EBU

OPERATING EUROVISION AND EURORADIO

Tech 3325

METHODS FOR THE MEASUREMENT OF THE PERFORMANCE OF STUDIO MONITORS

SOURCE: VIDEO SYSTEMS

Version 2.0

Geneva
January 2022

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Contents

Acknowledgements

Although this document is the result of much collaborative work within the EBU's Video Systems group, it would not have seen the light of day without the skill and dedication of Dagmar Driesnack, Richard Salmon, and Birgit Schmidt-Sodingen, who we gratefully thank for their contributions.

Methods for the Measurement of the performance of Studio Monitors

EBU Committee	First Issued	Revised	Re-issued
TC	2008	2022	

Keywords: Professional Video Monitor, Performance Measurement, SDR, HDR, HLG, PQ

Introduction

For the purposes of specifying and assessing the performance of a television picture monitor, it is necessary to measure or otherwise identify its key characteristics.

This document describes measurement methods and procedures for High Definition and Ultra-High-Definition[1] video monitors used in broadcast environments[2]. The measurement methods and procedures are independent of the classification of video monitors, and their application areas in television production. § 2 deals with Standard Dynamic Range (SDR) displays, while § 3 is dedicated to High Dynamic Range (HDR) displays.

This document addresses professional HDR video monitors and as such expects the display under test to ignore any associated metadata used to adjust the visual appearance of the image. Trade names used for such metadata include HDR10, HDR10+, Dolby Vision and SL-HDR. It is acceptable for monitors to switch transfer function based on payload signalling in e.g., SDI or SMPTE ST-2110.

This document defines test patterns and usage descriptions to allow testing of reference monitors as defined in Tech 3320 v4.1 [1]. EBU Members or other measurement organisations may decide to only undertake a subset of these tests, however:

1. Any report produced shall describe the limitations of the testing, including any tests not undertaken;
2. A limited test shall not be used to assign EBU Grade status to a product.

Warning: *Some of the tests described in this document carry with them the possibility of damage to the equipment being tested. Users should seek confirmation from manufacturers that they consent to these tests being applied to their products. The EBU accepts no responsibility should any test cause damage to equipment, regardless of the testing method (this includes image retention).*

Modern monitors have been known to display image retention artefacts, especially where large contrast ratios are encountered. To reduce the risks of such artefacts the length of time that test images are displayed should be limited and a resetting image of mid grey or random noise should be used. Suggested durations for the use of such images are provided in Table 1.

[1] A glossary of commonly (mis)used UHDTV terminology is available at: https://tech.ebu.ch/uhdtv/glossary

[2] Procedures for Standard Definition can be found in EBU Tech 3325, version 1.0 (September 2008).

Table 1: Suggested test and 'reset' image display durations to help reduce the risk of image retention.

Monitor Type	Maximum Test Image Display	Minimum "Resetting" Image Display
HDR	2 mins	1 min
SDR	5 mins	1 min

Signal level definitions as defined and restricted by the SDI interface:

"Peak White" for a 10-bit digital video signal (nominal video range) is code value (CV) 940 for the digital luma level and 512 for the digital chroma level (i.e., R=G=B=940).

"Super White" (109% white), for a 10-bit digital video signal (nominal video range), is 1019 for the luma level and 512 for the chroma level (i.e., R=G=B=1019).

Black level is a 10-bit digital signal level of 64 for the luma and of 512 for the chroma (i.e., R=G=B=64).

50% signal level is defined in 10-bit digital representation as luma 502, chroma 512 (or R=G=B=502).

Further signal level definitions are given in EBU R 103 [2].

Checking two sample interleave connections

When two sample Interleave is used, EBU Tech 3373 [3] should be used to ensure that the quad 3G-SDI cabling has been connected correctly.

Expected monitor output

The expected values of L, u' and v' in this publication have been calculated from the 10-bit quantized D'_Y, D'_{CB}, D'_{CR} code values, with high accuracy (see Annex 3 for the details). The expected values have subsequently been rounded to 3 (for L) and 4 (for u', v') decimal places, in line with the measurement accuracy of commonly used spectroradiometers.

The quantized nature of the code values and the rounding of the expected L, u', and v' mean the expected values may not be the same as the ideal values. Also note that due to the rounding alone, the L, u', v' values may not be accurate enough to make the reverse calculation result in the original D'_Y, D'_{CB}, D'_{CR}. Finally note the expected L, u', v' may differ from the previous version of this publication because of differences in the accuracy used for the calculations and representation.

8-bit signal generators

If an 8-bit signal generator is used to perform measurements, the target values of L, u' and v' need to be recalculated, as they generally will differ from the values calculated from 10-bit quantized D'_Y, D'_{CB}, D'_{CR}. Where an 8-bit generator is used, this must be shown in the measurement report.

Note that luminance ramps must always be used in at least 10-bits.

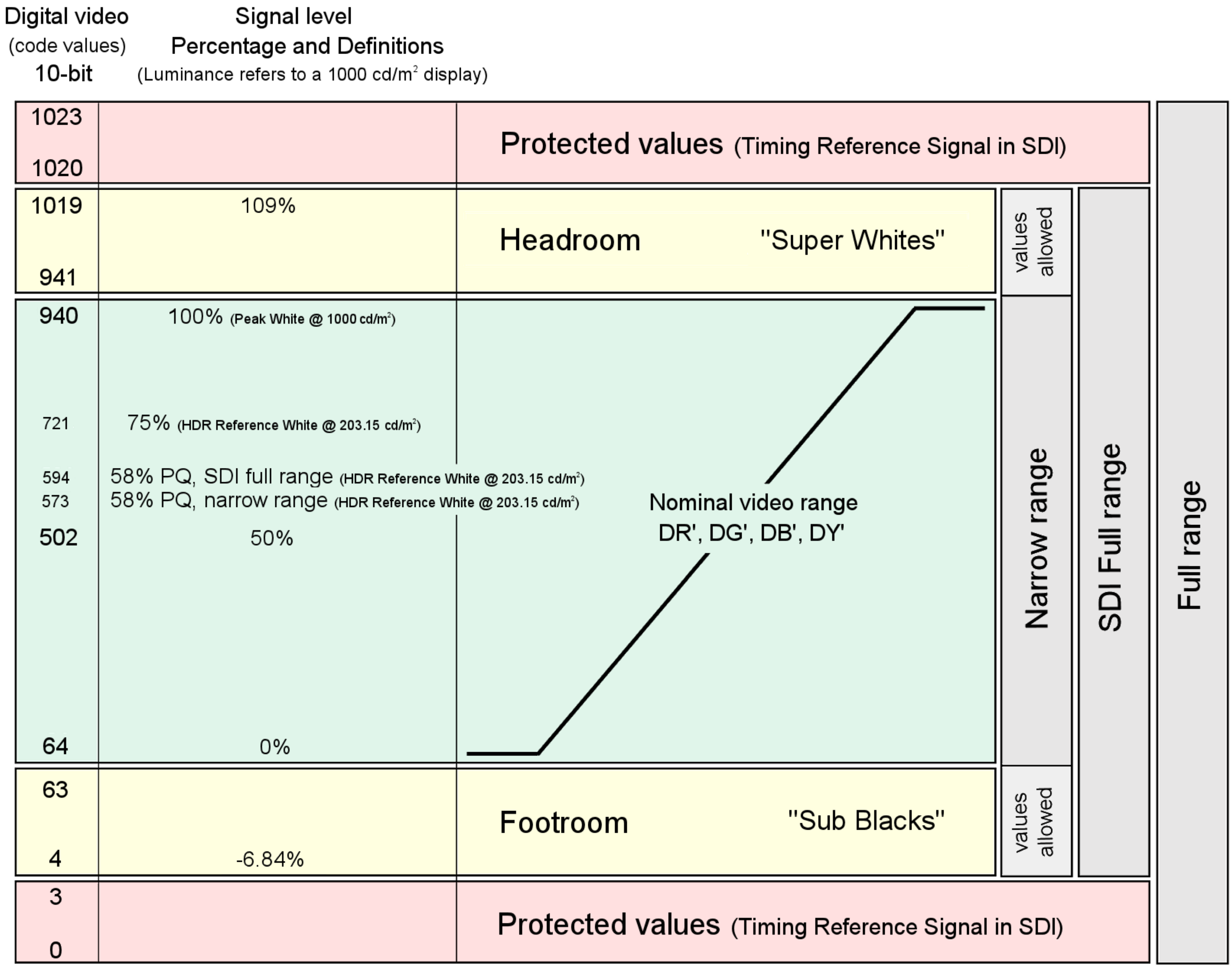


Figure 1: Signal level definitions according to EBU R 103

1. Procedures

1.1 Measurement conditions and precautions

Several methods have been developed for the measurement of a light source. It is sufficient to select suitable methods that can be applied to the particular characteristics of a picture monitor that has a discontinuous light output by reason of the scanning process and the nature of the spectral and temporal characteristics of the phosphor or other light source.

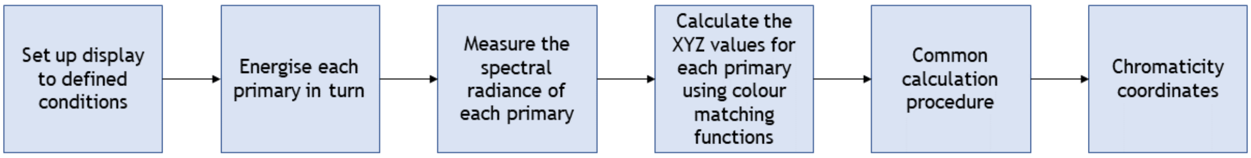


Figure 2: The main steps of a chromaticity coordinates measurement procedure

1.1.1 Suitable measuring techniques

All techniques involve measuring, wavelength-by-wavelength (λ), the light energy coming from the monitor. The spectral power distribution thus obtained (Pi), may be converted to tristimulus values by multiplying it by each of the colour matching functions ($\bar{x}, \bar{y}, \bar{z}$) in turn and integrating the resultant curves. Chromaticity coordinates may then be obtained by normalisation.

The colour matching functions, representing the amount of each CIE XYZ primary required to match the individual wavelengths in the colour under test are shown in Figure 1. They are the results of measurement of the colour vision of numbers of observers by Wright and others before 1931 and were accepted by the CIE as the definition of the CIE 2°Standard Observer; they are thus uniquely defined and provide the only basis for an objective measurement system.

In recent years spectroradiometers have been preferred for this work. If a Tristimulus Meter is used, one should be certain that the meter is accurate enough to measure the device under test.

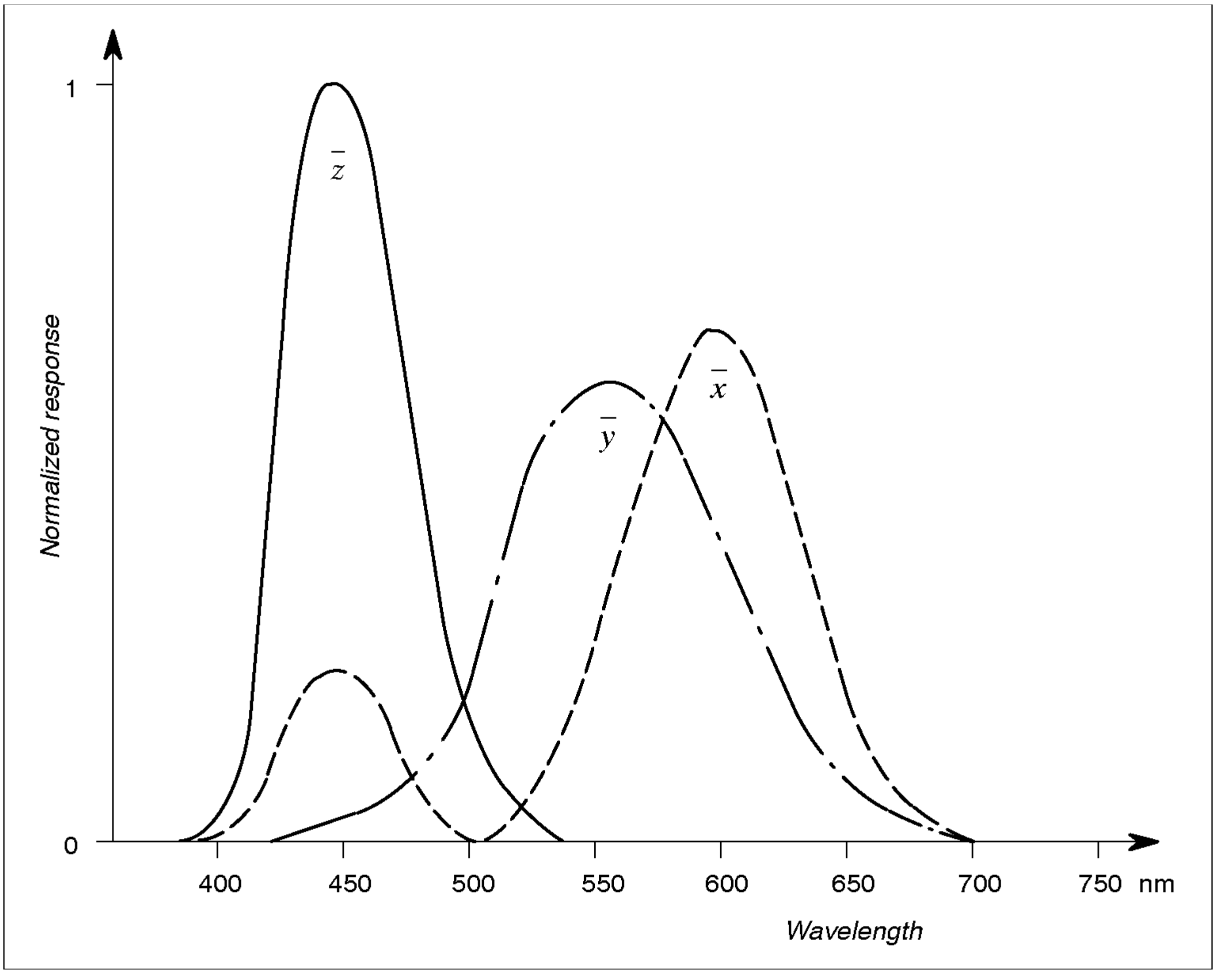


Figure 3: The colour matching functions (1931 2° Standard Observer).

1.1.2 Spectroradiometry

Spectroradiometric equipment comprises a means of measuring the light energy, wavelength by wavelength, across the whole spectral range and a data processor which calculates the tristimulus values by multiplication of this spectrum with the colour matching functions and then integration. Thus, provided that the bandwidth of the wavelength-scanning device is accurately controlled, and its gain characteristic is known, accurate results are obtained.

Two variations of the spectroradiometric method are now available. Simultaneous measurement uses a spectrum splitter and an assigned sensing cell for each wavelength. The wavelength scanning method uses one sensing cell at the output of a scanning spectrum splitter (monochromator).

Either method will produce the spectral radiance, Pi, of the colour. This should be measured over the visual part of the spectrum; 380 to 780 nm is a typical range. The instrument's calibration must be traceable to a standards bureau. Tristimulus values are then derived by multiplication and integration as described above, using data values of the appropriate colour matching functions tabulated by the CIE:

$$X = \int_{380}^{780} P_\lambda . \bar{x}_\lambda . d\lambda \qquad Y = \int_{380}^{780} P_\lambda . \bar{y}_\lambda . d\lambda \qquad Z = \int_{380}^{780} P_\lambda . \bar{z}_\lambda . d\lambda$$

When measuring narrowband light sources, using a spectroradiometer with proper spectral resolution and spectral bandwidth (5 nm or less is recommended for LEDs[3]) is of critical importance to limit the measurement errors.

1.1.3 Measurement points

Measurements are made at standardised positions within the screen area defined in terms of screen height and width; these are indicated in Figure 4.

Depending on the measurement, a subset of these measurement points can be defined.

	Coordinates (rel. to screen centre)	
Measuring Point	w	h
1 (screen centre)	0	0
2 and 5	0	±0.4 H
9 and 12	±0.4 W	0
3, 4, 6 and 7	±0.2 W	±0.2 H
8, 10, 11 and 13	±0.4 W	±0.4 H
Area of measurement should not be greater than a circle of diameter 0.1 H		

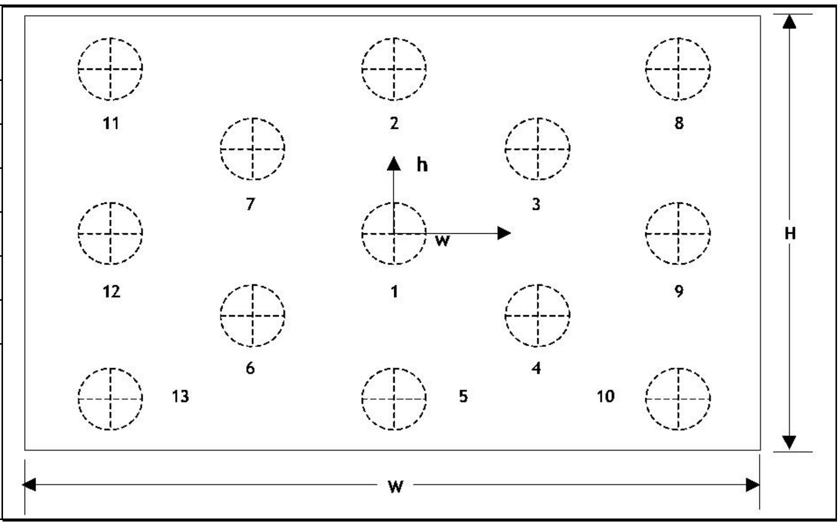


Figure 4: Measurement points within the screen

1.1.4 Measurement conditions

To ensure absolute and repeatable measurements, the following conditions should be observed:

- Measurements should be made in a darkened room (VESA FPDM2 [4] specifies this as less than 0.01 lux room brightness).
- Measurement distance is recommended to be according to the spatial resolution of the patterns (e.g., 3 times picture height for 1080p or 1.5x picture height for 2160p). It must be arranged such that the measurement window of the measuring device is entirely within the measurement patch on the display.
- Except in the case of viewing angle, the measurements should be made perpendicular to the surface of the display.
- Tests should be undertaken in such an order that minimizes the requirement to move the probe. This is not necessarily the order in which the tests are described in this publication.
- The display should be placed away from surfaces that might reflect light into the measuring

[3] See: Obtaining Spectral Data for Colorimetry, 2003, Ohno, Yoshi, NIST

equipment.

- Equipment indicator lamps etc. should be shielded from the measuring equipment.
- The monitor must be allowed to warm up until stability is achieved in accordance with the manufacturer's instructions. If a manufacturer recommends a particular type of input signal be applied during this warm-up period, this should be used. Otherwise, a grey signal that gives a luminance of approximately 15 cd/m^2 should be used.
- For SDR, the monitor should be set for a peak white of 100 cd/m^2 and adjusted in accordance with the manufacturer's procedures for the white colour temperature for D65. The full image area should be visible (i.e., no overscan).
- For HDR, the monitor should be set for a nominal peak white of at least 1000 cd/m^2 for Grade 1 and at least 600 cd/m^2 for Grade 2 and 3 and adjusted to the manufacturer's procedures for the white colour temperature for D65 using the EBU test pattern supplied (EBU_1 for narrow range and EBU_2 for full range). The full image area should be visible (i.e., no overscan).
- For measurements of simultaneous display contrast (sections 2.3.1 and 3.3.1) the display should be set up in reference/professional viewing conditions, rather than the darkened room used for other tests, as specified for SDR viewing in ITU-R BT.2035 [5] and for HDR in ITU-R BT.2100 [6].

  The black level should be set on the monitor using a PLUGE test signal such as that specified in ITU-R BT.814-4 [7].

1.1.5 Measurement precautions

There are several precautions that should be considered. These relate mainly to the characteristics of the measuring equipment used.

- The instrument optical axis should be normal to the surface of the display. Small deviations are probably not significant since most detectors use integrating apertures or diffusers.
- The instrument entrance aperture should be fully illuminated to prevent uneven illumination of the sensor(s).
- For flat panel displays, with potentially large variations in light output with viewing angle, only equipment using relay optics can be used, rather than meters which sit on the surface of the screen.
- The detector temporal performance must be linear. Due to the different ways in which different display technologies create luminance levels in time and the limited area of measurement, the detector may not be continuously illuminated by a constant light level. The temporal performance and integration characteristics must be linear and peak excitation must not cause overloading.
- Precautions must be taken to avoid the effects of veiling glare. VESA FPDM2 A101 [4] describes this in detail. The simplest method is to mask the area surrounding the measurement point with a flat, velvet-covered card. If this might affect the temperature of the screen surface by preventing natural cooling, then a gloss-black frustum (cone) of 45° should be used.
- Spectroradiometer slit and incremental wavelength must match each other. The slit widths define the effective "bandwidth" and aperture shape of the radiometer; these must match the incremental wavelength to resolve spectral emissions optimally. A pre–run should be performed

to determine peak response and to ensure that overloading does not occur.

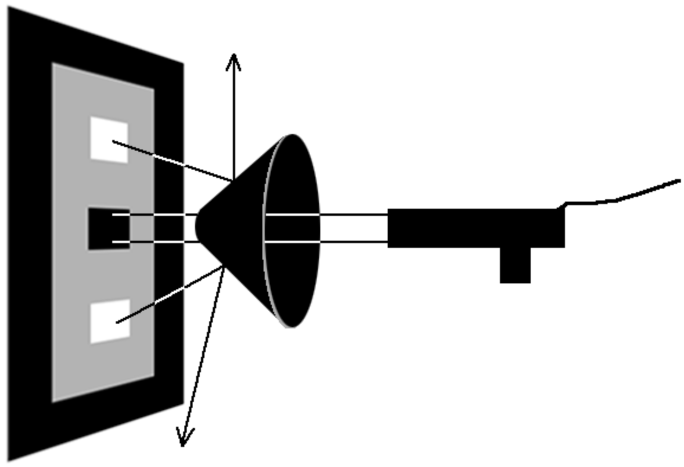


Figure 5: Arrangement of measuring instrument and frustum to avoid veiling glare

- Noise and zero levels should be checked. Detector sensitivity should be such that noise levels are not significant. Extraneous light can contribute to noise in the detected signal. Zero levels can be affected by electrical offsets and detector dark–current; these should be allowed for.
- Repeatability of measurements should be checked, and measures such as averaging several readings used if found not to be repeatable enough for the required accuracy of the measurement.

2. Measurements for HDTV SDR Displays

2.1 Test patterns SDR

When performing measurements of a device under test, the correct set of test patterns for the monitor's operating setting shall be used.

	Coordinates (rel. to screen centre)	
Measuring Point	w	h
1 (screen centre)	0	0
2 and 5	0	±0.4 H
9 and 12	±0.4 W	0
Each patch is a square of dimension H/7.5 (13.13% H)		

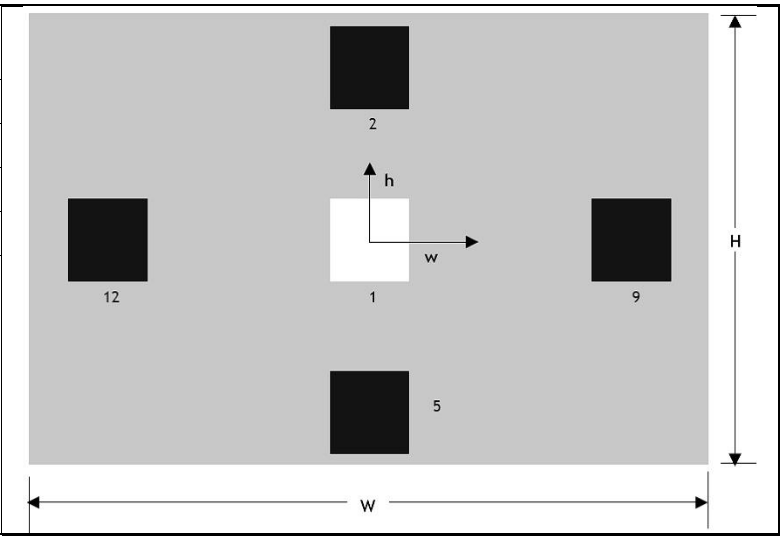


Figure 6: Test pattern EBU_1, Black, white and simultaneous contrast

Test pattern EBU_1 (see Figure 6) consists of a peak white level patch surrounded by four black level patches, all set against a background of 50% grey signal. The digital references for these levels are defined in the preamble.

Test pattern EBU_2 is the same as pattern 1, except that the white patch is now 109% “Super white”. The pattern includes text to indicate this.

Test pattern EBU_3-xx provides white patches at all 13 test points defined in Figure 7 on a black frame. A set of 13 patterns (pattern 3-1 to 3-13) illuminates each individual patch in turn. Pattern EBU_3-black is a completely black image. Pattern EBU_3-white is a completely (100%) white frame.

