(E')$

$L_W = 1\,000$ cd/m^2

$\gamma = 1.2$

$a = 0.17883277$

$b = 1 - 4a$

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

Conversion 5: Digital BT.1886 RGB colour representation to display-referred linear R, G, B

The digital BT.709 RGB colour representation can be converted to display-referred Recommendation ITU-R BT.2100 linear RGB by following the conversion steps below. The conversion depends on the bit depth. Typically a value of $L_W = 100$ cd/m^2 would be used (per Recommendation ITU-R BT.2035), with the black level value 'b' set to 0.0. The result can then be used as input to step 1 of Annex 1. This employs the EOTF specified in Annex 1 of Recommendation ITU-R BT.1886.

$E' = \left((E'_D/2^{n-8}) - 16\right)/219$ *Narrow Range*

where n is bit depth.

$\{R_{709}, G_{709}, B_{709}\} = EOTF(E')$

$R_{2100} = 0.6274R_{709} + 0.3293G_{709} + 0.0433B_{709}$

$G_{2100} = 0.0691R_{709} + 0.9195G_{709} + 0.0114B_{709}$

$B_{2100} = 0.0164R_{709} + 0.0880G_{709} + 0.8956B_{709}$

where:

$E' = \{R', G', B'\}$ are the normalized non-linear signals.

$EOTF(E') = L_W \times E'^{2.4}$

Annex 3
(informative)

Relative colour fidelity using HLG and the ΔITP_R metric

The ΔE_{ITP} metric defined and described in Annex 1 provides an indication of the perceptual difference between two signals if they were displayed on a perfect display. The metric cannot be directly applied to scene-referred relative signals that do not explicitly define a peak luminance at which the signal should be displayed. For scene-referred signals ΔE_{ITP} can only be applied when a nominal peak display luminance is assumed. At other peak display luminances, the metric only provides an ordinal measure of distortion.

In some applications, for example evaluation of encoding quantization spacing in HLG, it may be simpler to calculate an alternative metric based on relative HLG IC_TC_P, as defined in Table 7 of Recommendation ITU-R BT.2100. Due to the difference in scaling compared to PQ IC_TC_P, T and P for the relative metric is calculated as follows:

$$I = I$$

$$T = 0.5 \times 1.823698 \times C_T$$

$$P = 1.887755 \times C_P$$

This relative metric provides an ordinal measure of perceptual difference for scene referred signals. The Euclidean distance in this ITP space represents the magnitude of the colour difference, and is designated ΔITP_R.

This ΔITP_R metric is more analogous to the PSNR metric used to determine quantization spacing in video coding. However, it has the twin advantages that it provides better correlation with perceptual differences and simultaneously takes account of colour and luminance.

Annex 4
(informative)

Application of ΔE_{ITP} to evaluate colour fidelity

1 Evaluation of display colour accuracy

When characterizing a display, a typical measurement instrument is a colorimeter which reports measurements in either XYZ or xyY chromaticity. This example will assume XYZ measurements.

The accuracy of a display at reproducing the Rec. ITU-R BT.2111 colour bar pattern can be obtained by measuring, to start, the bottom right corner of the pattern (58%PQ BT.709 blue). The expected value can be calculated as follows:

1 Take the 10-bit full range code values that correspond to the blue patch (these can be found in Recommendation ITU-R BT.2111): [296, 201, 582];

2 Normalise the code values by dividing by 1023: [0.2893, 0.1964, 0.5689];

3 Convert to linear RGB using the PQ EOTF: [8.753, 2.291, 181.3];

4 Convert to ITP as described in Annex 1. The ITP value for the 58% PQ BT.709 blue is thus: [0.3554, 0.1346, −0.1613].

2 Colour difference calculation

Supposing that the colorimeter returns XYZ tristimulus values of [36, 15, 190], the XYZ values can be converted to ITP by following the XYZ to RGB conversion given in Annex 2, and then following the steps in Annex 1. Doing this yields values of [0.3568, 0.1321, −0.1629].

The colour difference can be calculated using the ΔE_{ITP} equation:

$$\Delta E_{ITP} = 720 \times \sqrt{(0.3554 - 0.3568)^2 + (0.1346 - 0.1321)^2 + \left((-0.1613) - (-0.1629)\right)^2}$$
$$\Delta E_{ITP} = 2.363$$

For display calibration, two significant digits is often enough precision, so the answer can be rounded to 2.4. This value of 2.4 means the difference between what was expected and what the display produced would be visible under a critical adaptation condition. In practice, a tolerance below 3 may be an acceptable level of accuracy for a reference display. However, the appropriate tolerance may vary significantly between applications.

Some displays may produce colours outside of the Recommendation ITU-R BT.2100 colour gamut. In this case, the XYZ to RGB conversion may produce negative numbers. ITP is still able to represent these colours. So, if measuring colour fidelity of these out of gamut colours is desired, the negative numbers should not clamp throughout the conversion to ITP.

3 Evaluation of the effect of signal processing on colour accuracy

Supposing that a display referred signal is processed and small colour errors are introduced, and it is desired to quantify the subjective effect of those colour errors, the input and output pixel values would be converted into the ITP domain using the PQ non-linearity, and ΔE_{ITP} would then be calculated to determine the magnitude of the subjective colour error. A value of $\Delta E_{ITP} > 1$ indicates the colour error may be perceptible.

As ITP can represent colours beyond Recommendation ITU-R BT.2100, it may be desired to constrain the ITP signal to the Recommendation ITU-R BT.2100 colour volume. This ensures that the ΔE_{ITP} values are representative of the displayed signal on a Recommendation ITU-R BT.2100 reference monitor. To constrain the signal, the ITP values would first be converted to RGB, negative values would be clamped to zero, and then it would be converted back to ITP.