	Coordinates (rel. to screen centre)	
Measuring Point	w	h
1 (screen centre)	0	0
2 and 5	0	±0.4 H
9 and 12	±0.4 W	0
3, 4, 6 and 7	±0.2 W	±0.2 H
8, 10, 11 and 13	±0.4 W	±0.4 H
Each patch is a square of dimension H/7.5 (13.13% H)		

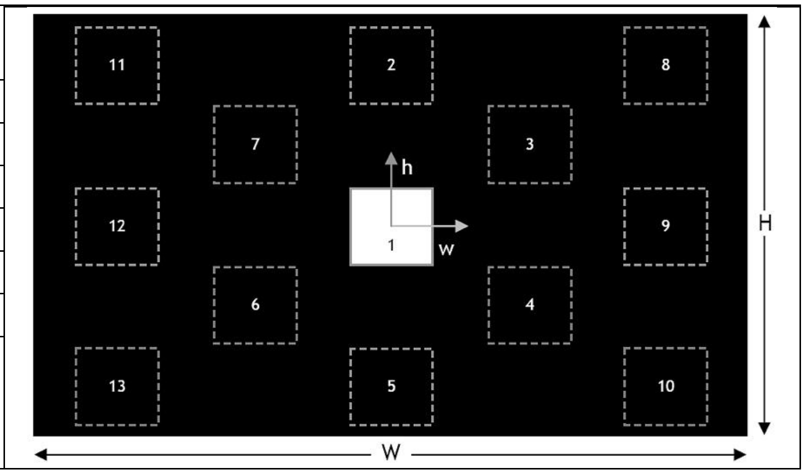
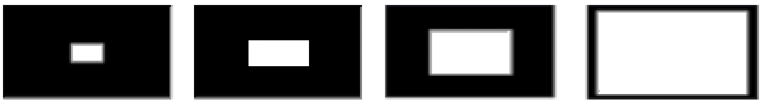
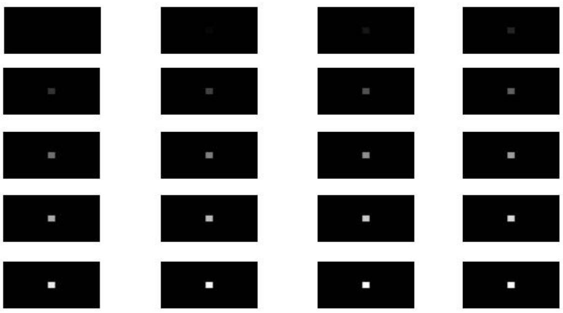


Figure 7: Test patterns EBU_3-1 to EBU_3-13

Test patterns EBU_3-1_4, **EBU_3-1_10**, **EBU_3-1_25** and **EBU_3-1_81** are versions of EBU_3-1 but with the white patch occupying respectively 4%, 10%, 25% and 81% of the screen area.



Test patterns EBU_4-xx are similar to EBU_3-1 but with the patches having the grey-scale values set out in Table 5: Luma levels of grey-scale test patches. Pattern EBU_4-1 is the same as EBU_3-black. Pattern EBU_4-19 is the same as EBU_3-1. Pattern EBU_4-20 has the patch at 109% white.



Test pattern EBU_5-xx is a series of patterns based on pattern EBU_3-1 but with the primaries red, green, blue and the 15 EBU test colours. These are patterns EBU_5-red_BT709SDR, EBU_5-green_BT709SDR and EBU_5-blue_BT709SDR, and EBU_5-1_BT709SDR to EBU_5-15_BT709SDR. The definitions of the colours are listed in Table 7.

Test sequence EBU_6 is scrolling text, both horizontally and vertically, at a variety of motion rates.

Test pattern EBU_7 is designed to enable a visual evaluation of various elements of monitor performance including fine gradations of colour, overscan, and filtering/scaling performance including filtering between YCbCr and RGB.

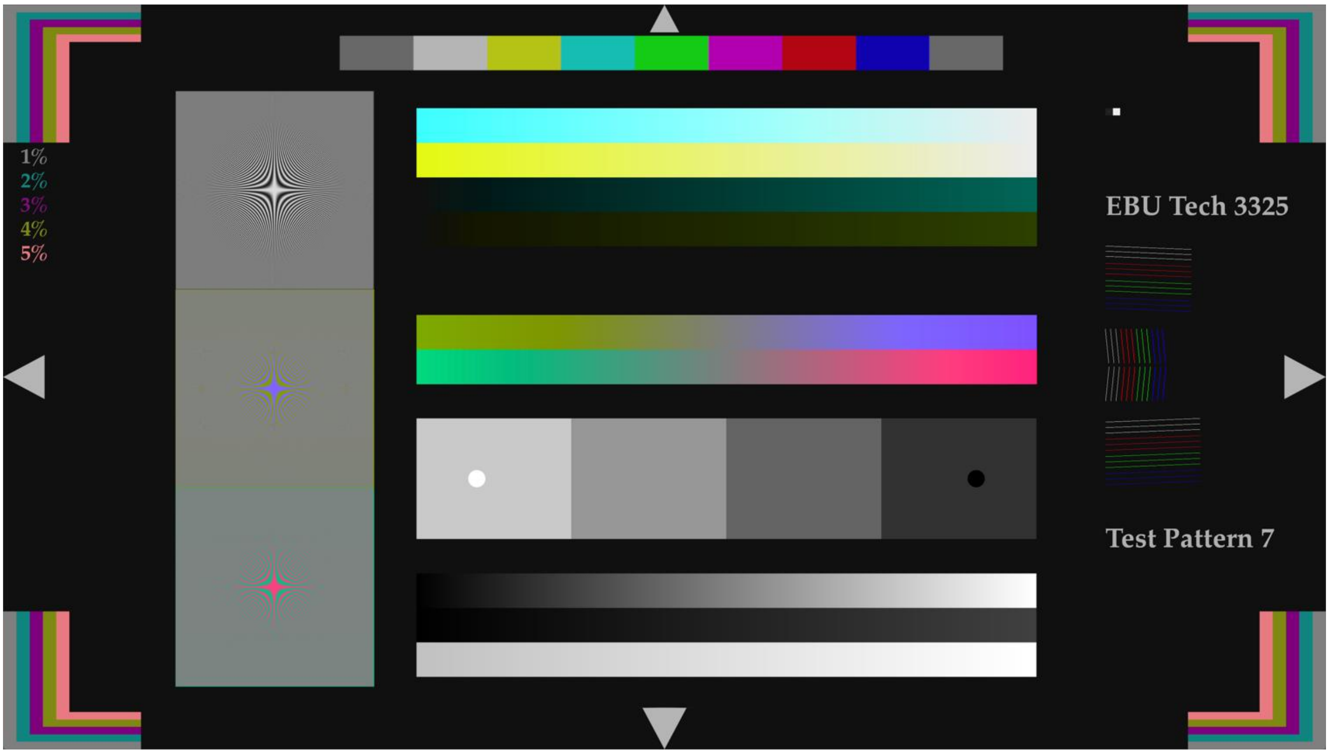


Figure 8: Test pattern EBU_7

Test sequence EBU_8 (interlace formats only) includes moving zone plates designed to indicate whether a display can indicate incorrect field order.

Test sequences EBU_9-top and **EBU_9-centre** provide a 5-line flash in a single field for determining delay.

Test pattern EBU_10 has a series of horizontal and vertical transitions between white, black and mid-grey, conditioned by the appropriate channel filter.

Test pattern EBU_11 includes a ramp of luma from sub-black to super-white, with similar ramps for each chroma signal superimposed on it.

Test pattern EBU_12-grey is a flat 50% grey frame. **Test pattern 12-burn** has 90% grey on the left-hand side of the screen and 10% grey on the right with a gentle transition at the join.

These test patterns are available online, see: tech.ebu.ch/publications/tech3325-testpatterns

2.2 Luminance range

White level is set to 100 cd/m^2 for SDR Grade 1, 200 cd/m^2 for SDR Grade 2, and 250 cd/m^2 or more for SDR Grade 3. Black level is set using the PLUGE test signal. During the adjustment, it should be checked whether the sub-black of the PLUGE test signal is observable. (Note: it is not considered acceptable for a monitor acting as a measurement tool to electronically clip the sub-black signal).

2.2.1 White level

The monitor is set to display Test pattern EBU_1 (Figure 6).

Measurement point: 1 in Figure 4.

Measurement equipment: Luminance meter

> **Note:** *other measurement methods are possible, for example using a spectroradiometer.*

Measurements are made to establish that the monitor can meet the specifications set out in EBU Tech 3320, and these results are reported in a table such as Table 2.

2.2.2 Super white level

This is measured using Test pattern EBU_2, ensuring that super white can be correctly displayed over the range of settings described above to produce the required range of "peak white" levels.

Table 2: White level measurements results (example)

Grade Luminance Settings	Grade 1A 100 cd/m^2	
Grade Luminance Settings	Grade 1B & 2 200 cd/m^2	
Grade Luminance Settings	Grade 3 up to 400 cd/m^2	
Measuring	White	109%
pattern	EBU_1	EBU_2
Luminance	99.1 cd/m^2	120.0 cd/m^2

2.2.3 Black level

- The monitor displays Test pattern EBU_3-black.

Measurement points: 2, 5, 9 and 12 in Figure 4

Measurement equipment: Luminance meter

> **Note:** *other measurement methods are possible, for example using a spectroradiometer*

Measurement result:

Table 3: Black level measurements results (example)

Measuring -point \ -pattern	Black 1
2	0.1333 cd/m²
5	0.1222 cd/m²
9	0.1444 cd/m²
12	0.1666 cd/m²
Average	0.142 cd/m²
Measurement tool:	e.g., tristimulus meter, average of 5 readings
Sub-black can be made visible:	yes

2.3 Contrast ratio

The contrast of a display can be defined as follows:

$$C = \frac{L_{\max}}{L_{\min}}$$

Where L_{max} is the luminance reproduced with peak white and L_{min} that reproduced with black. Assuming that black level has been set correctly, then in a darkened room L_{min} may be zero with no signal and hence contrast could theoretically be infinite. However, in the presence of ambient lighting, inaccurately set black level, or due to limitations of the display technology, L_{min} will be non-zero thus giving rise to a wide range of values for contrast.

Clearly, the use of separate white and black signals for the measurement of L_{max} and L_{min} can result in many different values for contrast, and therefore contrast must be calculated using measurements of white and black from within only one test. The simultaneous display contrast thus derived may contain an element of flare due to the presence of peak white and, again, the result will depend on the nature of the test signal and the way the display was set up. It is however considered a realistic measure of contrast under real viewing conditions for real picture content.

For measurement conditions see § 1.1.4.

Note: *In practice, panning and tilting of the spectroradiometer can be used as a simpler way of doing the contrast-measurement, but it is not the official method. If the values are close to the extremes of the allowable range, one could imagine undertaking a perpendicular measurement. This should be done after other measurements to prevent the possibility of the calibration of the spectroradiometer being affected by being moved.*

2.3.1 Simultaneous display contrast

A suitable test signal for contrast measurement is Test pattern EBU_1.

For this test, the measurement must be made under professional/operational viewing conditions, and the display set up with a PLUGE test signal specifically for this one measurement, as indicated in § 1.1.4.

Note: *The measurement method is equivalent in result (if not in detail of calculation order and viewing conditions) to ITU-R BT.815-1 [8].*

2.3.2 Full screen contrast

Suitable test signals for full screen contrast measurement are:

- Test pattern EBU_3-1 i.e., a peak (100%) white patch occupying 1% of the screen area in the centre of a black screen.
- A completely black screen, test pattern EBU_3-black, (with the set switched on and set up as for the other measurements) in a dark room.

Further test patterns (patterns EBU_3-1_04, EBU_3-1_25 and EBU_3-1_81), with the white patch occupying a larger percentage of the screen area. IEC 60107-1:1997 7.1.4 [9] describes a peak luminance (SDR) measurement (and hence contrast) using input signals displaying different window sizes (1%, 4%, 25%, 81%) of white area.

The black level L_{min} should be the mean of measurements made of the five positions (1, 2, 9, 5, 12), the white level L_{max} should be measured in the central position (1).

"Full screen (1% patch) contrast" is defined as the ratio between the luminance of the screen when displaying peak white on 1% of the screen area, and the luminance measured when displaying full screen black.

If a display is found to exhibit a fall-off in peak luminance with the size of the white patch, then 4%, 25% and 81% contrast measurements should also be made. “Full screen (x% patch) contrast” is defined as the ratio between the luminance of the screen when displaying x% area patch of white and when displaying full screen black level measured in a completely dark room.

Note: *The measurement must be performed in a completely dark room. Before making these measurements, white is set at 100 cd/m^2 for SDR or the peak luminance the display is capable of, and black level is set using PLUGE.*

Measurement equipment: Luminance meter

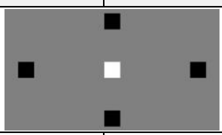
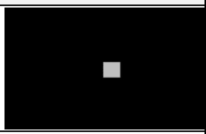
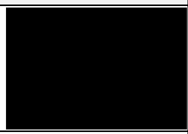
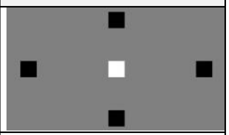
Note: *other measurement methods are possible, for example using a spectroradiometer.*

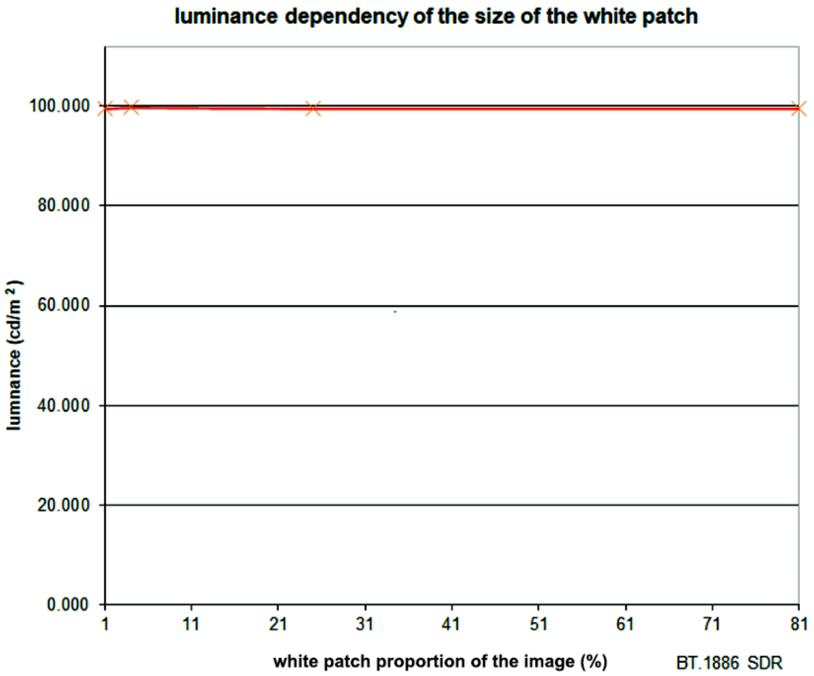
Measurement result SDR:

Table 4: Contrast ratio measurement results (example)

Measuring pattern / point	Simultaneous Display Contrast			Full Screen Contrast		
	White	Black	Contrast	White	Black	Contrast
	1	1	C_S	4-19	3-black	C_F
1	99.090	[cd/m²]		99.617	[cd/m²]	
2	[cd/m²]			[cd/m²]	0.11971	
5			475		0.10908	735
9					0.16042	
12					0.15297	
Average	99.090	0.209		99.617	0.13555	
Measurement tool:	e.g., xyz tristimulus meter, average of 5 readings					

⇧

Simultaneous Display Contrast			Full Screen Contrast			109% White 'Super White'
White	Black	Contrast	White	Black	Contrast	
cv 940	cv 64		cv 940	cv 64		cv 1019
		C_S			C_F	
99.090 [cd/m²]	0.209 [cd/m²]	475	99.617 [cd/m²]	0.13555 [cd/m²]	735	120.024 [cd/m²]
(cv = "code value")			L_W	L_B		



Desired value: 99.330 cd/m²

Full screen contrast fall-off luminance

Pattern no.	Pattern size (% of screen)	Luminance (cd/m²)
3-1-1	1	99.362
3-1-4	4	99.723
3-1-25	25	99.666
3-1-81	81	99.664

Figure 9: Luminance measurement vs. patch size measurement results (example)

2.4 Electro-Optical Transfer Function

2.4.1 Measurement procedure

For this measurement it is essential that the measurement conditions described in § 2.2 are correctly set.

When measuring the transfer function, it is required to measure the light output level over the complete nominal range between black (digital luma signal level of 64 in 10-bit digital representation and 512 for chroma), and peak white (digital luma signal level of 940 in 10-representation and 512 for chroma).

Testers should note that although u'v' are not used for this test, they are required for later tests.

The test inputs (Test patterns EBU_4-1 to EBU_4-19) are a series of test patches in measurement position 1 (Figure 4) in the centre of an otherwise black frame. The patch is a square of dimension H/7.5 (13.13% of picture height, H) having levels disposed between digital luma levels 64 and 940, such that there is an equal interval between each, except near black and white, according to the table below:

Table 5: Luma levels of grey-scale test patches

Grey-scale Measurement Number	Luma level in 10-bit	Grey-scale Measurement Number	Luma level in 10-bit
1	64	11	554
2	86	12	606
3	138	13	658
4	190	14	710
5	242	15	762
6	294	16	814
7	346	17	866
8	398	18	918
9	450	19	940
10	502	20	1019

Note: The brightness and contrast settings of the monitor must NOT be altered during measurement.

Measurement equipment: Luminance meter

Note: *other measurement methods are possible, for example using a tristimulus meter or spectroradiometer equipment.*

2.4.2 Presentation of the measurement results

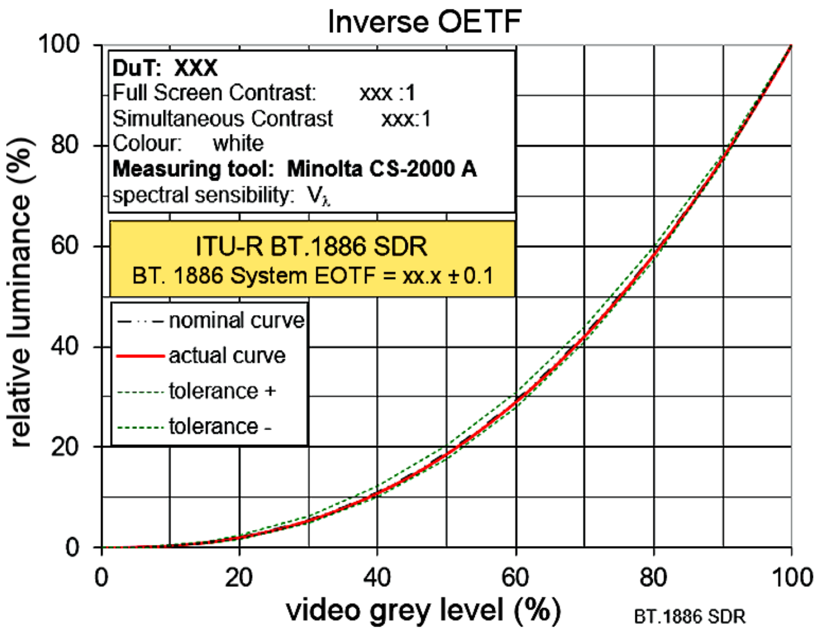


Figure 10: SDR Electro Optical Transfer Function (EOTF) measurement results: rel. Luminance level vs. grey level (%) (example)

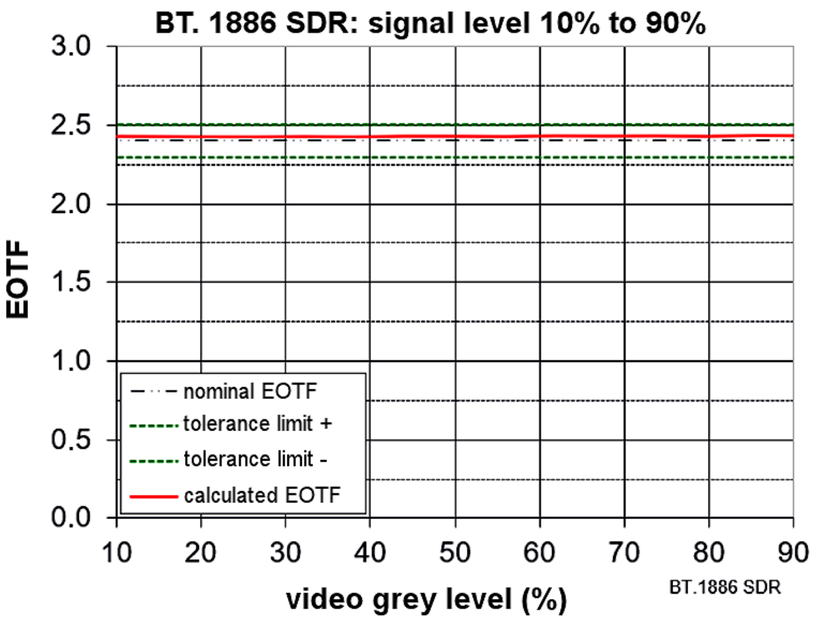


Figure 11: SDR EOTF measurement results: EOTF value vs. grey level (%) (example)

The method for calculating the values of the EOTF from the signal level is given in Annex 1.

2.5 Grey scale reproduction

2.5.1 Measurement conditions

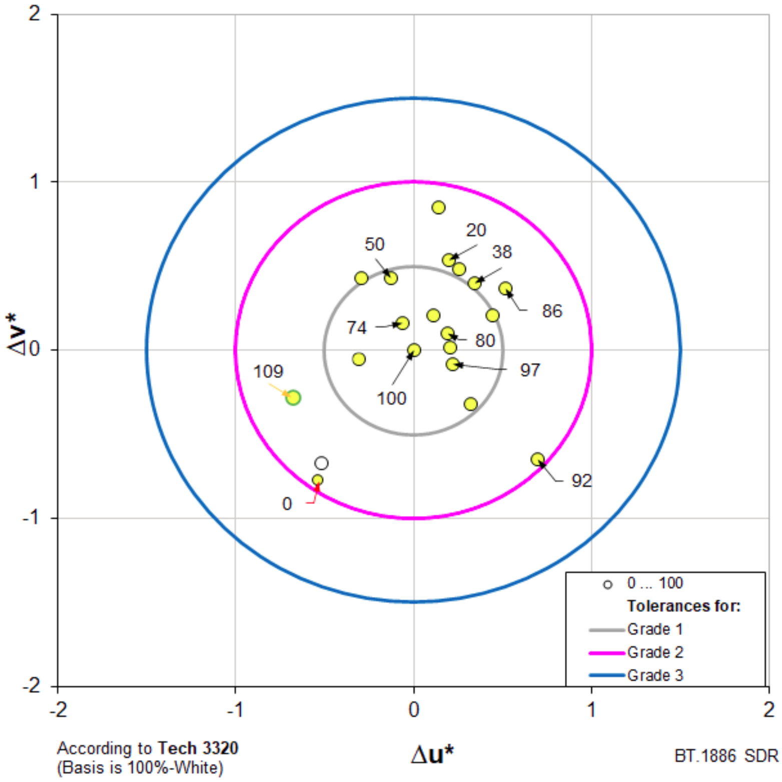
The test input is formed by Test patterns EBU_4-1 to EBU_4-20. It is essential that the measurement conditions described in § 2.2 are correctly set.

Measurement point: 1

Measurement equipment: Tristimulus meter or spectroradiometer equipment

2.5.2 *Presentation of the measurement results*

Measurement result:



"EBU-Grade 1": within the grey circle
"EBU-Grade 2": within the pink circle
"EBU-Grade 3": within the blue circle.

Figure 12: Grey scale reproduction (centre: 100% luma level) measurement results (example)

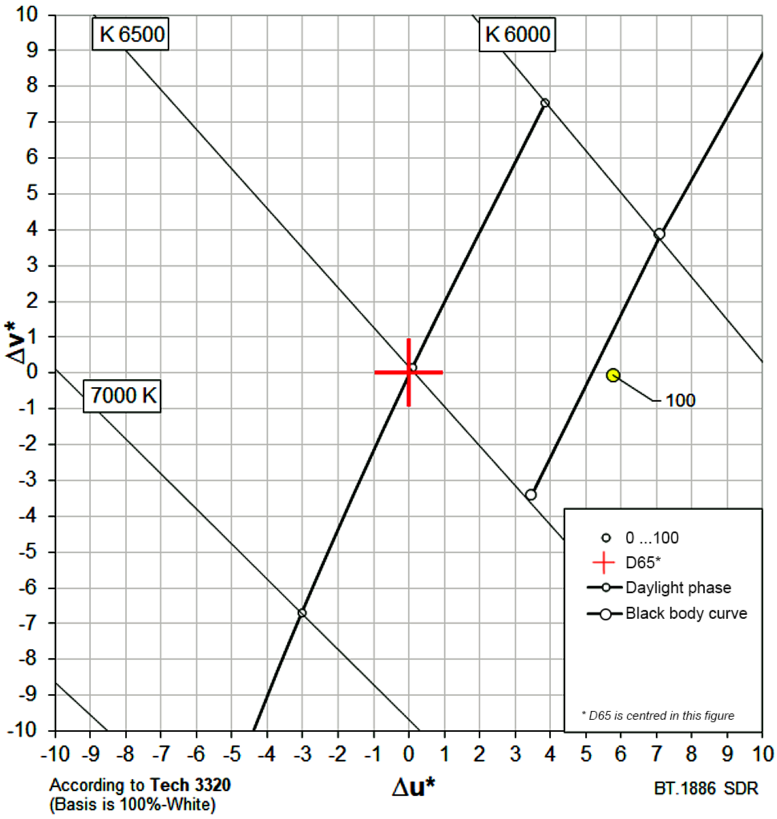


Figure 13: Grey scale reproduction measurement results (example)

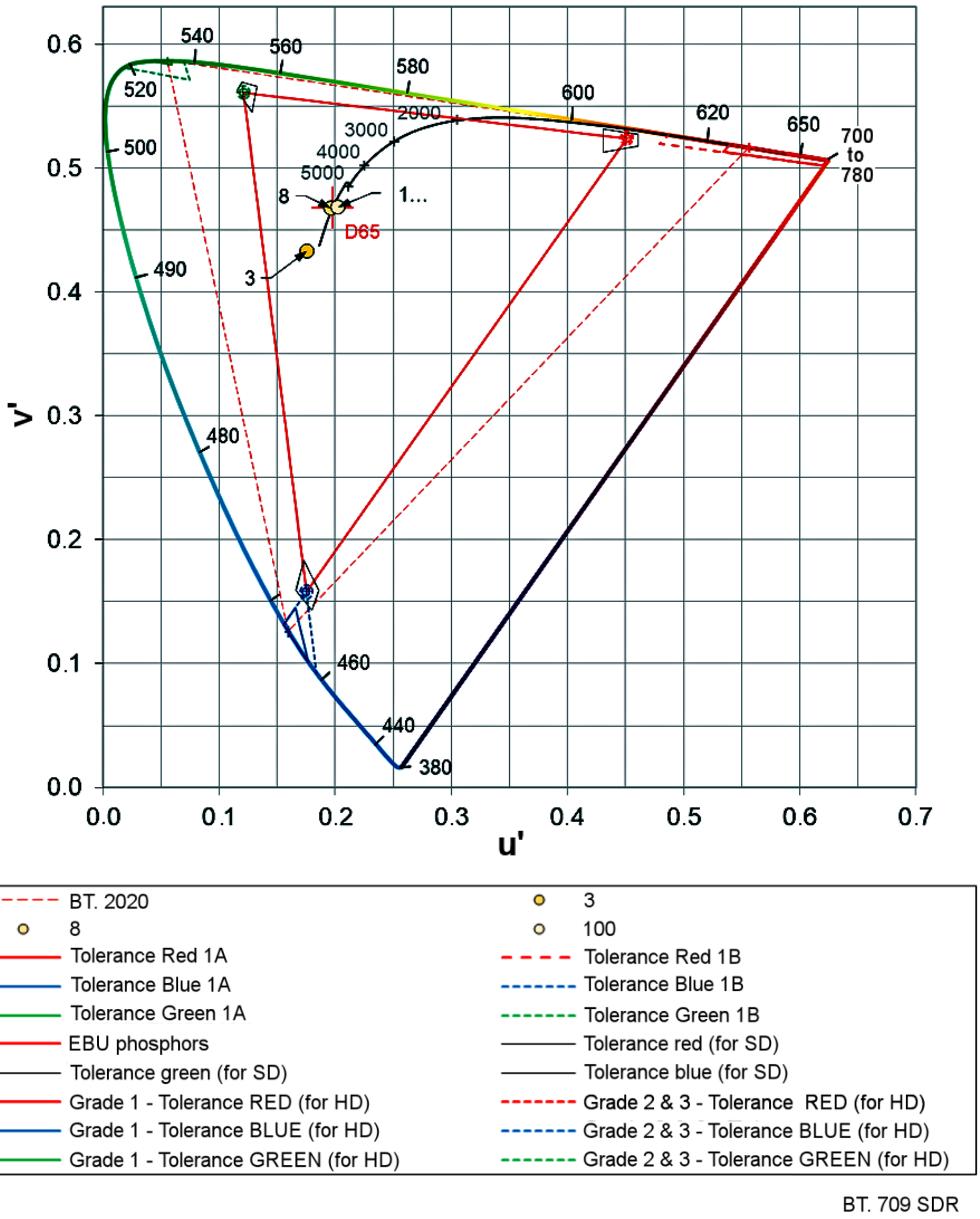


Figure 14: Grey scale reproduction measurement results (example)

2.6 Colour gamut and colour reproduction

2.6.1 Measurement conditions

The test inputs are Test patterns EBU_5-red_BT709SDR, EBU_5-green_BT709SDR and EBU_5-blue_BT709SDR. It is essential that the measurement conditions described in § 2.2 are correctly set.

The primary colour patches should be set to the digital (10-bit) values listed in Table 1 (HD-SDI, ITU-R BT.709-5 part 2 [10]) calculated according to the procedure set out in ITU-R BT.1120 [11].

Table 6: Code values for the primary colour patches used at 100 cd/m²

	10-bit code values at monitor input			Expected monitor output			
Primary	D'_Y	D'_{CB}	D'_{CR}	Y_{exp} [cd/m²] (= L · L_{ref})	L [0:1]	u'	v'
Red	250	409	960	21.3	0.213 (=Y_R)	0.4507	0.5229
Green	691	167	105	71.5	0.715 (=Y_G)	0.1250	0.5625
Blue	127	960	471	7.2	0.072 (=Y_B)[4]	0.1754	0.1579
Note: ITU-R BT.709 (-> 709-SDR); L_{ref} = 100 cd/m²							

A set of 15 EBU test colours was defined in EBU Tech 3237 [12] and its supplement [13], based on certain Munsell chips, and these are also a useful set of test colours for characterising a display in ITU-R BT.709 colour space. Whilst these test colours were originally intended as camera input test colours, here we use these colours referred to the output of the display.

For the measurement of the EBU test colours on SDR ITU-R BT.709 monitors (based on sample data given in EBU Tech 3237 [12] and its supplement [13], and assuming a display EOTF of 2.35) the patches should be set to the digital 10-bit Rec.709 values given in the following table.

Table 7: 10-bit Rec. ITU-R BT.709 code values for the 15 EBU Test Colours defined in EBU Tech 3327 supplement 1

		10-bit code values at monitor input			Expected monitor output			
Sample	**Description**	**D'_Y**	**D'_{CB}**	**D'_{CR}**	**Y_{exp} [cd/m²] (= L · L_{ref})**	**L [0:1]**	**u'**	**v'**
	White point	940	512	512	100.0	1.000	0.1978	0.4683
EBU 1	Dark Skin	381	470	578	9.6	0.096	0.2526	0.5013
EBU 2	Light Skin	636	457	599	37.7	0.377	0.2365	0.4931
EBU 3	Light Greyish Red	582	478	592	29.8	0.298	0.2365	0.4850
EBU 4	Light Yellow Green	577	340	480	29.9	0.299	0.1805	0.5453
EBU 5	Light Bluish Green	579	544	411	29.8	0.298	0.1630	0.4552
EBU 6	Light Violet	586	597	543	30.1	0.301	0.2088	0.4155
EBU 7	Foliage	433	443	487	13.4	0.134	0.1816	0.5205
EBU 8	Medium Red	460	465	703	19.3	0.193	0.3246	0.4972
EBU 9	Medium Green	658	380	370	43.6	0.436	0.1504	0.5329
EBU 10	Medium Blue	470	639	468	17.2	0.172	0.1789	0.3707
EBU 11	Dark Red	319	490	616	6.5	0.065	0.3047	0.4898
EBU 12	Dark Green	487	422	396	20.0	0.200	0.1461	0.5320
EBU 13	Dark Blue	321	617	491	6.0	0.060	0.1828	0.3420
EBU 14	Medium Yellow Red	655	349	673	43.4	0.434	0.2724	0.5274
EBU 15	Medium Purple	494	601	593	20.0	0.200	0.2348	0.4031
Note: ITU-R BT.709 (-> 709-SDR). L_{ref} = 100 cd/m²								

[4] When used in calculations, the full accuracy shall be maintained. In this example, the calculation would use Y_R = 0.21263900587151, Y_G = 0.715168678767756 and Y_B = 0.0721923153607337.

These are provided as test patterns EBU_5-1_BT709SDR to 5-15_BT709SDR.

Above expected monitor L, u', v' values have been calculated for the exact 10-bit D'_Y, D'_{CB}, D'_{CR} values. These may thus differ slightly from the original EBU Tech 3237 colour definitions (from which the quantised D'_Y, D'_{CB}, D'_{CR} values were derived).

Measurement point: 1

Measurement equipment: Tristimulus meter or spectroradiometer equipment.

2.6.2 Presentation of the measurement results

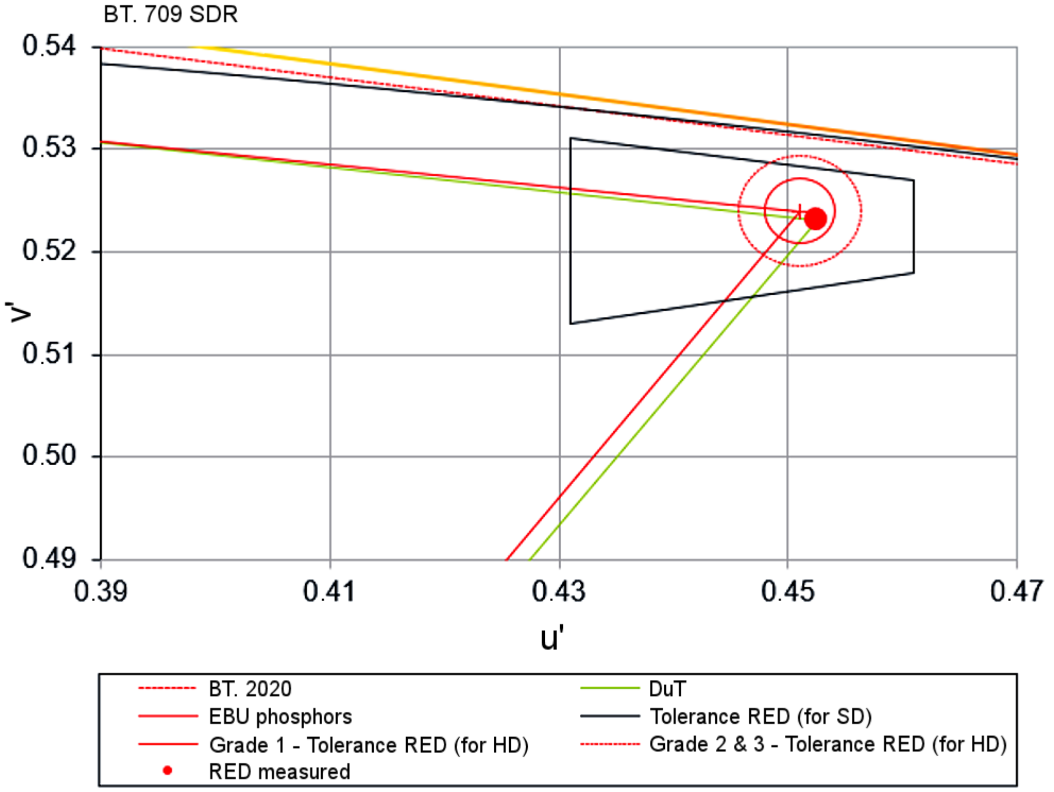


Figure 15: Red primary measurement result (example)

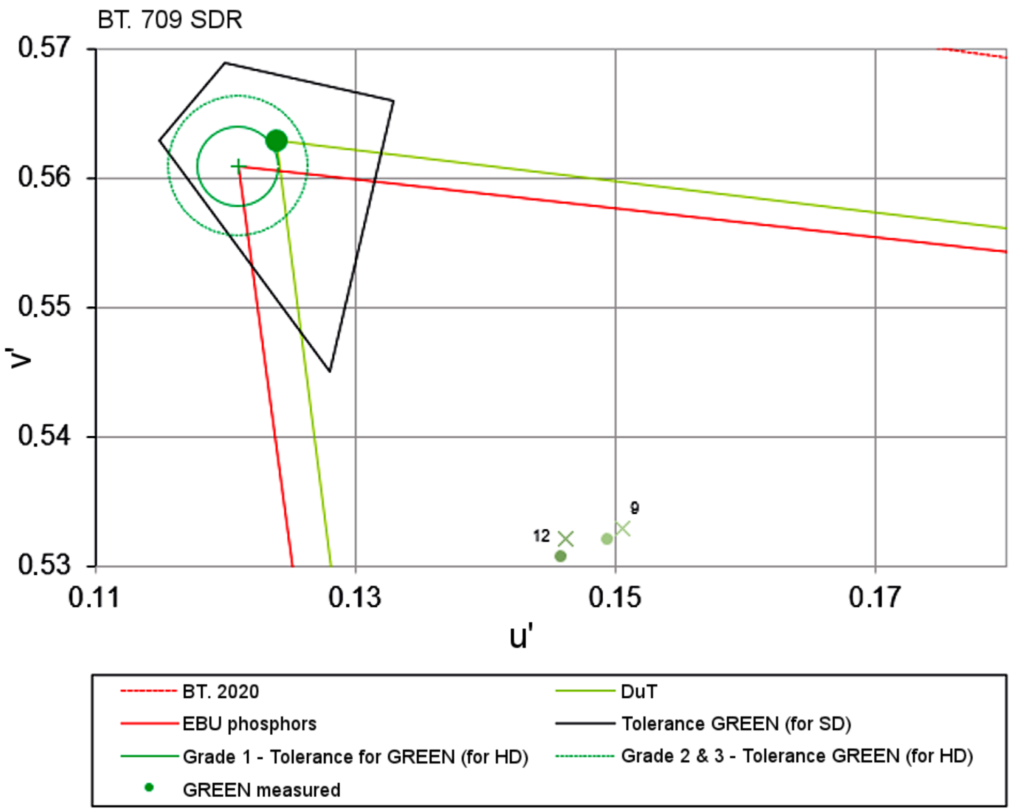


Figure 16: Green primary measurement result (example)

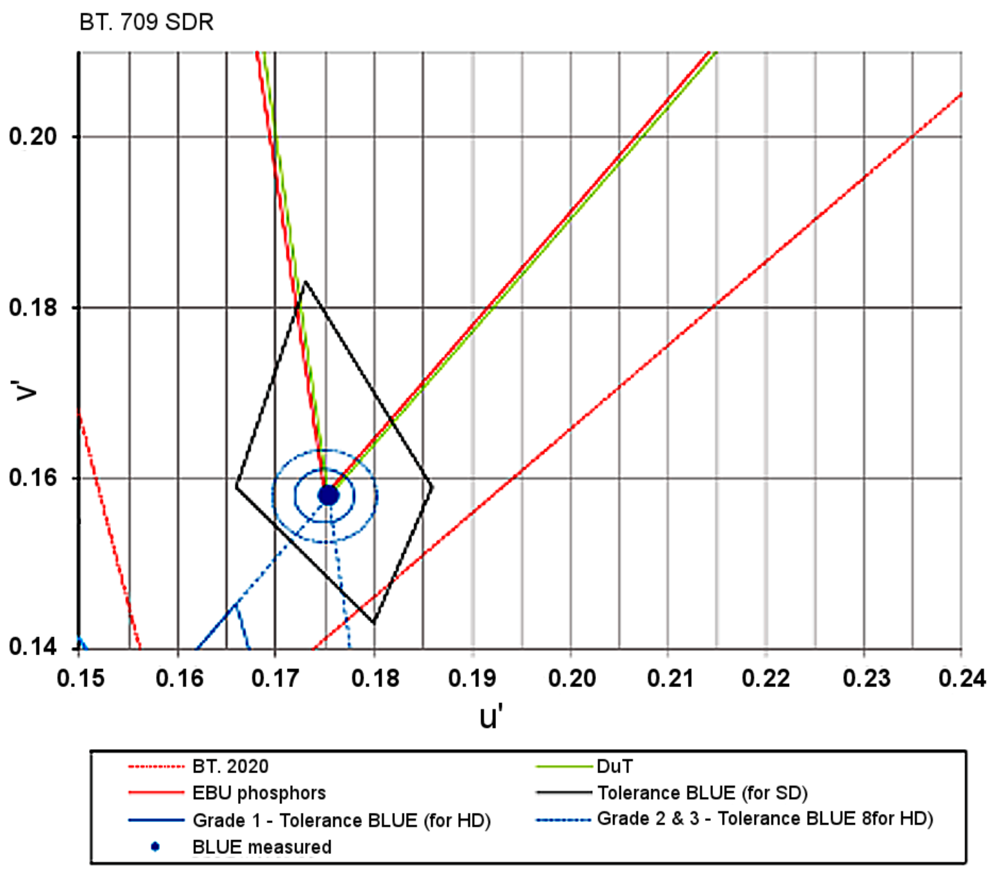


Figure 17: Blue primary measurement result (example)

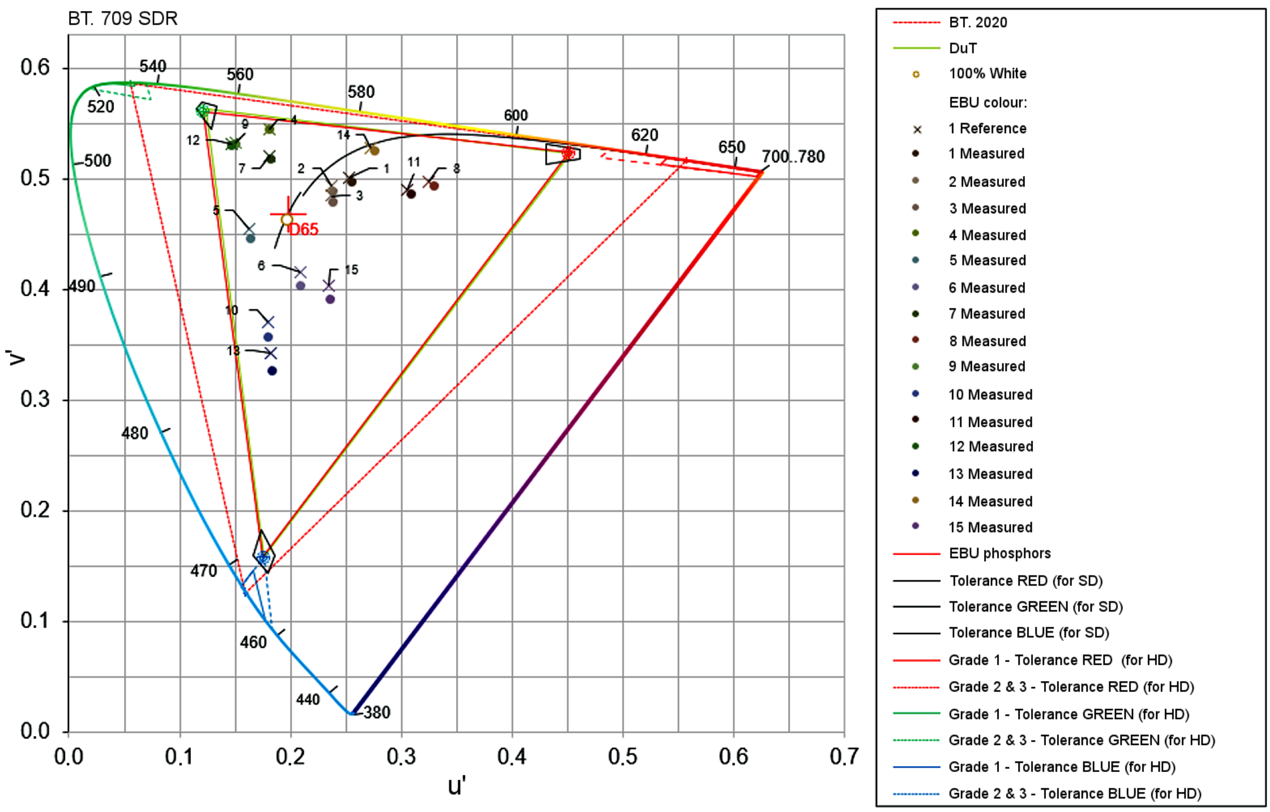


Figure 18: Colour gamut and Colour reproduction representation for ITU-R BT.709 SDR

Table 8 shows an example of measured values for the 15 EBU colour patches. The luminance is related to the 100% white level.

Table 8: Example of the measured Y_c and the calculated Δu^*, Δv^* and ΔE^* for the 15 EBU Tech 3273 colours (calculated CIE Luv)

EBU	EBU reference values					Measured			Calculated CIE Luv					
Colour	Y_{exp}	u'_{exp}	v'_{exp}	Y_{exp}/Y_w	$L_{exp/w}^*$	$\Delta u'$	$\Delta v'$	Y_c	Y_c/Y_w	$L_{c/w}^*$	ΔL^*	Δu^*	Δv^*	ΔE^*
1	9.60	0.2526	0.5013	0.096000	37.11	0.0049	0.0000	11.3	0.113000	40.08	2.97	2.55	0.00	3.91
2	37.7	0.2365	0.4931	0.377000	67.80	0.0038	-0.0009	41.0	0.410000	70.18	2.38	3.47	-0.82	4.28
3	29.8	0.2365	0.4850	0.298000	61.48	0.0039	-0.0001	32.9	0.329000	64.08	2.60	3.25	-0.08	4.16
4	29.9	0.1805	0.5453	0.299000	61.57	0.0041	-0.0020	32.9	0.329000	64.08	2.51	3.42	-1.67	4.56
5	29.8	0.1630	0.4552	0.298000	61.48	0.0022	0.0001	32.1	0.321000	63.43	1.94	1.81	0.08	2.66
6	30.1	0.2088	0.4155	0.301000	61.74	0.0043	0.0050	32.5	0.325000	63.75	2.01	3.56	4.14	5.82
7	13.4	0.1816	0.5205	0.134000	43.36	0.0058	-0.0021	15.2	0.152000	45.91	2.55	3.46	-1.25	4.48
8	19.3	0.3246	0.4972	0.193000	51.04	0.0004	-0.0007	21.9	0.219000	53.92	2.88	0.28	-0.49	2.94
9	43.6	0.1504	0.5329	0.436000	71.96	0.0021	-0.0031	46.0	0.460000	73.55	1.59	2.01	-2.96	3.92
10	17.2	0.1789	0.3707	0.172000	48.51	0.0025	0.0093	18.8	0.188000	50.45	1.94	1.64	6.10	6.61
11	6.50	0.3047	0.4898	0.065000	30.64	0.0043	0.0011	7.70	0.077000	33.35	2.71	1.86	0.48	3.32
12	20.0	0.1461	0.5320	0.200000	51.84	0.0021	-0.0025	22.0	0.220000	54.03	2.19	1.47	-1.76	3.17
13	6.00	0.1828	0.3420	0.060000	29.41	0.0029	0.0059	6.90	0.069000	31.58	2.17	1.19	2.42	3.46
14	43.4	0.2724	0.5274	0.434000	71.83	0.0021	-0.0013	47.6	0.476000	74.57	2.75	2.04	-1.26	3.64
15	20.0	0.2348	0.4031	0.200000	51.84	0.0034	0.0061	22.3	0.223000	54.34	2.51	2.40	4.31	5.53

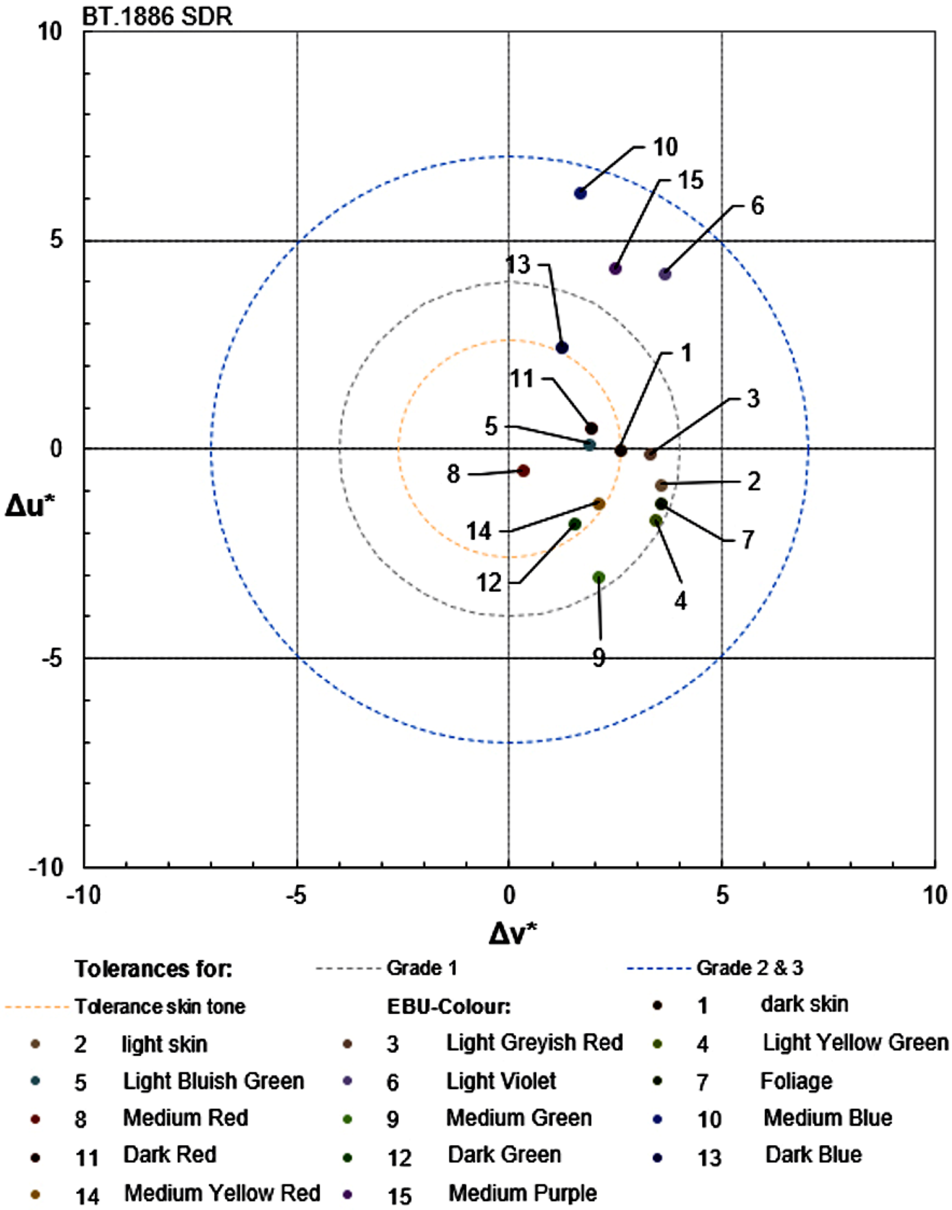


Figure 19: Deviation from the standard 15 EBU Test colours (example)

2.7 Colour temperature and uniformity

2.7.1 Definition of uniformity

Uniformity is defined as the evenness of light output and chromaticity over the picture area.

2.7.2 Measurement conditions – colour temperature

The input test signal is a test pattern having a 100% white frame, such as test pattern EBU_3-white. If the display is not able to maintain adequate output level with this pattern, Test pattern EBU_3, or test patterns EBU_3-1 to EBU_3-13, where only one patch at a time is illuminated, may be used. All measurements are made parallel to a line perpendicular to the centre of the display.

<u>**Measurement points:**</u> 1 to 13 (see Figure 4)

<u>**Measurement equipment:**</u> Tristimulus meter or spectroradiometer equipment

2.7.3 Presentation of the measurement results – colour temperature

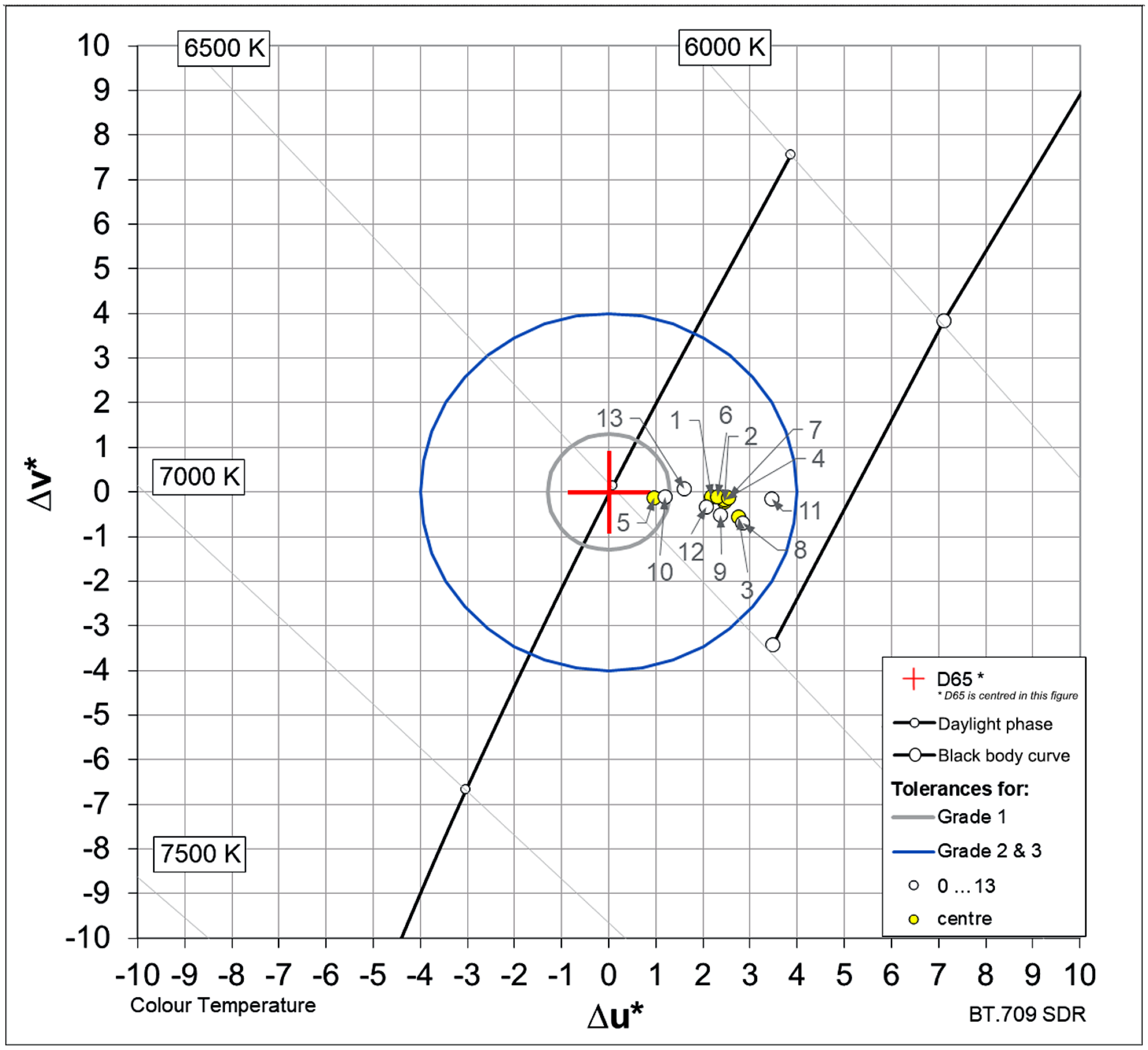


Figure 20: Colour Temperature measurement results presentation (example) (centre of the tolerance circles: D65)

2.7.4 Measurement procedure – luminance large area uniformity

Measurements are to be carried out at all thirteen standardised positions within the screen area and may be made at the same time as the chrominance measurements. The display should be driven with a peak white video signal across the whole frame. Suitable signals are Test patterns EBU_3-1 to EBU_3-13.

Measurement points: 1 to 13 (see Figure 4).

Measurement equipment: Tristimulus meter or spectroradiometer equipment.

2.7.5 Presentation of the luminance large area uniformity measurement result

Table 9: Luminance large area uniformity measurement results (example)

	Test point	Luminance (Y) cd/m^2	Luminance (Y) % of point 1
centre	1	99.039	100
	2	99.827	100.8
	3	103.999	105.0
	4	99.350	100.3
	5	83.977	84.8
	6	97.284	98.2
	7	101.392	102.4
	8	92.484	93.4
	9	102.942	103.9
	10	82.592	83.4
	11	92.020	92.9
	12	97.470	98.4
	13	81.202	82.0

BT.709 SDR

Tolerance of mean luminance (%)	±5	Reference
Maximum Luminance Deviation (%)	-18.0	Measured

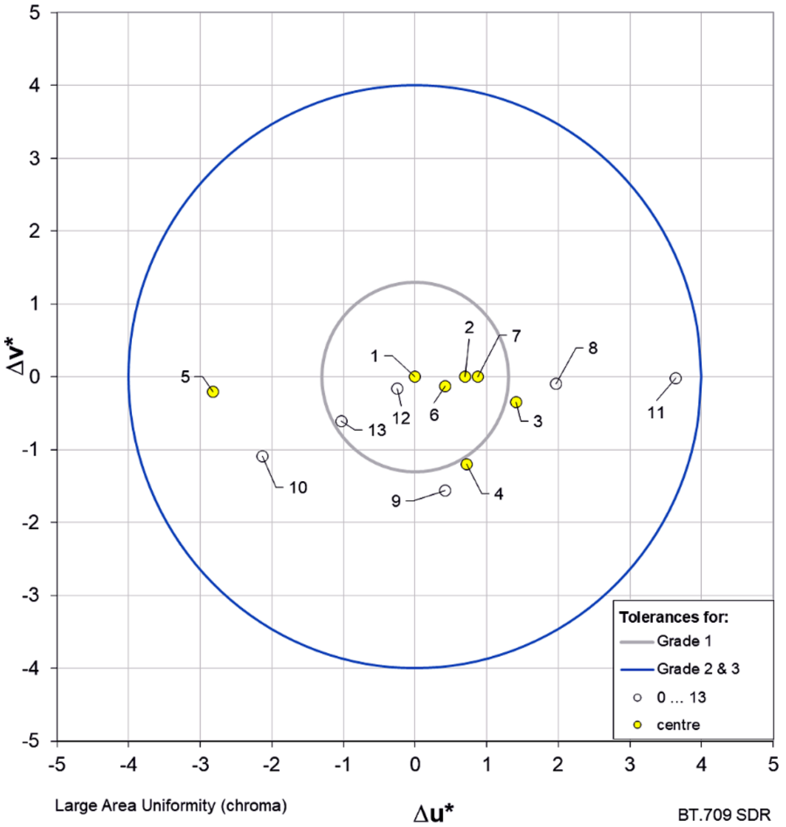


Figure 21: Uniformity
(centre of the tolerance circles: measurement point 1)

2.7.6 Measurement procedure - luminance small area uniformity

This measurement is done using an array light measurement device (LMD) over the entire display screen. The output is a pseudo colour image showing the relative luminance level of small areas. The visual analysis of this image can provide information about the localisation of non-uniformity areas, rate of luminance variations, and presence of periodic and fixed patterns. The uniformity score is computed using the standard deviation as in:

$$\text{Uniformity (\%)} = 100 * \left(1 - \frac{\sigma}{\bar{x}}\right), \text{ with } \sigma = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(x_i - \bar{x})}$$

and where $\{x_1, x_2, \ldots, x_N\}$ are the luminance samples, $\bar{x}$ is the mean value of the luminance samples and N is the number of luminance samples.

Measurement points: over the entire display screen

Measurement equipment: Array LMD or DLSR camera using a method proposed by the CBC [14]

Presentation of results:

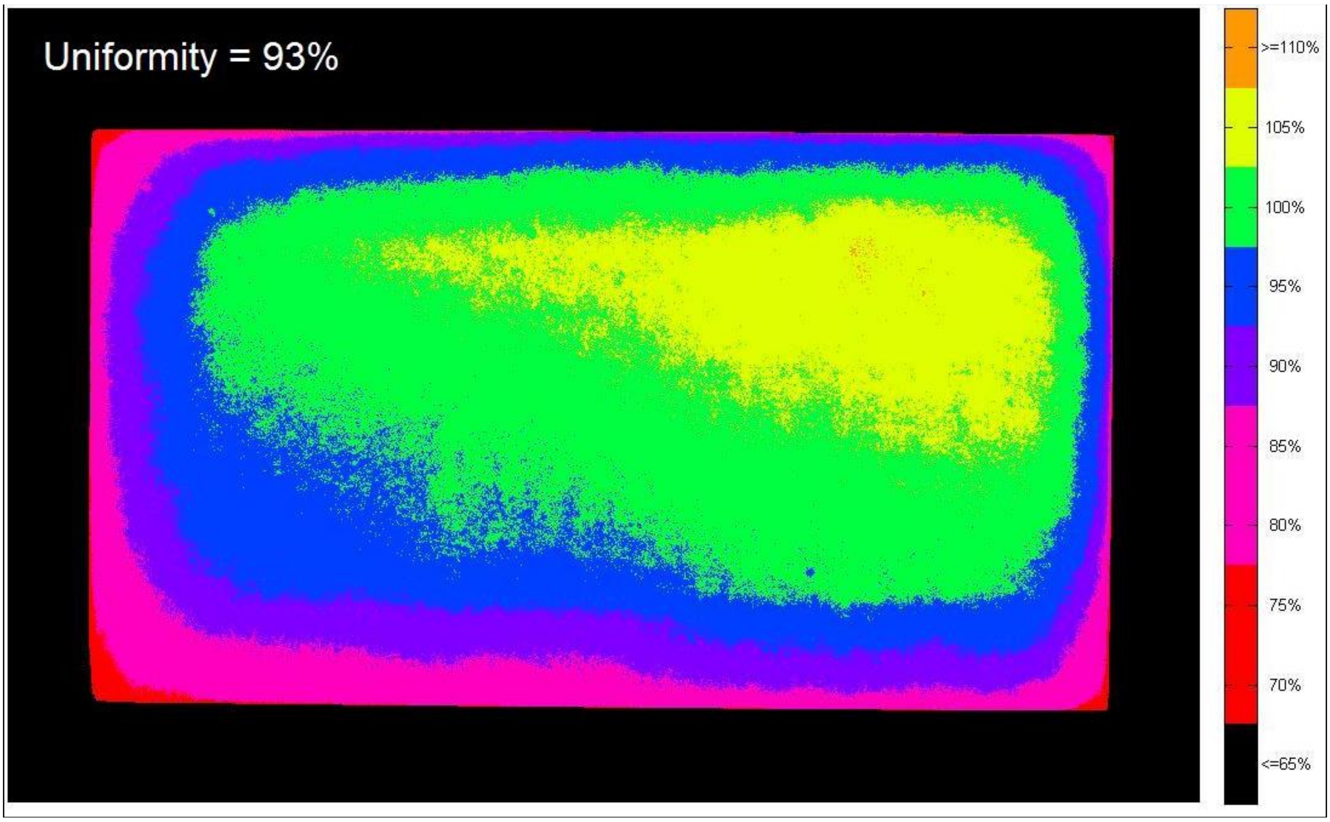


Figure 22: Uniformity Measurement representation (example)

2.8 Viewing-angle dependency

2.8.1 Measurement conditions

The test input is a series of test patches in measurement position 1 (Figure 4) in the centre of an otherwise black frame. The patch is a square of dimension H/7.5 (13.13 % of picture height, H), with a level as per Table 10. Test patterns EBU_4-1, EBU_4-2, EBU_4-10 and EBU_4-19 may be used.

Table 10: Code values for grey-scale test patches for viewing-angle dependency measurements

Grey-scale Measurement Number	Code Value @10-bit
1	64
2	86
10	502
19	940

The measurements must take place in a darkened room, avoiding any extraneous light falling on the sensor. Luminance is measured for grey-scale measurement numbers 1 and 19. Chrominance (in CIE 1976 u'v') is measured for grey-scale measurement numbers 2, 10 and 19.

A full set of viewing angle measurements is defined as:

- A series of luminance measurements is taken over the horizontal range of viewing angles from -30° to +30° with the white patch (Test pattern EBU_4-19), with vertical inclinations of 15 degrees below horizontal (-15°), horizontal (0°) and at 15 degrees above horizontal (+15°).
- A series of luminance measurements is taken over the horizontal range of viewing angles from -45° to +45° with the black patch (Test pattern EBU_4-1), with vertical inclinations of 20°, 0° and +20°.
- A series of luminance and chrominance measurements is taken over the horizontal range of viewing angles from -45° to +45° with the white patch (Test pattern EBU_4-19), with vertical inclinations of 20°, 0° and +20°.
- A series of chrominance measurements is taken over the horizontal range of viewing angles from -45° to +45° with the grey patches (Test patterns EBU_4-2 and EBU_4-10) with vertical inclinations of 20°, 0° and +20°.

For situations where viewing angle is less critical or where such measurements are not physically possible, only the measurement of the extremes in the horizontal domain need be undertaken. However, such a limitation in measurement shall be noted in any report issued and shall not be used to assign an EBU Grade status to a product.

Measurement point: 1.

Measurement equipment: Tristimulus meter or spectroradiometer equipment.

2.8.2 Presentation of the measurement results

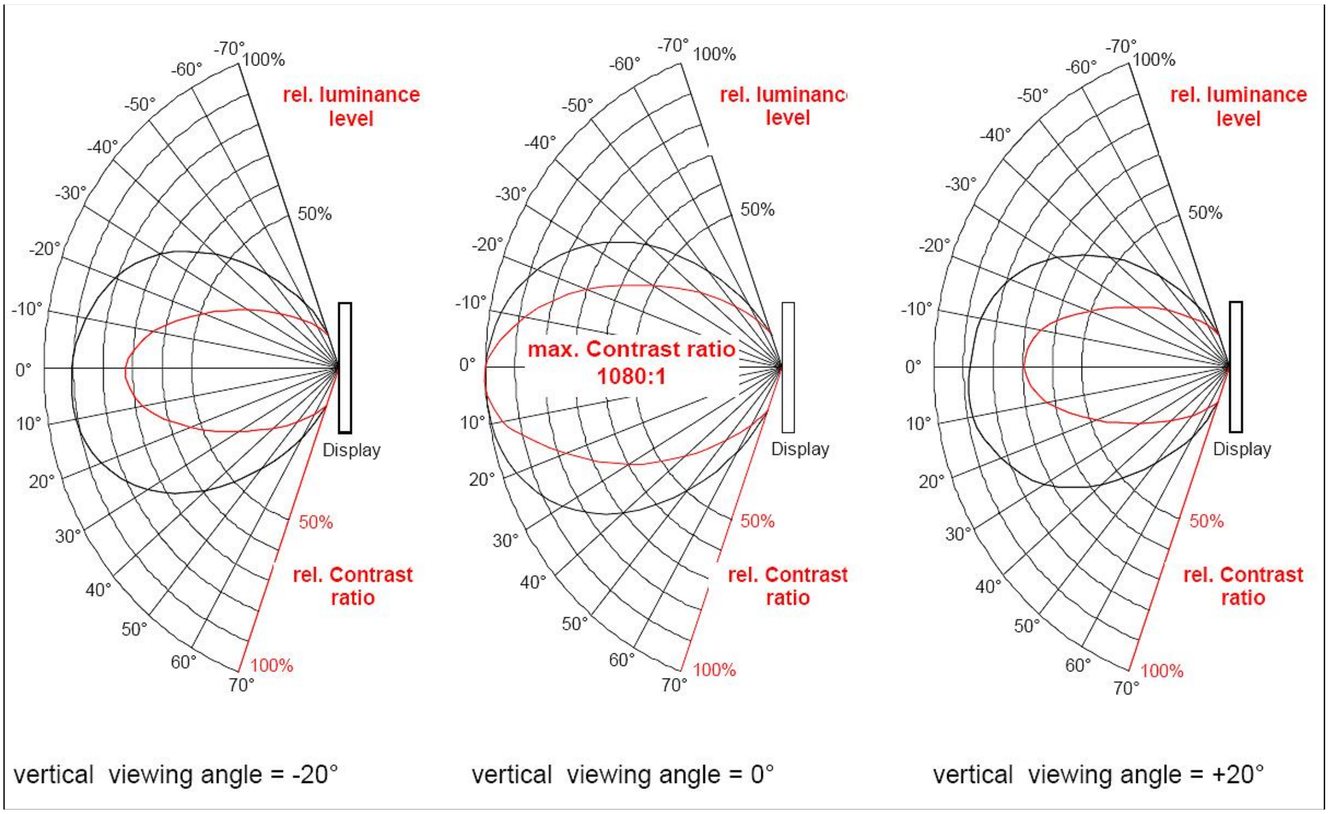


Figure 23: Viewing Angle Dependency measurement results presentation (example)

Figure 23 shows an example for 20°; similar diagrams are used for 15°.

For the chrominance measurements the results should be tabulated and presented in diagrams as shown in Figures 24, 25 & 26.

2.9 Motion artefacts

Metrics and methods for the quantitative measurement of motion artefacts are not available now. Until they are, subjective assessment shall be used as an evaluation method. To provide a visual check on motion rendition a test sequence with scrolling text is provided as Test sequence EBU_6.

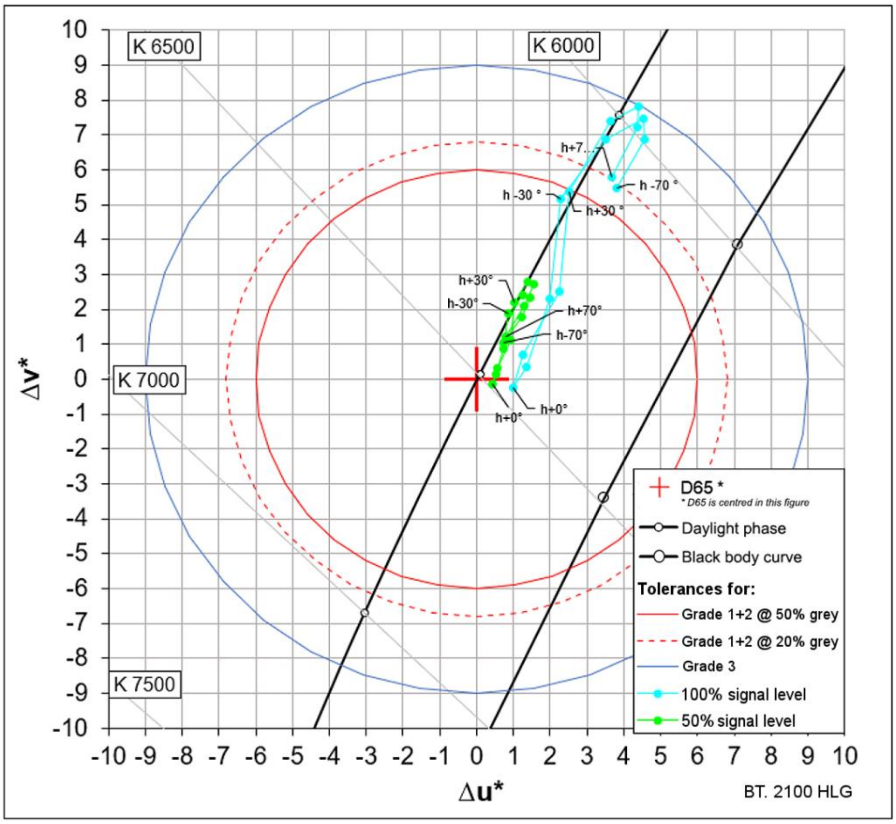
2.10 Screen resolution

Whilst the manufacturers' data should indicate conformance with the requirement, a visual check of conformance can be performed by conducting a set of tests using (e.g.) Test pattern EBU_7, in 1280 x 720, and 1920 x 1080 versions.

Presentation of results:

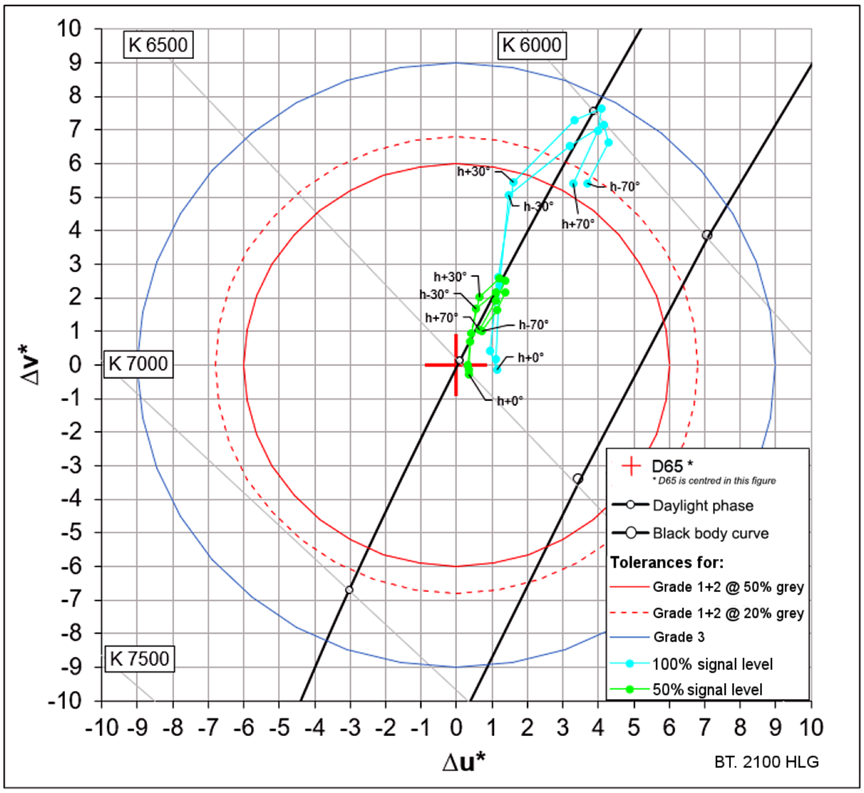
Table 11: Screen resolution visual check results presentation (example)

Resolution:	Manufacturers Data:	'x'	Confirmed: Yes ▫ , No ▫



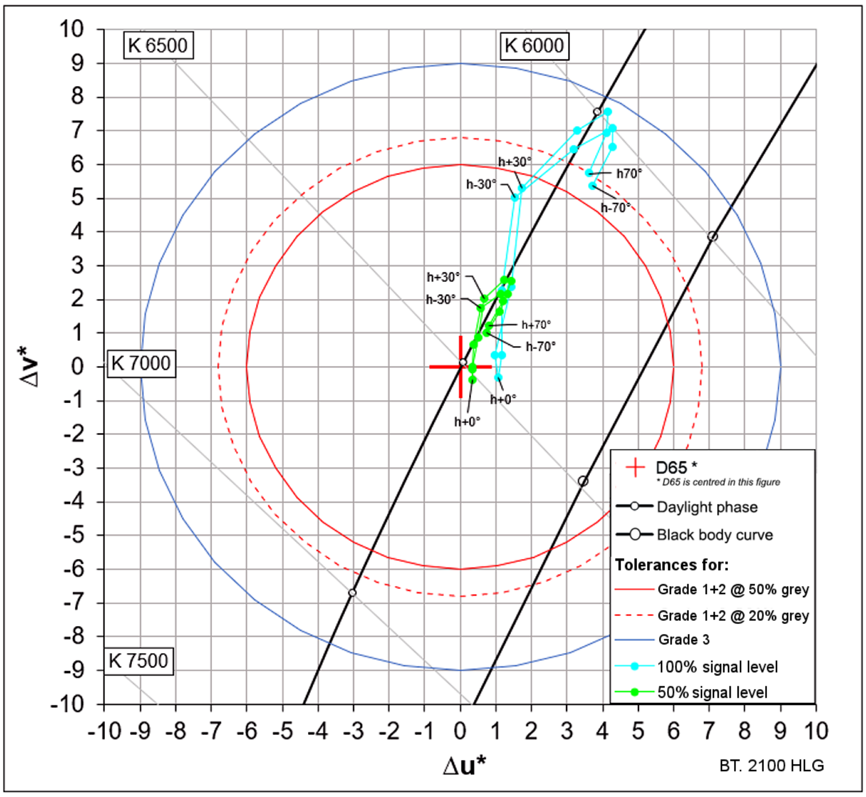
Viewing-angle chrominance change at 0° vertical inclination

Figure 24: Chrominance changes measurement results presentation at 3% grey-level with EBU tolerance circles (examples)



Viewing-angle chrominance change at -15° vertical inclination

Figure 25: Chrominance changes measurement results presentation at 50% grey-level with EBU tolerance circles (examples)



Viewing-angle chrominance change at +15° vertical inclination

Figure 26: Chrominance changes measurement results presentation at 100% grey-level with EBU tolerance circles (examples)

2.11 Image scaling, de-interlacing and overscan

Test pattern EBU_7 will also enable the visual confirmation of the scaling quality, overscan and, for HD progressive inputs, that the image is not inappropriately de-interlaced.

A valid conclusion of this test might be that the monitor is not suitable for monitoring signals that have a pixel structure that does not scale well to the native resolution of the display.

Test sequence EBU_6, with scrolling text, is available as an aid to assessment of de-interlacing quality. PSF (progressive segmented frame) versions are provided for assessment of the display's ability to correctly display such material.

To test for the presence of a field dominance problem, Test sequence EBU_8, which includes a portion with field lines out of order, may be used.

This test procedure is just a visual check, no quantitative measurement is required.

Table 12: Image scaling, de-interlacing and overscan test results presentation (example)

Test signal	1920 x 1080i	1280 x 720p
Scaling quality (Overscan off):	Appears to be unscaled - good	Some slight ringing on horizontal edges
Interlace material displayed native?	Yes ▫ , No ▫	N/A
De-interlacing modes:		
Short delay display mode:	Some compromises evident	N/A
normal display mode:	Good	
Film mode/ psf detection:		
Short delay display mode:	Yes ▫ , No ▫	N/A
normal display mode:	Yes ▫ , No ▫	N/A
Field dominance problem exhibited?	Yes ▫ , No ▫	N/A
Entire picture seen with overscan off?	Yes ▫ , No ▫	Yes ▫ , No ▫
Overscan mode available?	Yes ▫ , No ▫	Yes ▫ , No ▫

2.12 Delay time

A variety of methods can be used to measure the delay between the arrival of the electrical signal and its appearance on the screen. A scanning display will have a different characteristic from a display that reads a whole frame before displaying it.

For the following measurements, Test sequences EBU_9-top and EBU_9-centre are used. These contain five lines of peak white in a single field (i.e., a white flash in an otherwise black signal). The transition between black and white is at the top of the screen (9-top) for the first measurement and at the middle of the centre line (9-centre) for the second measurement.

Manufacturers are requested to explicitly state the delay time relating to the top line of the screen, and so the delay at this point on the screen should be measured:

> ***Note:*** *The delay reported should be the time between the arrival of the timing transition in the serial electrical signal at the monitor input and the moment at which the light output from the screen has risen to 50% of its final value.*

The most important issue is that of lip-sync and to assess this, a second test position at the centre (both vertically and horizontally), of the screen is used.

> ***Note:*** *The delay reported should be the time between the arrival of the timing transition in the serial electrical signal representing the middle line of the image at the monitor input and the moment at which the light output from the screen has risen to 50% of its final value.*

Any variation between these two measurements is interesting as part of the understanding of the delay characteristic of the screen.

The usual test method to detect the light output from the screen will involve the use of a photodiode that only covers a few display lines. The time delay between the electrical and optical signals is determined on an oscilloscope. Since the delays concerned are of the order of ms, the ramp-up of the photo diode detector (of the order of hundreds of μs) as the 5 lines are illuminated in sequence is not significant. Any A-to-D or D-to-A converters that are included in the test arrangement should be tested to confirm that they have negligible delay, or that their delay is accounted for.

A block diagram showing the possible arrangement of the equipment is given below.

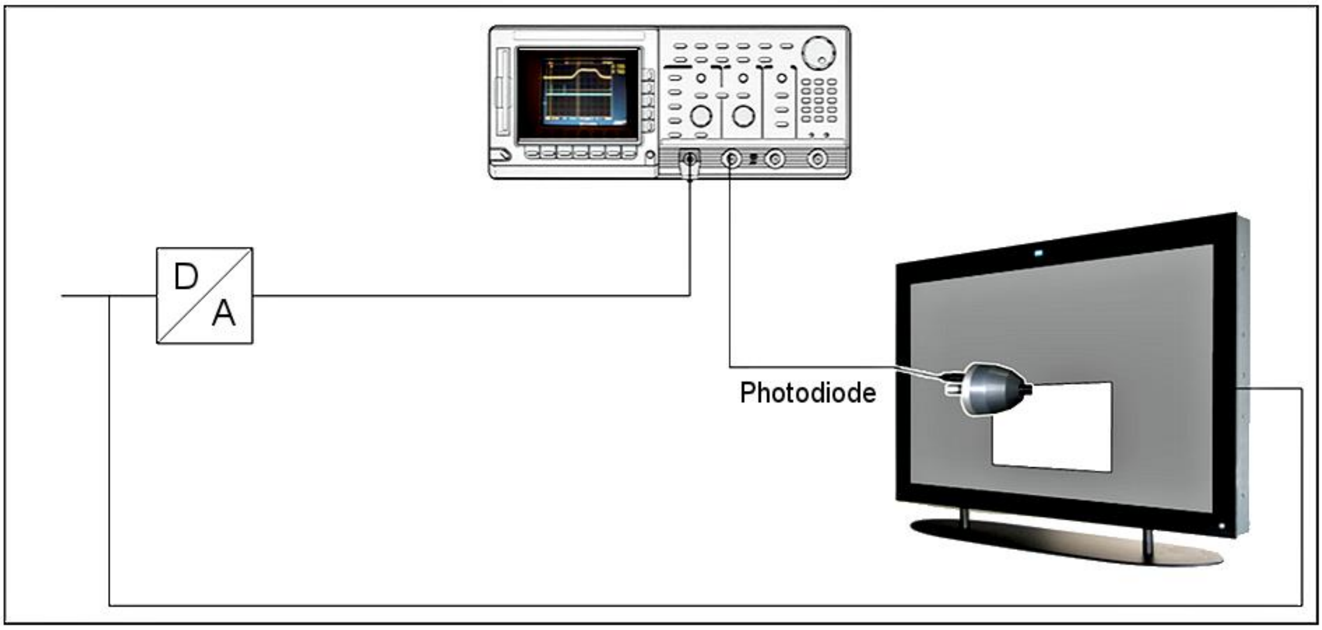


Figure 27: **Arrangement of equipment for the measurement of a/v delay**

Table 13: Delay measurement results presentation (example)

Test signal:	1920 x 1080i/25	1280 x 720p/50
Short delay display mode:	Top: delay: . . . . ms Centre: delay: . . . . ms	Top: delay: . . . . ms Centre: delay: . . . . ms
Normal display mode:	Top: delay: . . . . ms Centre: delay: . . . . ms	Top: delay: . . . . ms Centre: delay: . . . . ms

2.13 Mura (imperfections in LCD, LED and OLED panels)

VESA FPDM2 [4], section 301-3D defines a suitable test procedure.

Note: 'Mura' is a defect that looks like a small-scale crack with very small changes in luminance or colour. 'Mura' is likely to be noticeable in the flat portions of images even if the size of the Mura is very small. Mura will be revealed in a small area uniformity test.

2.14 Stability

Stability of black level, white level and colour temperature should be measured regularly over the first 30 minutes. Results for black and white levels should be normalised to 100% and plotted against time. Colour temperature variations with time should be plotted on a diagram like Figure 20. Any variation in black level visible using PLUGE should be reported.

2.15 Pixel defects

A high-resolution photograph (or a series of photographs covering the whole the screen area) on which it is possible to resolve the individual sub-pixels, should be taken on 10% and 50% signal level grey frames, to check for both bright and dark stuck or dead pixels. Pixel defects, classified according to ISO 13406 2 [15], should be reported.

Pixels which are stuck on or are stuck at a high luminance level are detected by displaying a black frame. Pixels which are stuck off or stuck at a low luminance level can be detected using 100% level red, green and blue frames.

2.16 Ringing and handling of under- and over-shoots

A visual check at a viewing distance of 1H is made using Test pattern EBU_10. Any visible ringing or overshoots generated by the display should be reported.

If sub-black and super-white patches of a test signal (for example, PLUGE) are not reproduced, this should be reported, since it indicates that overshoots present in the signal may be disguised.

2.17 Treatment of illegal signals

Hyperbolic zone plates such as those in Test pattern EBU_7 provide a useful indication of the behaviour of a display in handling frequency components beyond the theoretical channel limit.

A test pattern that includes out-of-range colours should be used to check how the display handles such colours.

Note that signals can be within the range standardised for YCbCr but when matrixed to RGB do not fall within the 10-bit code value range – these are defined as out-of-range colours.

2.18 Image sticking (long-term after-image)

The luminance levels are measured on a 50% grey frame (test pattern EBU_12-grey) at measurement locations 9 and 12. A test pattern having 90% grey on the left-hand side of the screen and 10% grey on the right (and with a gentle transition at the join – Test pattern EBU_12-burn) is displayed for 1 hour. Then the 50% grey frame is displayed for 1 hour. At the end of that time the measurements are repeated, and the results tabulated.

If image sticking or burn-in appears to be an issue, the user might, in consultation with the manufacturer, consider conducting a test such as that specified in VESA FPDM2 [4], section 305-2. Problems with image retention are discussed in EBU R 129 [16].

2.19 Signal interfaces

Measurements of conformance to interface standards may be undertaken as specified in the relevant interface standards documents.

2.20 Acoustic Noise

Acoustic noise standards used are the Noise Rating (NR) curves defined by Kosten and van Os [17] and standardised in now withdrawn versions of ISO 1996. An example of the presentation of results is shown in Figure 28.

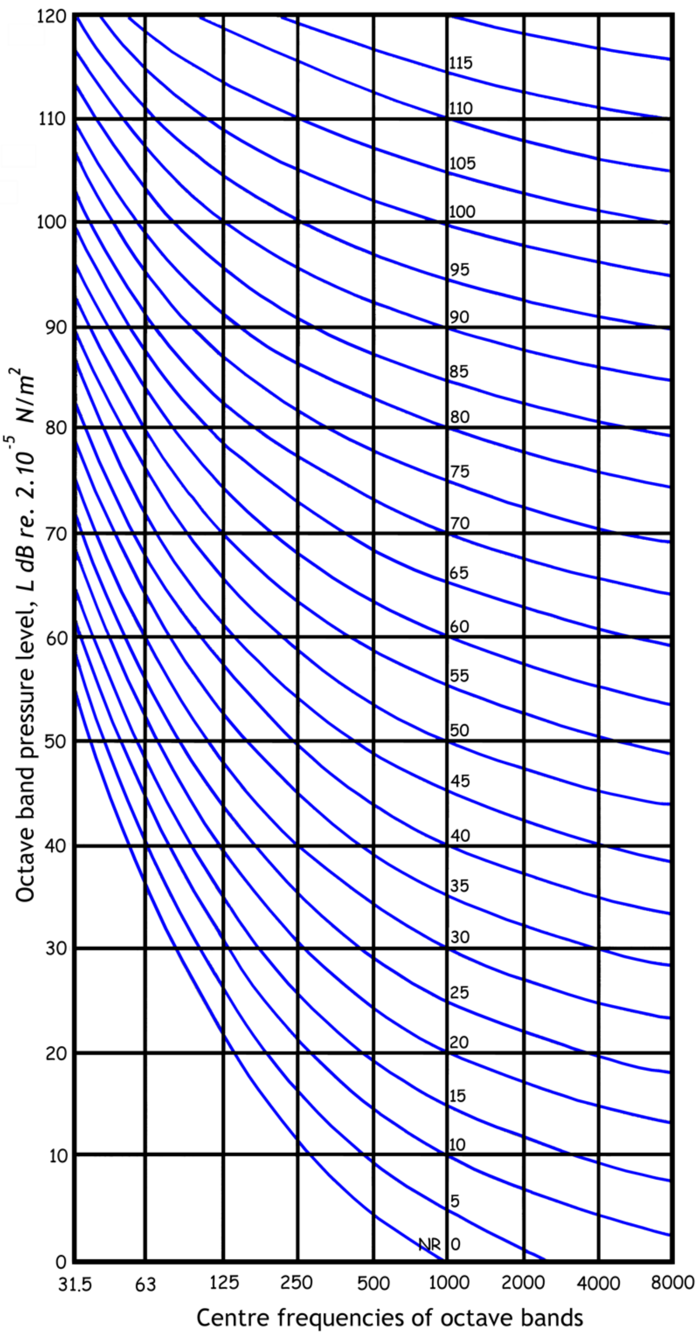


Figure 28: Noise Rating (NR) Curves

2.21 Crosstalk and Streaking

Flat panel display devices can exhibit crosstalk between line or column circuitry, between power supply and line or column circuitry or from induced current in circuitry by external influences such as Electro-Magnetic Interference. The perceived visual artefact caused by crosstalk is known as streaking.

3 Measurements for HDR and WCG Displays

3.1 Test patterns for HDR and WCG

With the introduction of HDR there are two transfer functions which must be taken account of for display measurement: ITU-R BT.2100 HLG and ITU-R BT.2100 PQ [6]. Furthermore, there is also the distinction of signal level definitions (see Introduction and EBU R 103 [2]): narrow and (SDI) full. ITU-R BT.2100 HLG is defined as a narrow range signal. ITU-R BT.2100 PQ is mainly used as a full range signal (0 to 1023 in a 10-bit environment, 4 to 1019 for SDI) but can also be used as narrow range. This document uses the following nomenclature: 'Test pattern EBU_n_x_y' where n identifies the test pattern number, x the test point or variation and y one of the following encoding variants:

- _BT2100HLG: 100% signal level of HLG, SDI narrow range
- _BT2100HLG75: 75% signal level of HLG, SDI narrow range
- _BT2100PQ_full: 100% signal level of PQ (Lref =10.000 cd/m²), SDI full range
- _BT2100PQ_narrow: 100% signal level of PQ (Lref =10.000 cd/m²), SDI narrow range
- _BT2100PQ58_full: 58% signal level of PQ (Lref =203.15 cd/m²), SDI full range
- _BT2100PQ58_narrow: 58% signal level of PQ (Lref =203.15 cd/m²), SDI narrow range
- _BT2100PQ1000nit_full: 75.2% signal level of PQ (Lref =1000 cd/m²; reference peak luminance of a Grade 1 display), SDI full range
- _BT2100PQ1000nit_narrow: 75.2% signal level of PQ (Lref =1000 cd/m²; reference peak luminance of a Grade 1 display), SDI narrow range.

An example is 'Test pattern 3_05_BT2100PQ58_full'. When performing measurements of a device under test, the correct set of Test patterns for the monitors operating setting shall be used.

	Coordinates (rel. to screen centre)	
Measuring Point	w	h
1 (screen centre)	0	0
2 and 5	0	±0.4 H
9 and 12	±0.4 W	0
Each patch is a square of dimension H/7.5 (13.13% H)		

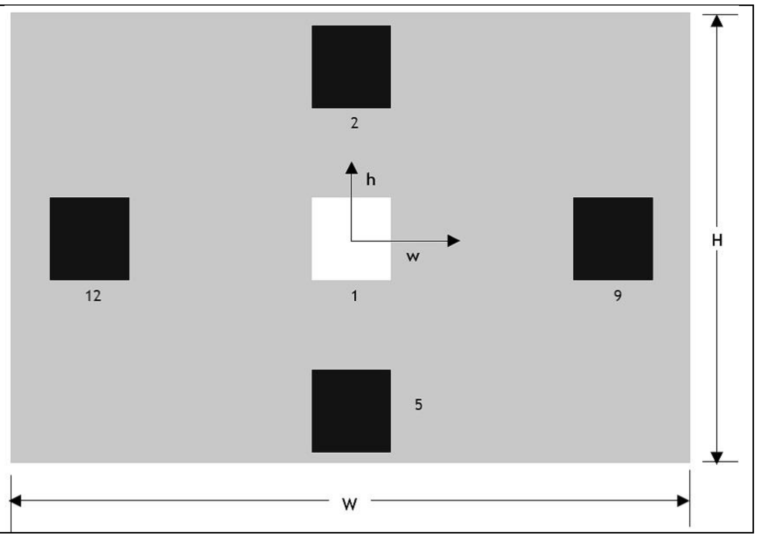


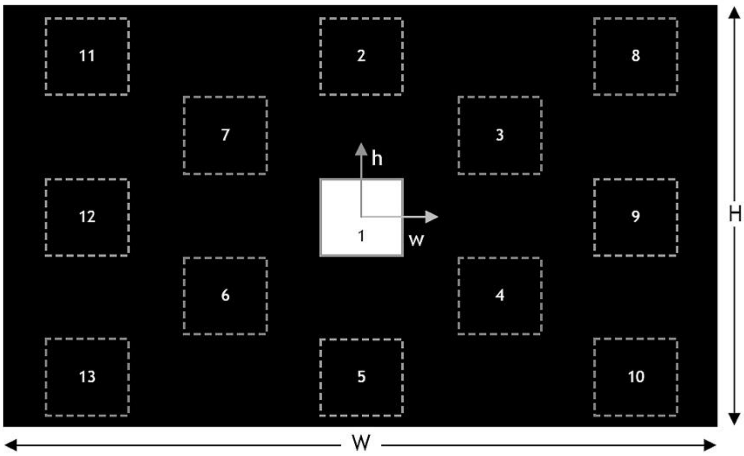
Figure 29: Test pattern EBU_1, Black, white and simultaneous contrast

Test pattern EBU_1 (see Figure 30) consists of a nominal peak white level patch surrounded by four black level patches (0%), all set against a background of 38.2% grey signal for ITU-R BT.2100 HLG and PQ (CV 399). The digital references for these levels are defined in the preamble.

Test pattern EBU_2 is the same as pattern 1, except that the white patch is now “Super white” (CV 1019). The pattern includes text to indicate this.

Test pattern EBU_3-xx provides white patches at all 13 test points defined in Figure 30, on a black frame. A set of 13 patterns (pattern EBU_3-1 to EBU_3-13) illuminates each individual patch in turn. Pattern EBU_3-black is a completely black image. Pattern EBU_3-white is a completely (100%) white frame.

	Coordinates (rel. to screen centre)	
Measuring Point	w	h
1 (screen centre)	0	0
2 and 5	0	±0.4 H
9 and 12	±0.4 W	0
3, 4, 6 and 7	±0.2 W	±0.2 H
8, 10, 11 and 13	±0.4 W	±0.4 H
Each patch is a square of dimension H/7.5 (13.13% H)		

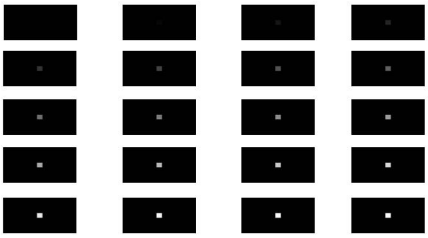


Digital video signal (code value) 10-bit	ITU-R BT.2020 SDR	ITU-R BT.2100 HLG	ITU-R BT.2100 PQ58_full	ITU-R BT.2100 PQ58_narrow
Black (background)	64	64	4	64
White patch (HDR reference white)	940	721	594	573

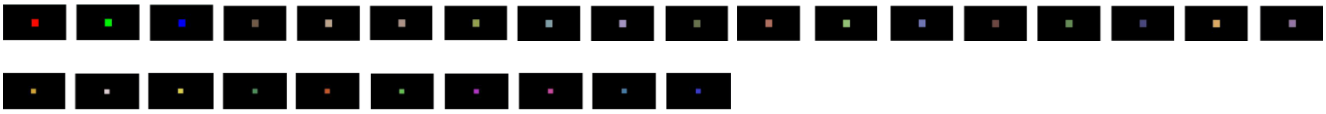
Figure 30: Test patterns EBU_3-1 to EBU_3-13

Test patterns EBU_3-1_4, EBU_3-1_10, EBU_3-1_25 and EBU_3-1_81 are versions of EBU_3-1 but with the white patch occupying respectively 4%, 10%, 25% and 81% of the screen area. When running HDR measurements the white patch uses HDR reference white level (according to 203.15 cd/m²).

Test patterns EBU_4-xx are similar to EBU_3-1 but with the patches having the grey-scale values as set out in Table 16.



Test pattern EBU_5-xx is a series of patterns based on pattern EBU_3-1 but with the corresponding primaries red, green, blue and the 31 EBU test colours. The definitions of the colours are listed in § 3.6.1



Test sequence EBU_6 is scrolling text, both horizontally and vertically, at a variety of motion rates.

Test pattern EBU_7 is designed to enable a visual evaluation of various elements of monitor performance including fine gradations of colour, overscan, and filtering/scaling performance including filtering between YCbCr and RGB.

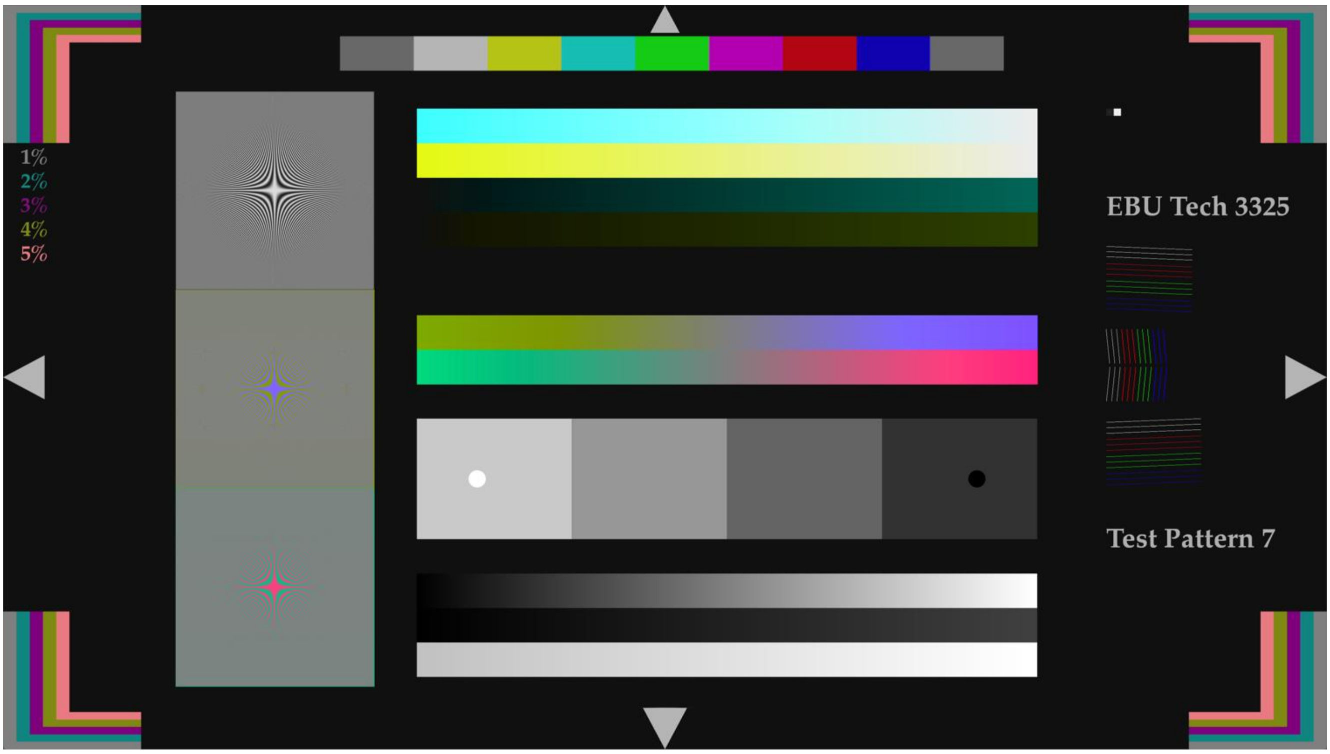


Figure 31: Test pattern EBU_7

Test sequence EBU_8 is not available for HDR.

Test sequences EBU_9-top and **EBU_9-centre** provide a 9-line flash in a single 1080p frame (18 lines in a 2160p frame) for determining delay.

Test pattern EBU_10 has a series of horizontal and vertical transitions between white, black and mid-grey, conditioned by the appropriate channel filter**.**

Test pattern EBU_11 includes a ramp of luma from sub-black to super-white, with similar ramps for each chroma signal superimposed on it.

Test pattern EBU_12-grey is a flat 50% grey frame. **Test pattern EBU_12-burn** has 90% grey on the left-hand side of the screen and 10% grey on the right with a gentle transition at the join)

These test patterns are available online, see: tech.ebu.ch/publications/tech3325-testpatterns

3.2 Luminance range

3.2.1 White level

For HLG or narrow range PQ, the monitor is set to display Test pattern EBU_1 (Figure 2). For full range PQ Test pattern EBU_1 is available, too.

Measurement point: 1 in Figure 4

Measurement equipment: Luminance meter

Note: other measurement methods are possible, for example using a spectroradiometer.

Measurements are made to establish that the monitor can meet the specifications set out in EBU Tech 3320, and these results are reported in a table, such as Table 14.

3.2.2 Super white level and overrange code values

'Super white' describes the display's response to code values larger than the peak of the narrow range signal. For HLG and narrow range PQ this is measured using Test pattern EBU_2. In the HLG case it ensures that super white can be correctly displayed by the monitor. For narrow range PQ the display is expected to indicate the signal is out of range. For more details, see EBU Tech 3320. Note: for full range PQ, there is no concept of super white or overrange code values.

Table 14: White level measurements results
(narrow range example using 'Test pattern 2_BT2100HLG)

Grade Luminance Settings	Grade 1A & 1B ≥1000 cd/m^2	
Grade Luminance Settings	Grade 2 ≥600 cd/m^2	
Grade Luminance Settings	Grade 3 ≥500 cd/m^2	
Measuring	White	109%
pattern	EBU_1	EBU_2
Luminance	1000.7 cd/m^2	1020.6 cd/m^2

3.2.3 Black level

Prior to undertaking tests in this section, the tester should verify that the measurement device used can accurately measure the black level of the device under test.

White level is set to 1000 cd/m^2 for HDR Grade 1, at least 600 cd/m^2 for HDR Grade 2 and at least 500 cd/m^2 for HDR Grade 3. These white levels are used as Y_n values for further calculations. Black level is set using the PLUGE test signal. During the adjustment, it should be checked whether the sub-black of the PLUGE test signal is observable. (Note: it is not considered acceptable for a monitor acting as a measurement tool to electronically clip the sub-black signal). This test uses Test pattern EBU_3-black.

Measurement points: 2, 5, 9 and 12 in Figure 4.

Measurement equipment: Luminance meter

Note: other measurement methods are possible, for example using a spectroradiometer

Measurement result:

Table 15: Black level measurements results (example)

Measuring -pattern / -point	Black 1
2	0.009 cd/m^2
5	0.017 cd/m^2
9	0.061 cd/m^2
12	0.059 cd/m^2
Average	0.037 cd/m^2
Measurement tool:	e.g., tristimulus meter, average of 5 readings
Sub-black can be made visible:	yes

3.3 Contrast ratio

The contrast of a display can be defined as follows:

$$C = \frac{L_{\max}}{L_{\min}}$$

Where L_{max} is the luminance reproduced with nominal peak white and L_{min} that reproduced with black. Assuming that black level has been set correctly, then in a darkened room L_{min} may be zero with no signal and hence contrast could theoretically be infinite. However, in the presence of ambient lighting, inaccurately set black level, or due to limitations of the display technology, L_{min} will be non-zero thus giving rise to a wide range of values for contrast.

Clearly, the use of separate white and black signals for the measurement of L_{max} and L_{min} can result in many different values for contrast, and therefore contrast must be calculated using measurements of white and black from within only one test. The simultaneous display contrast thus derived may contain an element of flare due to the presence of nominal peak white and, again, the result will depend on the nature of the test signal and the way the display was set up. It is however aimed at providing a realistic measure of contrast under real viewing conditions for real picture content.

Note: Large discrepancies between results for the measurements defined in § 3.3.1 and § 3.3.2 may indicate a limitation in the display's ability to accurately display images with higher average picture levels.

For measurement conditions see § 1.1.4.

3.3.1 Simultaneous display contrast

A suitable test signal for contrast measurement is Test pattern EBU_1.

For this test, the measurement must be made under professional/operational viewing conditions, and the display set up with a PLUGE test signal specifically for this one measurement, as indicated in § 1.1.4.

Note: The measurement method is equivalent in result (if not in detail of calculation order and viewing conditions) to ITU-R BT.815-1.

3.3.2 Full screen contrast

Suitable test signals for full screen contrast measurement are:

- Test pattern EBU_4-19 i.e., a nominal peak (100%) white patch occupying 1% of the screen area in the centre of a black screen.
- A completely black screen, test pattern EBU_3-black, (with the set switched on and set up as for the other measurements) in a dark room.

Further test patterns (patterns EBU_3-1_4, EBU_3-1_25 and EBU_3-1_81 as ITU-R BT.2020, ITU-R BT.2100 HLG or ITU-R BT.2100 PQ), with the white patch occupying a larger percentage of the screen area. IEC 60107-1:1997 7.1.4 [9] describes a peak luminance (SDR) or HDR reference white measurement (and hence contrast) using input signals displaying different window sizes (1%, 4%, 25%, 81%) of white area.

The black level L_{min} should be the mean of measurements made of the five positions (1, 2, 9, 5, 12), the white level L_{max} should be measured in the central position (1).

"Full screen (1% patch) contrast" is defined as the ratio between the luminance of the screen when displaying nominal peak white on 1% of the screen area, and the luminance measured when displaying full screen black.

If a display is found to exhibit a fall-off in peak luminance with the size of the white patch, then 4%, 25% and 81% contrast measurements should also be made. "Full screen (x% patch) contrast" is defined as the ratio between the luminance of the screen when displaying x% area patch of white and when displaying full screen black level measured in a completely dark room.

> ***Note:*** *The measurement must be performed in a completely dark room. Before making these measurements, white is set to the peak luminance the display is capable of for HDR using Test pattern EBU_2, and black level set using PLUGE.*

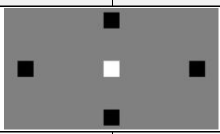
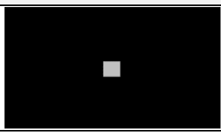
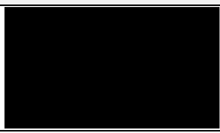
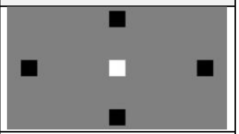
Measurement equipment: Luminance meter

> ***Note:*** *other measurement methods are possible, for example using a spectroradiometer.*

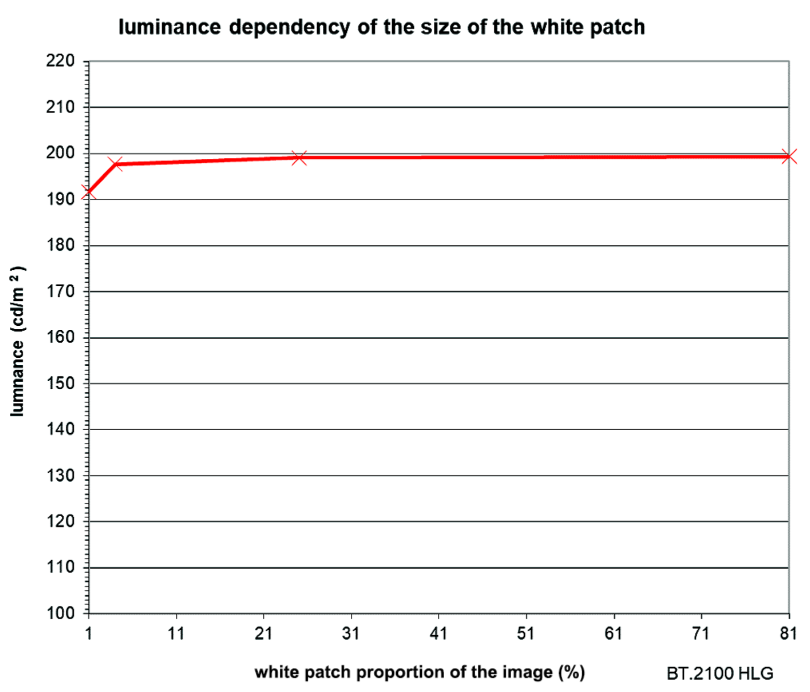
Table 16: Contrast ratio measurement results (example)

Measuring pattern / point	Simultaneous Display Contrast			Full Screen Contrast		
	White	Black	Contrast	White	Black	Contrast
	1	1	C_S	4-19	3-black	C_F
1	994.932	[cd/m²]		965.214	[cd/m²]	
2	[cd/m²]	0.009		[cd/m²]	0.00061	
5		0.017	27165		0.00056	1699258
9		0.061			0.00058	
12		0.059			0.00053	
Average	994.932	0.037		965.214	0.00057	
Measurement tool:	e.g., xyz tristimulus meter, average of 5 readings					

⇧

Simultaneous Display Contrast			Full Screen Contrast			109% White 'Super White'
White	Black	Contrast	White	Black	Contrast	
cv 940	cv 64		cv 940	cv 64		cv 1019
		C_S			C_F	
994.932 [cd/m²]	0.037 [cd/m²]	27165	965.214 [cd/m²]	0.00057 [cd/m²]	1699258	962.394 [cd/m²]

(cv = "code value") L_W L_B



Desired value: 197.774 cd/m²

Full screen contrast fall-off luminance

Pattern no.	Pattern size (% of screen)	Luminance (cd/m²)
3-1-1	1	191.750
3-1-4	4	197.733
3-1-25	25	199.096
3-1-81	81	199.323

Figure 32: Luminance measurement vs. patch size (area) measurement results (example)

3.4 Electro-Optical Transfer Function

3.4.1 Measurement procedure

For this measurement it is essential that the measurement conditions described in 3.1 are correctly set.

When measuring a transfer function, it is required to measure the light output level over the complete nominal video range between black (digital luma signal level of 64 in 10-bit digital representation and 512 for chroma), and nominal peak white (digital luma signal level of 940 in 10-representation and 512 for chroma) for narrow range signals. If ITU-R BT.2100 PQ in full range is set the patches are identical but with a black background of code value 4.

Testers should note that although u'v' are not used for this test, they are required for later tests.

The test inputs (patterns 4-1 to 4-19) are a series of test patches in measurement position 1 (Figure 4) in the centre of an otherwise black frame. The patch is a square of dimension H/7.5 (13.13% of picture height, H) having levels disposed between digital luma levels 64 and 940, such that there is an equal interval between each, except near black and white, according to the following table:

Table 17: Luma levels of grey-scale test patches

Grey-scale Measurement No.	Luma level in 10-bit
1	64
2	86
3	138
4	190
5	242
6	294
7	346
8	398
9	450
10	502
11	554

Grey-scale Measurement No.	Luma level in 10-bit
PQ-Ref (58%)	594 (PQ, SDI full range) 573 (PQ, narrow range)
12	606
13	658
14	710
HLG-Ref (75%)	721 (HLG)
15	762
16	814
17	866
18	918
19	940
20	1019

The brightness and contrast settings of the monitor must not be altered during the measurements.

The tolerances required for an HDR monitor are calculated using the Excel document EBU Tech 3325s2 [18]. This will generate a plottable Transfer Function curve with upper and lower tolerance limits. L_W in the Excel document is the peak luminance of the monitor. Calculation of tolerance ranges is based on the 20% and 80% HLG signal output luminance levels in cd/m^2 and matches for both HLG and PQ measurements.

Measurement equipment: Luminance meter

> ***Note:*** *other measurement methods are possible, for example using a tristimulus meter or spectroradiometer equipment*

3.4.2 Presentation of the measurement results

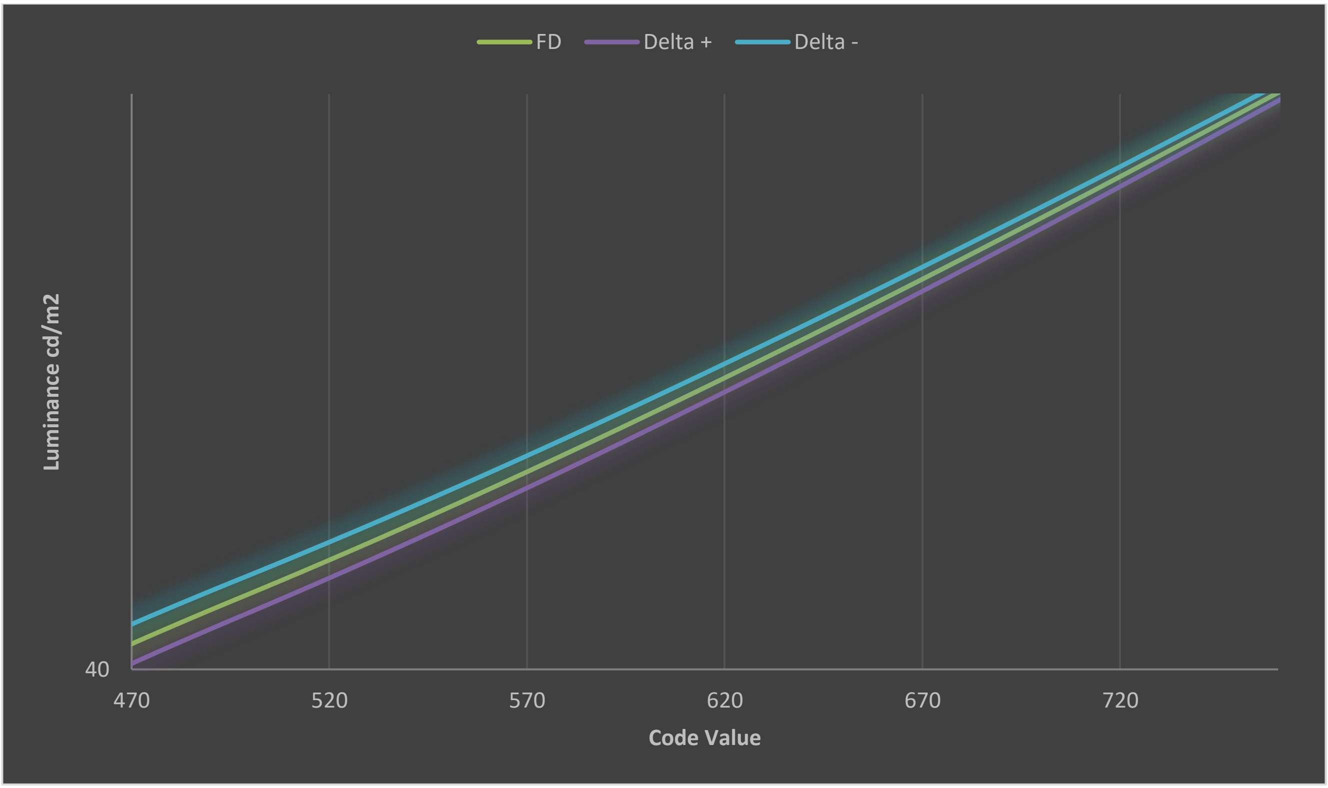


Figure 33: Presentation of HLG – rel. Luminance level vs. grey level (%) (example)

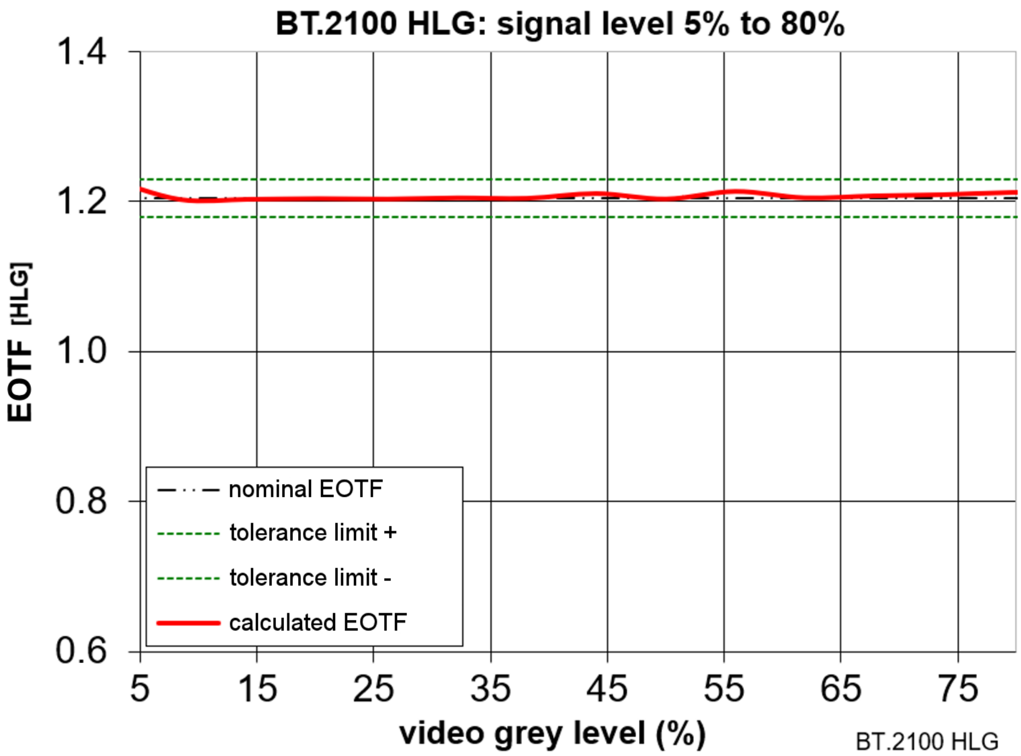


Figure 34: Presentation of HLG - HLG value vs. grey level (%) (example)

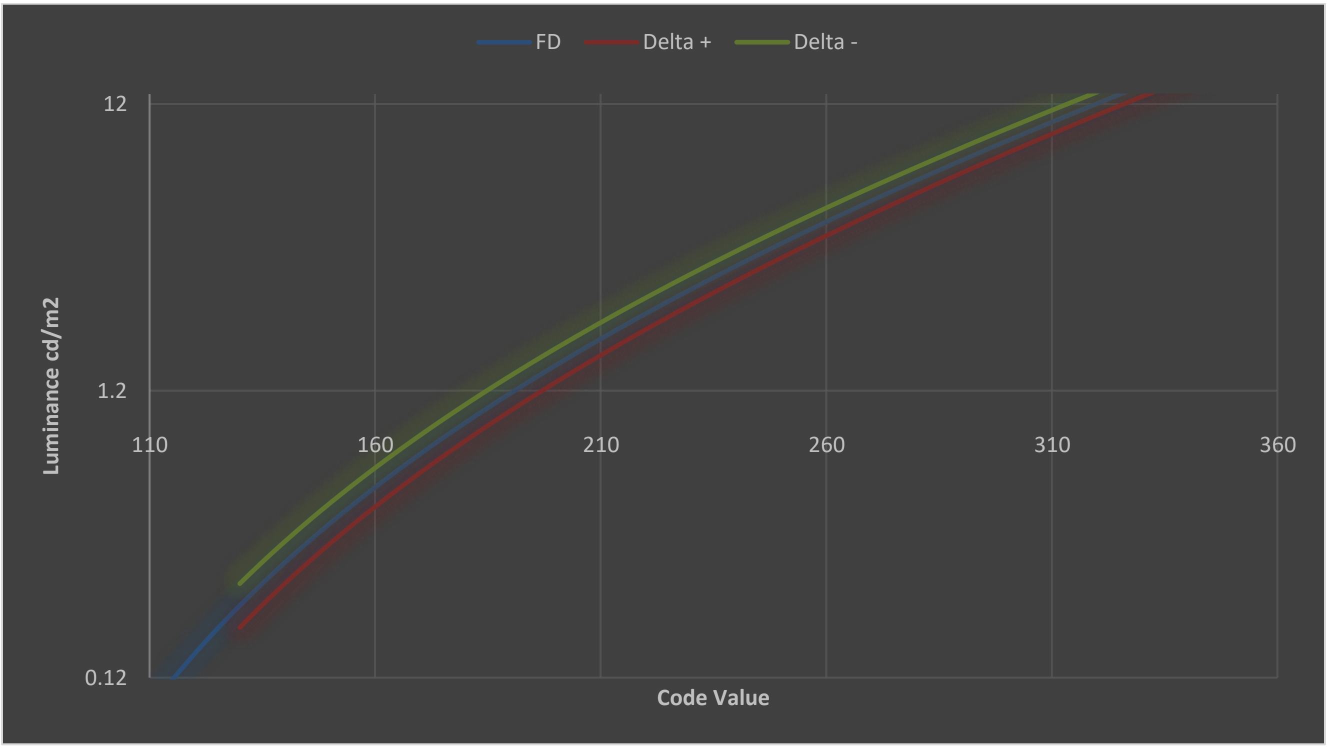


Figure 35: Presentation of PQ - Code Value vs. absolute luminance measured on the screen (example)

3.5 Grey scale reproduction

3.5.1 Measurement conditions

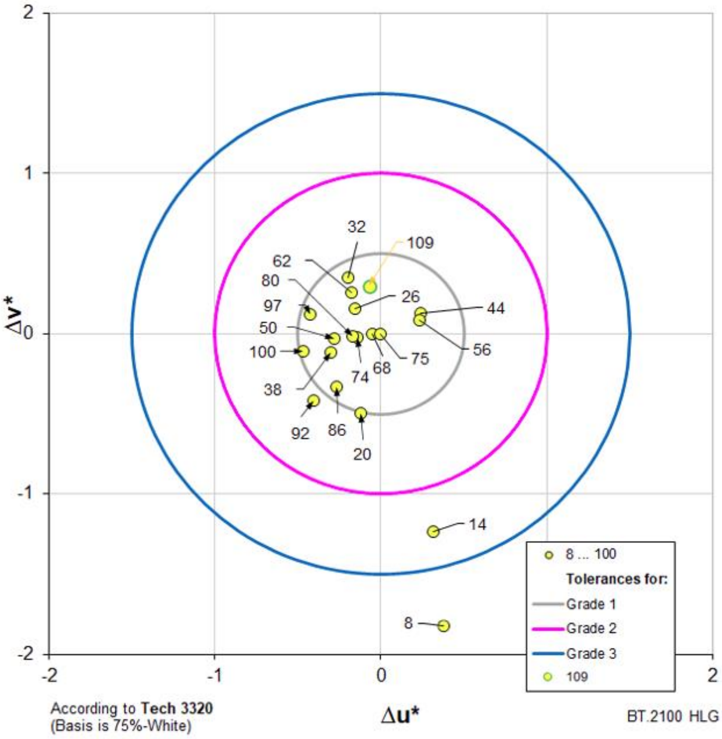
The test input consists of Test patterns EBU_4-1 to EBU_4-20. It is essential that the measurement conditions described in § 3.2 are correctly set.

Measurement point: 1

Measurement equipment: Tristimulus meter or spectroradiometer equipment

3.5.2 *Presentation of the measurement results*

Measurement result:



"EBU-Grade 1": within the grey circle.
"EBU-Grade 2": within the pink circle.
"EBU-Grade 3": within the blue circle.

Figure 36: Grey Scale Reproduction (example)
(centre: 75% luma level for HLG, 58% luma level for PQ)

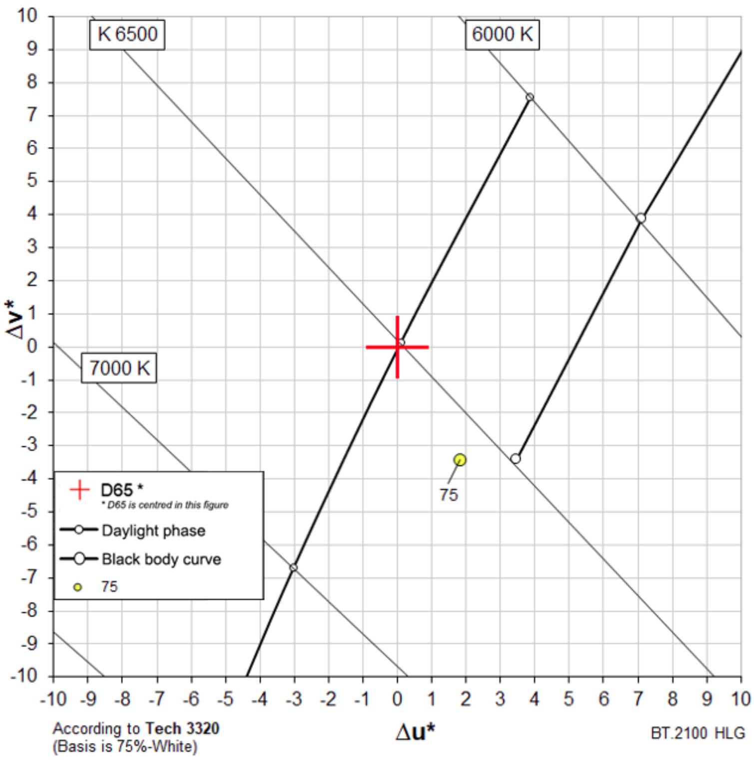


Figure 37: Results of grey scale measurements (example)

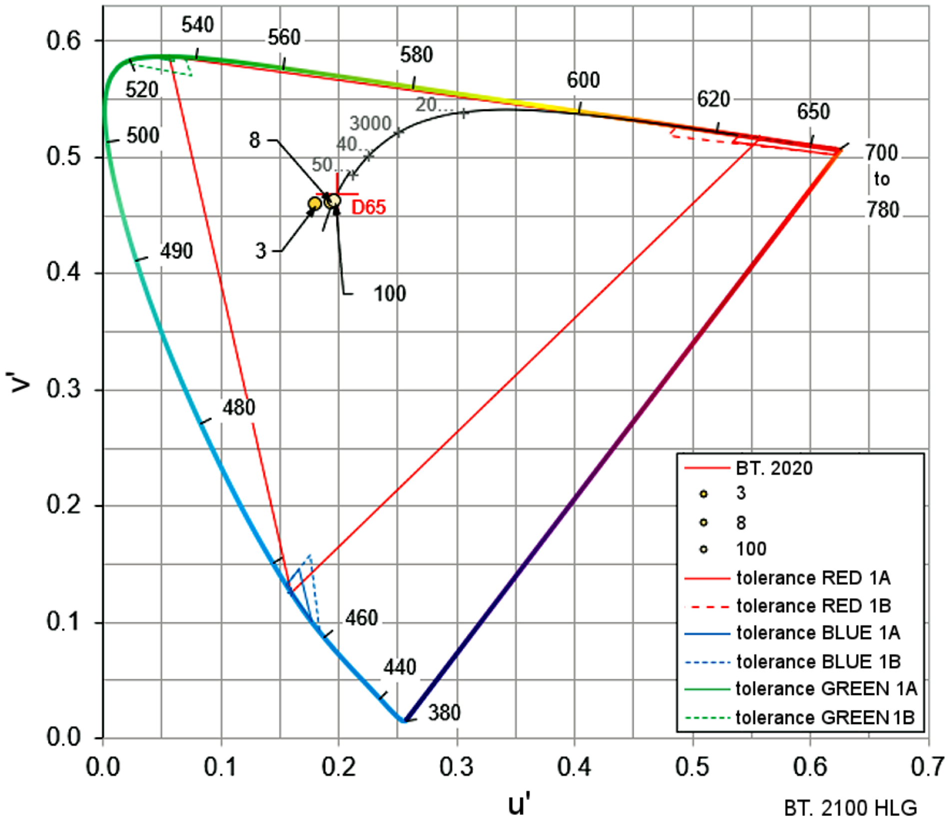


Figure 38: Grey Scale Measurements in CIE 1976 (example)

3.6 Colour gamut and colour reproduction

3.6.1 Measurement conditions

The test inputs for colour gamut are test patterns EBU_5-red_xx, EBU_5-green_xx and EBU_5-blue_xx. The correct primaries depend on the measurement mode (ITU-R BT.2020, ITU-R BT.2100 HLG, ITU-R BT.2100 PQ).

It is essential that the measurement conditions described in § 3.2 are correctly set.

The primary colour patches should be set to following digital (10-bit) values.

> ***Note:*** *Rounding to digital code values shall be performed using the method in ITU-R BT.2100 [6].*

Table 18: Code values for the primary colour patches

	10-bit code values at monitor input			Expected monitor output[5]			
Primary	D'_Y	D'_{CB}	D'_{CR}	Y_{exp} [cd/m²] (= $L \cdot L_{ref}$)	L [0:1]	u'	v'
BT.2020 SDR (L_{ref} = 100 cd/m²)							
Red	294	387	960	26.3	0.263 (=Y_R)	0.5566	0.5165
Green	658	189	100	67.8	0.678 (=Y_G)	0.0556	0.5868
Blue	116	960	476	5.9	0.059 (=Y_B)	0.1593	0.1258
ITU-R BT.2100 HLG (L_{ref} = 1000 cd/m²)							
Red	294	387	960	201	0.201 (=Y_R)	0.5566	0.5165
Green	658	189	100	627	0.627 (=Y_G)	0.0556	0.5868
Blue	116	960	476	34	0.034 (=Y_B)	0.1593	0.1258
BT.2100 PQ_narrow (L_{ref} = 10000 cd/m²)							
Red	294	387	960	2623	0.262 (=Y_R)	0.5566	0.5165
Green	658	189	100	6780	0.678 (=Y_G)	0.0556	0.5868
Blue	116	960	476	593	0.059 (=Y_B)	0.1593	0.1258
ITU-R BT.2100 PQ (SDI full range -> PQ_full); L_{ref} = 10000 cd/m²							
Red	269	369	1019	2475	0.248 (=Y_R)	0.5566	0.5165
Green	694	143	42	6780	0.678 (=Y_G)	0.0556	0.5868
Blue	61	1019	471	550	0.055 (=Y_B)	0.1593	0.1258
@ PQ1000nits: ITU-R BT.2100 (SDI narrow range -> PQ1000nit_narrow); L_{ref} = 1000 cd/m²							
Red	237	418	849	263	0.263 (=Y_R)	0.5566	0.5165
Green	511	269	202	683	0.683 (=Y_G)	0.0556	0.5868
Blue	103	849	485	59	0.059 (=Y_B)	0.1593	0.1258
@ PQ1000nits: ITU-R BT.2100 (SDI full range -> PQ1000nit_full); L_{ref} = 1000 cd/m²							
Red	202	405	897	264	0.264 (=Y_R)	0.5566	0.5165
Green	521	235	158	676	0.678 (=Y_G)	0.0556	0.5868
Blue	46	897	481	60	0.060 (=Y_B)	0.1593	0.1258

A set of 15 EBU test colours was defined in EBU Tech 3237 [12] and its supplement [13], based on certain Munsell chips, and these are also a useful set of test colours for characterising a display in ITU-R BT.709 colour space.

[5] Note that although rounded values are shown here, when using these values for calculations high accuracy must be maintained.

Whilst these test colours were originally intended as camera input test colours, here we use these colours referred to the output of the display. For HDR displays, additional colours are also tested (EBU_5-16 to EBU_5-31).

The expected monitor L, u', v' values have been calculated for the exact 10-bit D'_{Y}, D'_{CB}, D'_{CR} values. These may thus differ slightly from the original EBU Tech 3237 colour definitions (from which the quantised D'_{Y}, D'_{CB}, D'_{CR} values were derived).

For the measurement of the EBU test colours on UHD ITU-BT.2020 **SDR Monitors**, the patches should be set to the digital 10-bit ITU-R BT.2020 SDR values given in the following table.

Table 19: 10-bit BT.2020 SDR code values for the 31 EBU Test Colours

		10-bit code values at monitor input			Expected monitor output			
SDR-colours @ BT.2020 SDR → EBU_5-1_BT2020SDR to EBU_5-31_BT2020SDR. L_{ref} = 100 cd/m²								
Sample	**Description**	**D'_Y**	**D'_{CB}**	**D'_{CR}**	**Y_{exp} [cd/m²] (= $L \cdot L_{ref}$)**	**L [0:1]**	**u'**	**v'**
	White point	940	512	512	100.0	1.000	0.1978	0.4683
EBU 1	Dark Skin	391	474	552	9.6	0.096	0.2537	0.5011
EBU 2	Light Skin	645	463	563	37.7	0.377	0.2369	0.4929
EBU 3	Light Greyish Red	591	481	558	29.8	0.298	0.2360	0.4848
EBU 4	Light Yellow Green	588	377	494	29.9	0.299	0.1810	0.5453
EBU 5	Light Bluish Green	590	538	461	29.7	0.297	0.1626	0.4552
EBU 6	Light Violet	593	586	531	30.1	0.301	0.2087	0.4154
EBU 7	Foliage	441	454	498	13.4	0.134	0.1818	0.5204
EBU 8	Medium Red	490	460	629	19.5	0.195	0.3247	0.4973
EBU 9	Medium Green	676	400	442	43.7	0.437	0.1504	0.5329
EBU 10	Medium Blue	480	624	492	17.2	0.172	0.1791	0.3705
EBU 11	Dark Red	337	488	576	6.5	0.065	0.3043	0.4890
EBU 12	Dark Green	505	434	456	20.0	0.200	0.1459	0.5321
EBU 13	Dark Blue	330	605	503	6.0	0.060	0.1821	0.3425
EBU 14	Medium Yellow Red	673	374	607	43.6	0.436	0.2722	0.5272
EBU 15	Medium Purple	506	587	561	20.0	0.200	0.2348	0.4036
EBU 16	Luminous Bright Orange	445	380	607	15.0	0.150	0.3186	0.5409
EBU 17	Carnation Pink	625	506	551	34.5	0.345	0.2268	0.4692
EBU 18	Canary	590	330	562	30.7	0.307	0.2408	0.5510
EBU 19	Lush Green	325	478	454	5.9	0.059	0.1173	0.5248
EBU 20	Luminous Bright Red	312	439	643	6.6	0.066	0.4347	0.5213
EBU 21	Luminous Green	453	404	410	16.1	0.161	0.1007	0.5616
EBU 22	Blueish Purple	262	638	617	4.5	0.045	0.3001	0.3002
EBU 23	Reddish Purple	304	563	645	6.5	0.065	0.3805	0.4101
EBU 24	Anchusa	296	566	462	4.4	0.044	0.1363	0.3933
EBU 25	True Blue	215	668	495	2.1	0.021	0.1647	0.1999

For the measurement of the EBU test colours on HDR ITU-BT.2100 **HLG Monitors** the patches should be set to the digital 10-bit ITU-R BT.2100 HLG values given in the following table[6].

Table 20: 10-bit BT.2100 HLG code values for the 31 EBU Test Colours

		10-bit code values at monitor input			Expected monitor output			
SDR-colours @ HLG75 (L_{ref} = 203.1521 cd/m²) → provided as Test patterns EBU_5-1_BT2100HLG75 to EBU_5-15_BT2100HLG75								
Sample	**Description**	**D'_Y**	**D'_{CB}**	**D'_{CR}**	**Y_{exp} [cd/m²] (= $L \cdot L_{ref}$)**	**L [0:1]**	**u'**	**v'**
	White point	721	512	512	203.2	1.000	0.1978	0.4683
EBU 1	Dark Skin	356	472	555	19.5	0.096	0.2534	0.5011
EBU 2	Light Skin	569	467	551	76.8	0.378	0.2364	0.4932
EBU 3	Light Greyish Red	529	481	553	60.5	0.298	0.2359	0.4851
EBU 4	Light Yellow Green	527	378	495	60.9	0.300	0.1808	0.5452
EBU 5	Light Bluish Green	529	536	462	60.5	0.298	0.1631	0.4552
EBU 6	Light Violet	531	571	531	61.1	0.301	0.2090	0.4154
EBU 7	Foliage	400	451	496	27.2	0.134	0.1808	0.5211
EBU 8	Medium Red	437	460	627	39.4	0.194	0.3246	0.4974
EBU 9	Medium Green	583	411	456	88.6	0.436	0.1505	0.5327
EBU 10	Medium Blue	432	618	492	39.9	0.172	0.1792	0.3702
EBU 11	Dark Red	307	486	581	13.2	0.065	0.3038	0.4893
EBU 12	Dark Green	457	431	453	40.4	0.199	0.1462	0.5322
EBU 13	Dark Blue	301	617	502	12.2	0.060	0.1821	0.3417
EBU 14	Medium Yellow Red	581	385	580	88.6	0.436	0.2732	0.5271
EBU 15	Medium Purple	457	585	565	40.8	0.201	0.2353	0.4037
HDR-colours @ HLG (L_{ref} = 1000 cd/m²) → provided as Test patterns EBU_5-16_BT2100HLG to EBU_5-31_BT2100HLG								
	White point	940	512	512	1000	1.000	0.1978	0.4683
EBU 16	Luminous Bright Orange	643	303	611	150	0.150	0.3180	0.5409
EBU 17	Carnation Pink	794	508	539	346	0.346	0.2270	0.4693
EBU 18	Canary	760	281	556	307	0.307	0.2412	0.5509
EBU 19	Lush Green	507	448	400	59	0.059	0.1169	0.5244
EBU 20	Luminous Bright Red	452	390	711	66	0.066	0.4347	0.5213
EBU 21	Luminous Green	637	354	375	160	0.160	0.1003	0.5617
EBU 22	Blueish Purple	382	709	703	45	0.045	0.2999	0.3001
EBU 23	Reddish Purple	439	614	718	65	0.065	0.3805	0.4103
EBU 24	Anchusa	464	605	412	44	0.044	0.1362	0.3938
EBU 25	True Blue	311	763	484	21	0.021	0.1651	0.2001

[6] These values have been re-calculated using more accurate matrix parameters and therefore are more accurate than those previously published as a supplement to the previous version of Tech 3325.

EBU 26	Bright Saturated Red	541	253	784	228	0.228	0.4957	0.5251
EBU 27	Bright Saturated Green	832	207	407	689	0.689	0.0985	0.5777
EBU 28	Bright Saturated Blue	365	824	586	56	0.056	0.1826	0.1723
EBU 29	Bright Saturated Cyan	878	528	397	755	0.755	0.1181	0.4749
EBU 30	Bright Saturated Magenta	620	659	734	289	0.289	0.3653	0.3786
EBU 31	Bright Saturated Yellow	891	162	546	874	0.874	0.2163	0.5623

For the measurement of the EBU test colours on HDR ITU-BT.2100 **PQ Monitors** the patches should be set to the digital 10-bit ITU-R BT.2100 PQ values given in the following tables[7].

Table 21: 10-bit BT.2100 PQ full range code values for the 31 EBU Test Colours

	SDI Full Range	10-bit code values at monitor input			Expected monitor output			
SDR-colours @ PQ58. SDI full range (Lref = 203.1521 cd/m²) → provided as Test patterns EBU_5-1_BT2100PQ58_full to EBU_5-15_BT2100PQ58_full								
Sample	**Description**	**D'_Y**	**D'_{CB}**	**D'_{CR}**	**Y_{exp} [cd/m²] (= $L \cdot L_{ref}$)**	**L [0:1]**	**u'**	**v'**
	White point	594	512	512	202.9	0.999	0.1978	0.4683
EBU 1	Dark Skin	360	486	536	19.5	0.096	0.2528	0.5017
EBU 2	Light Skin	491	491	532	76.6	0.377	0.2366	0.4930
EBU 3	Light Greyish Red	468	498	532	60.7	0.299	0.2367	0.4848
EBU 4	Light Yellow Green	465	438	505	60.7	0.299	0.1806	0.5454
EBU 5	Light Bluish Green	467	523	489	60.3	0.297	0.1630	0.4558
EBU 6	Light Violet	469	542	520	61.4	0.302	0.2079	0.4150
EBU 7	Foliage	391	475	504	27.2	0.134	0.1812	0.5208
EBU 8	Medium Red	414	485	568	39.2	0.193	0.3246	0.4970
EBU 9	Medium Green	502	462	484	88.8	0.437	0.1501	0.5331
EBU 10	Medium Blue	412	563	502	34.7	0.171	0.1792	0.3701
EBU 11	Dark Red	321	495	555	13.2	0.065	0.3047	0.4892
EBU 12	Dark Green	425	468	483	40.6	0.200	0.1462	0.5318
EBU 13	Dark Blue	318	569	507	12.2	0.060	0.1831	0.3425
EBU 14	Medium Yellow Red	500	447	548	88.2	0.434	0.2724	0.5275
EBU 15	Medium Purple	426	547	536	40.6	0.200	0.2341	0.4030
HDR-colours @ PQ1000 nits. SDI full range (Lref = 1000 cd/m²) → provided as EBU_5-16_BT2100PQ1000nit_full to EBU_5-31_BT2100PQ1000nit_full [8]								
	White point	769	512	512	999	0.999	0.1978	0.4683
EBU 16	Luminous Bright Orange	544	394	570	150	0.150	0.3172	0.5409
EBU 17	Carnation Pink	651	509	529	347	0.347	0.2263	0.4699
EBU 18	Canary	629	385	539	308	0.308	0.2422	0.5507

[7] These values have been re-calculated using more accurate matrix parameters and therefore are more accurate than those previously published as a supplement to the previous version of EBU Tech 3325.

[8] PQ at 1000 cd/m² was chosen to visually perceive the same colour between HLG and PQ.

EBU 19	Lush Green	455	482	456	59	0.059	0.1173	0.5241
EBU 20	Luminous Bright Red	430	434	617	66	0.066	0.4340	0.5213
EBU 21	Luminous Green	546	427	440	160	0.160	0.1000	0.5620
EBU 22	Blueish Purple	372	624	619	45	0.045	0.2994	0.2995
EBU 23	Reddish Purple	420	565	623	65	0.065	0.3800	0.4096
EBU 24	Anchusa	428	559	459	44	0.044	0.1360	0.3937
EBU 25	True Blue	329	649	495	21	0.021	0.1649	0.1996
EBU 26	Bright Saturated Red	493	250	678	229	0.229	0.4963	0.5250
EBU 27	Bright Saturated Green	693	332	443	689	0.689	0.0986	0.5777
EBU 28	Bright Saturated Blue	383	716	555	79	0.079	0.1757	0.1582
EBU 29	Bright Saturated Cyan	724	521	436	768	0.768	0.1171	0.4768
EBU 30	Bright Saturated Magenta	558	594	646	309	0.309	0.3735	0.3849
EBU 31	Bright Saturated Yellow	741	297	541	924	0.924	0.2322	0.5602

Table 22: 10-bit BT.2100 PQ narrow range code values for the 31 EBU Test Colours

	SDI Narrow Range	10-bit code values at monitor input			Expected monitor output			
SDR-colours @ PQ58. narrow-range (Lref = 203.1521 cd/m²) → provided as test pattern EBU_5-1_BT2100PQ58_narrow to EBU_5-15_BT2100PQ58_narrow								
Sample	**Description**	**D'_Y**	**D'_{CB}**	**D'_{CR}**	**Y_{exp} [cd/m²] (= $L \cdot L_{ref}$)**	**L [0:1]**	**u'**	**v'**
	White point	573	512	512	203.8	1.003	0.1978	0.4683
EBU 1	Dark Skin	373	489	533	19.7	0.097	0.2527	0.5020
EBU 2	Light Skin	484	494	530	76.4	0.376	0.2377	0.4924
EBU 3	Light Greyish Red	464	500	529	60.1	0.296	0.2355	0.4845
EBU 4	Light Yellow Green	462	448	506	60.5	0.298	0.1810	0.5449
EBU 5	Light Bluish Green	464	522	492	60.3	0.297	0.1632	0.4550
EBU 6	Light Violet	465	538	519	60.9	0.300	0.2079	0.4156
EBU 7	Foliage	399	480	505	27.2	0.134	0.1813	0.5203
EBU 8	Medium Red	419	488	561	39.4	0.194	0.3245	0.4974
EBU 9	Medium Green	494	468	488	88.8	0.437	0.1509	0.5331
EBU 10	Medium Blue	417	557	503	34.9	0.172	0.1788	0.3694
EBU 11	Dark Red	339	497	550	13.2	0.065	0.3057	0.4894
EBU 12	Dark Green	428	473	487	40.6	0.200	0.1468	0.5322
EBU 13	Dark Blue	336	562	507	12.2	0.060	0.1822	0.3423
EBU 14	Medium Yellow Red	492	455	544	88.2	0.434	0.2736	0.5274
EBU 15	Medium Purple	429	542	533	40.6	0.200	0.2343	0.4045
HDR-colours @ PQ1000nits. narrow-range (Lref = 1000 cd/m²) → provided as test pattern EBU_5-16_BT2100PQ1000nit_narrow to EBU_5-31_BT2100PQ1000nit_narrow								
	White point	723	512	512	1004	1.004	0.1978	0.4683
EBU 16	Luminous Bright Orange	530	408	563	150	0.150	0.3176	0.5410

EBU 17	Carnation Pink	621	510	527	345	0.345	0.2264	0.4689
EBU 18	Canary	602	401	535	306	0.306	0.2406	0.5509
EBU 19	Lush Green	453	486	463	59	0.059	0.1174	0.5237
EBU 20	Luminous Bright Red	432	443	604	66	0.066	0.4341	0.5215
EBU 21	Luminous Green	532	438	449	161	0.161	0.1001	0.5617
EBU 22	Blueish Purple	382	610	606	45	0.045	0.3001	0.300
EBU 23	Reddish Purple	423	558	609	65	0.065	0.3802	0.4102
EBU 24	Anchusa	431	553	466	44	0.044	0.1364	0.3939
EBU 25	True Blue	346	632	497	21	0.021	0.1649	0.1997
EBU 26	Bright Saturated Red	486	283	657	228	0.228	0.4959	0.5250
EBU 27	Bright Saturated Green	658	354	452	693	0.693	0.0989	0.5776
EBU 28	Bright Saturated Blue	392	691	549	79	0.079	0.1753	0.1579
EBU 29	Bright Saturated Cyan	684	520	445	770	0.770	0.1168	0.4767
EBU 30	Bright Saturated Magenta	542	584	629	308	0.308	0.3726	0.3842
EBU 31	Bright Saturated Yellow	698	324	538	919	0.919	0.2337	0.5600

Measurement point: 1

Measurement equipment: Tristimulus meter or spectroradiometer equipment

3.6.2 Presentation of the measurement results

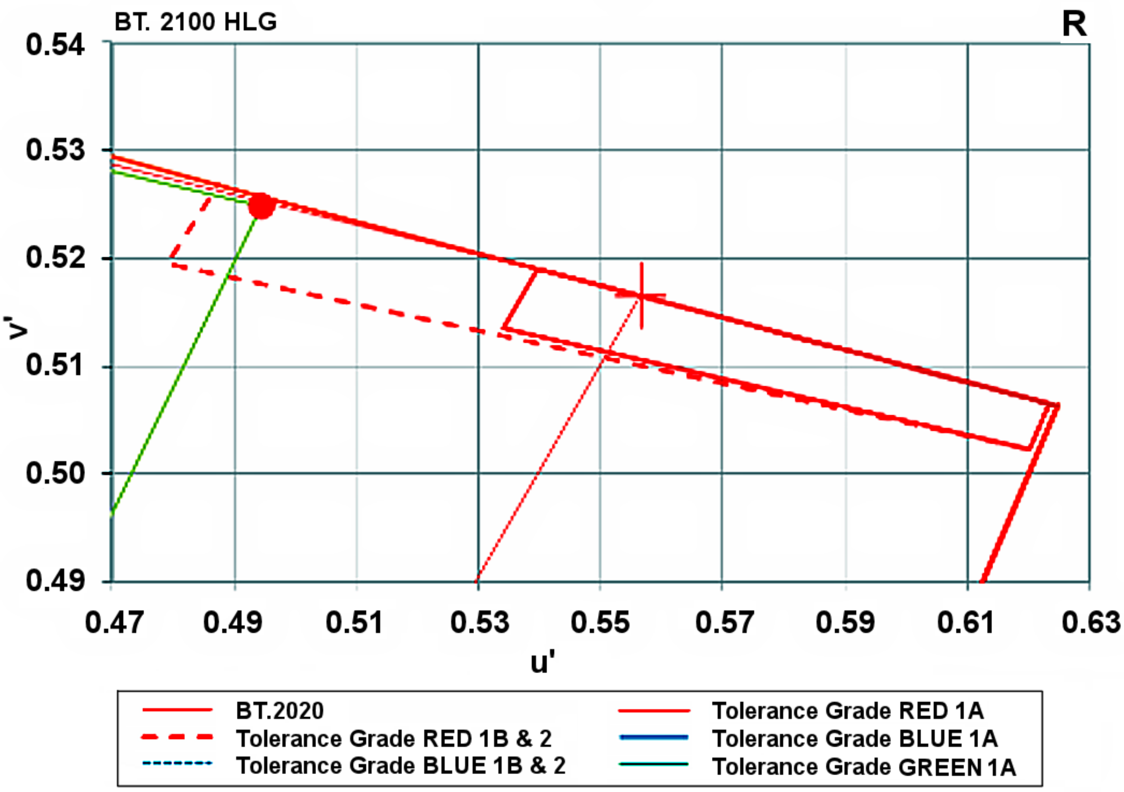


Figure 39: Red primary measurement result (example)

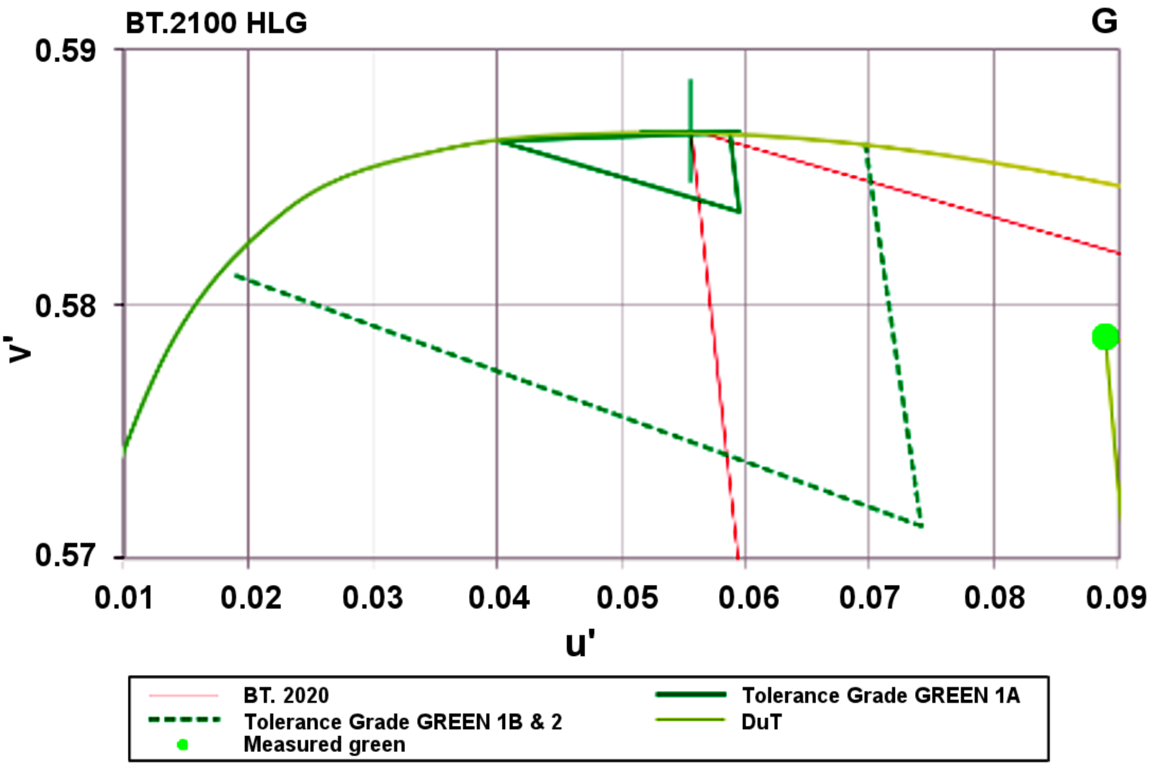


Figure 40: Green primary measurement result (example)

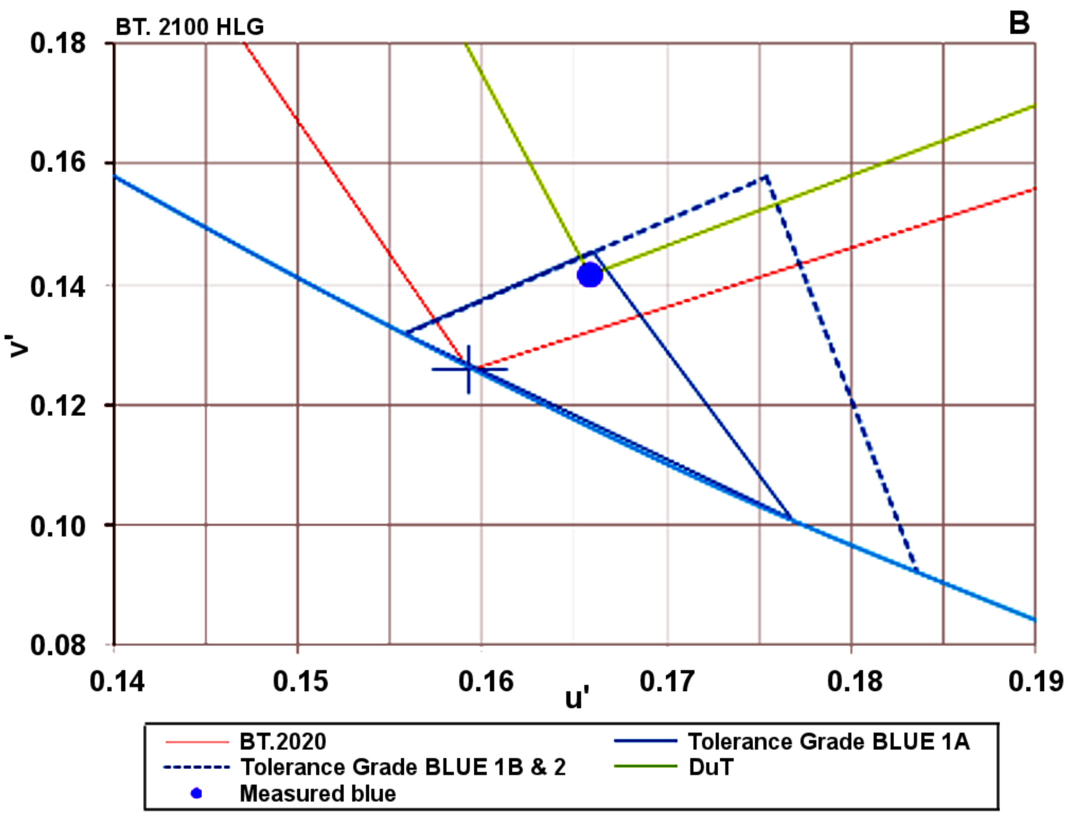


Figure 41: Blue primary measurement result (example)

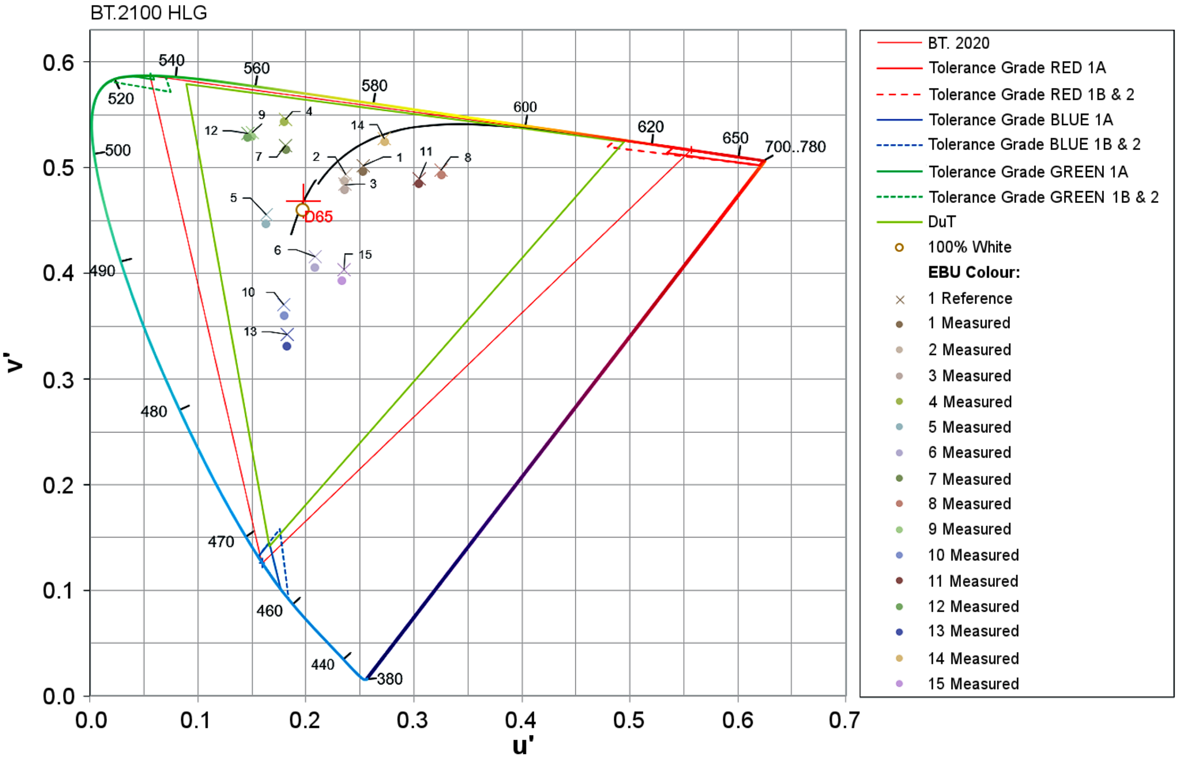


Figure 42: Colour gamut and Colour reproduction representation EBU Test Colours 1-15 (example)

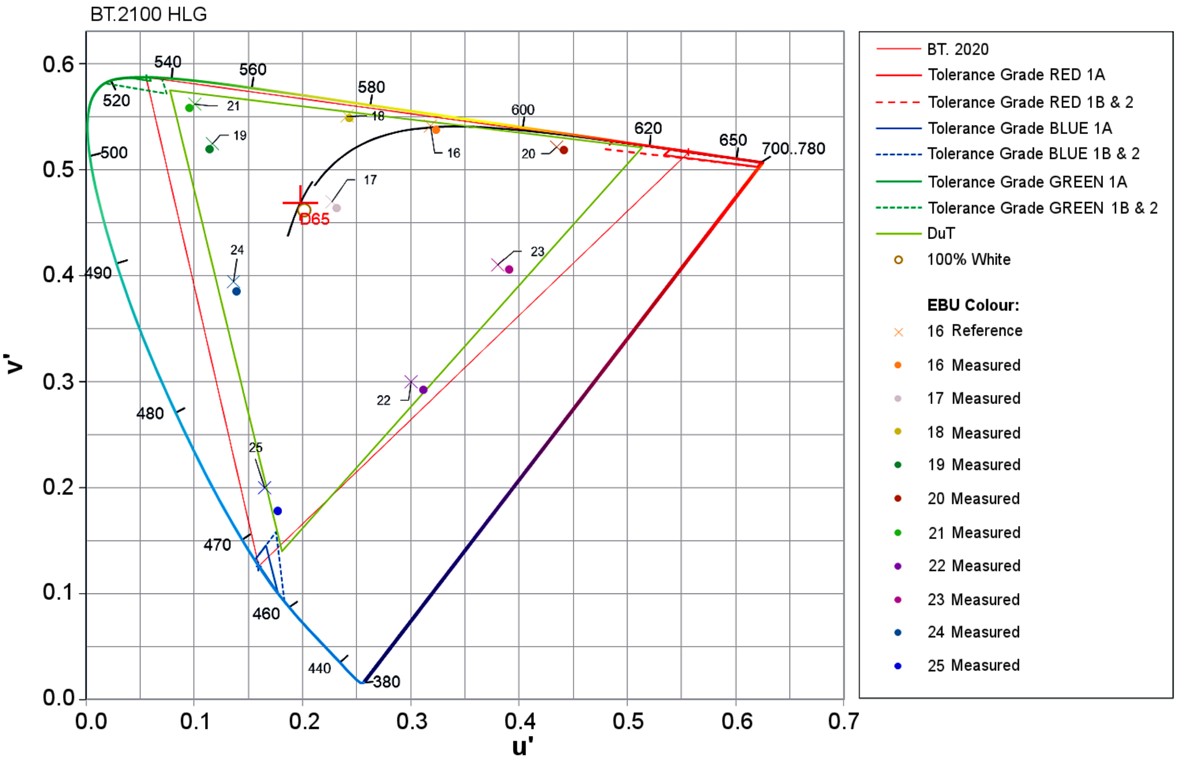


Figure 43: Colour gamut and Colour reproduction representation EBU Test Colours 16-25 (example)

The following table shows an example of measured values for the 15 EBU-Colour patches. The luminance is related to the 100% white level.

Table 23: Example of the measured Y_c and the calculated Δu^*, Δv^*, and ΔE^* for the test colours EBU 1 – EBU 15

EBU	EBU Reference values					Measured			Calculated CIE Luv					
Colour	Y_{exp}	u'_{exp}	v'_{exp}	Y_{exp}/Y_w	$L_{exp/w}^*$	$\Delta u'$	$\Delta v'$	Y_c	Y_c/Y_w	$L_{c/w}^*$	ΔL^*	Δu^*	Δv^*	ΔE^*
1	19.5	0.2530	0.5015	0.095965	37.11	0.0008	-0.0041	19.9	0.098150	37.51	0.40	0.39	-2.00	2.08
2	76.6	0.2366	0.4931	0.376969	67.80	-0.0001	-0.0044	78.1	0.384532	68.35	0.56	-0.09	-3.91	3.95
3	60.5	0.2364	0.4848	0.297736	61.46	-0.0006	-0.0045	61.6	0.303248	61.93	0.48	-0.48	-3.62	3.69
4	60.7	0.1807	0.5452	0.298720	61.54	0.0004	-0.0020	61.7	0.303489	61.95	0.41	0.32	-1.61	1.69
5	60.5	0.1629	0.4552	0.297736	61.46	0.0005	-0.0070	61.8	0.303888	61.99	0.53	0.40	-5.64	5.68
6	61.2	0.2087	0.4157	0.301181	61.76	-0.0009	-0.0083	62.6	0.308297	62.36	0.61	-0.73	-6.73	6.80
7	27.2	0.1813	0.5207	0.133858	43.34	-0.0004	-0.0033	27.6	0.135753	43.62	0.28	-0.23	-1.87	1.91
8	39.4	0.3248	0.4974	0.193898	51.14	-0.0002	-0.0033	40.3	0.198337	51.65	0.51	-0.13	-2.22	2.28
9	88.6	0.1505	0.5329	0.436024	71.96	0.0000	-0.0032	90.0	0.442849	72.42	0.46	0.00	-3.01	3.05
10	35	0.1791	0.3706	0.172244	48.54	-0.0007	-0.0092	35.8	0.175960	49.00	0.46	-0.45	-5.86	5.90
11	13.2	0.3046	0.4895	0.064961	30.63	-0.0021	-0.0041	13.5	0.066373	30.97	0.34	-0.85	-1.65	1.88
12	40.4	0.1462	0.5321	0.198819	51.70	0.0003	-0.0032	40.9	0.201304	51.98	0.28	0.20	-2.16	2.19
13	12.2	0.1825	0.3422	0.060039	29.42	-0.0014	-0.0085	12.6	0.062023	29.92	0.49	-0.54	-3.31	3.39
14	88.4	0.2726	0.5273	0.435039	71.90	0.0015	-0.0022	89.9	0.442347	72.39	0.49	1.41	-2.07	2.55
15	40.6	0.2349	0.4034	0.199803	51.81	-0.0014	-0.0073	41.8	0.205635	52.47	0.65	-0.95	-4.98	5.11

Table 24: Example of the measured Y_c and the calculated Δu^*, Δv^* and ΔE^* for the test colours EBU 16 – EBU 25

EBU	EBU Reference values					Measured			Calculated CIE Luv					
Colour	Y_{exp}	u'_{exp}	v'_{exp}	Y_{exp}/Y_w	$L_{exp/w}^*$	$\Delta u'$	$\Delta v'$	Y_c	Y_c/Y_w	$L_{c/w}^*$	ΔL^*	Δu^*	Δv^*	ΔE^*
16	150	0.3176	0.5410	0.150000	45.63	0.0052	-0.0031	151	0.151000	45.77	0.14	3.09	-1.84	3.60
17	346	0.2264	0.4689	0.346000	65.44	0.0044	-0.0059	346	0.346000	65.44	0.00	3.74	-5.02	6.26
18	307	0.2406	0.5509	0.307000	62.25	0.0016	-0.0027	306	0.306000	62.17	-0.09	1.29	-2.18	2.54
19	59.0	0.1174	0.5237	0.059000	29.16	-0.0026	-0.0050	59.3	0.059300	29.24	0.08	-0.99	-1.90	2.14
20	66.0	0.4341	0.5215	0.066000	30.88	0.0070	-0.0031	66.6	0.066600	31.02	0.14	2.82	-1.25	3.09
21	160	0.1001	0.5617	0.160000	46.97	-0.0050	-0.0038	161	0.161000	47.11	0.13	-3.06	-2.33	3.85
22	45.0	0.3001	0.3000	0.045000	25.26	0.0117	-0.0082	45.4	0.045400	25.38	0.12	3.86	-2.71	4.72
23	65.0	0.3802	0.4102	0.065000	30.64	0.0101	-0.0050	64.8	0.064800	30.59	-0.05	4.02	-1.99	4.48
24	44.0	0.1364	0.3939	0.044000	24.95	0.0026	-0.0085	43.6	0.043600	24.83	-0.12	0.84	-2.74	2.87
25	21.0	0.1649	0.1997	0.021000	16.00	0.0123	-0.0220	21.1	0.021100	16.05	0.05	2.57	-4.59	5.26
26	228	0.4959	0.5250	0.228000	54.87	0.0049	-0.0013	230	0.230000	55.07	0.21	3.51	-0.93	3.64
27	689	0.0989	0.5776	0.689000	86.45	0.0024	0.0037	683	0.683000	86.16	-0.30	2.69	4.14	4.95
28	56.0	0.1753	0.1579	0.056000	28.38	-0.0054	-0.0169	56.5	0.056500	28.51	0.13	-2.00	-6.26	6.58
29	755	0.1168	0.4767	0.755000	89.63	0.0023	0.0009	756	0.756000	89.67	0.05	2.68	1.05	2.88
30	289	0.3726	0.3842	0.289000	60.69	-0.0049	-0.0023	286	0.286000	60.43	-0.27	-3.85	-1.81	4.26
31	874	0.2337	0.5600	0.874000	94.91	0.0012	0.0032	876	0.876000	94.99	0.08	1.48	3.95	4.22

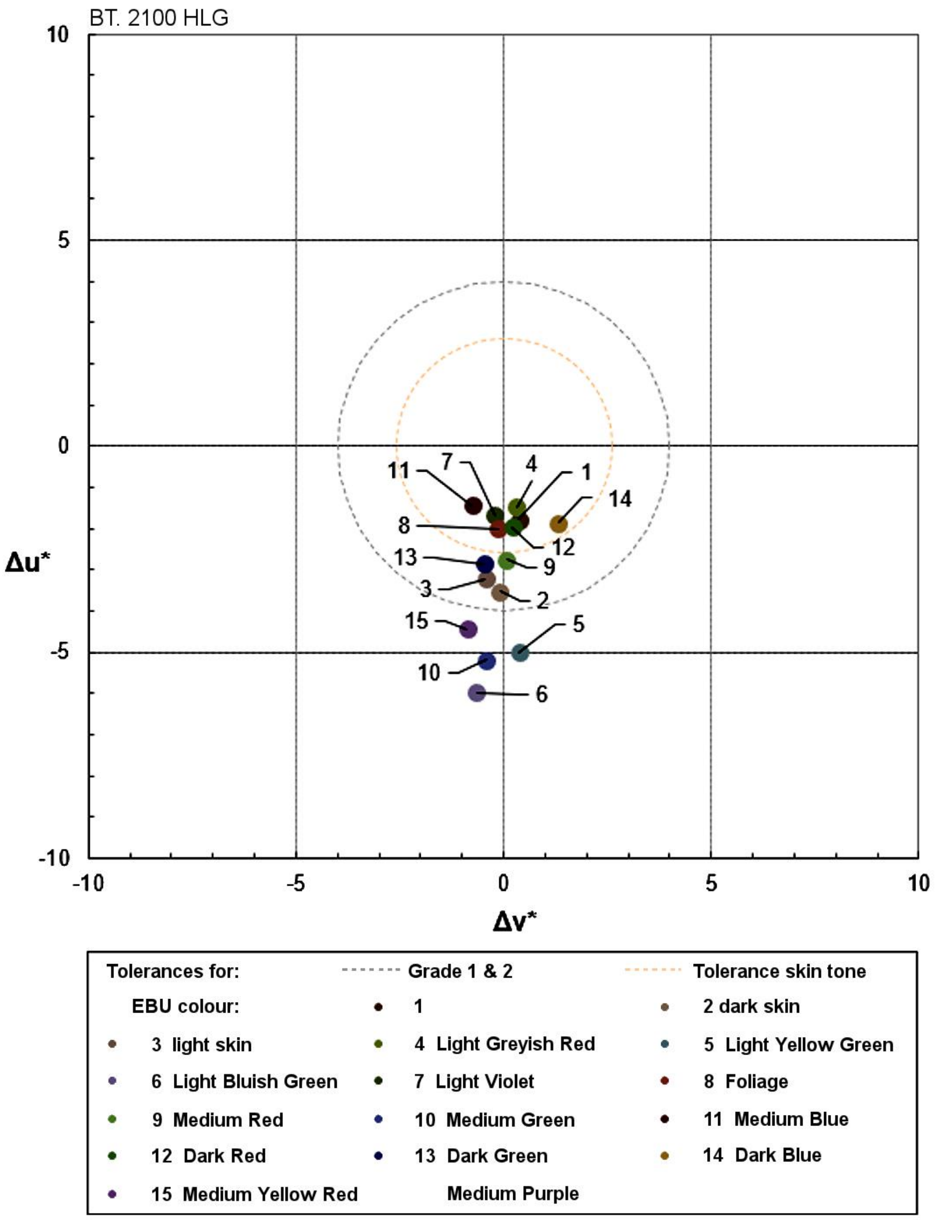


Figure 44: Deviation from the standard EBU test colours 1-15 (example)

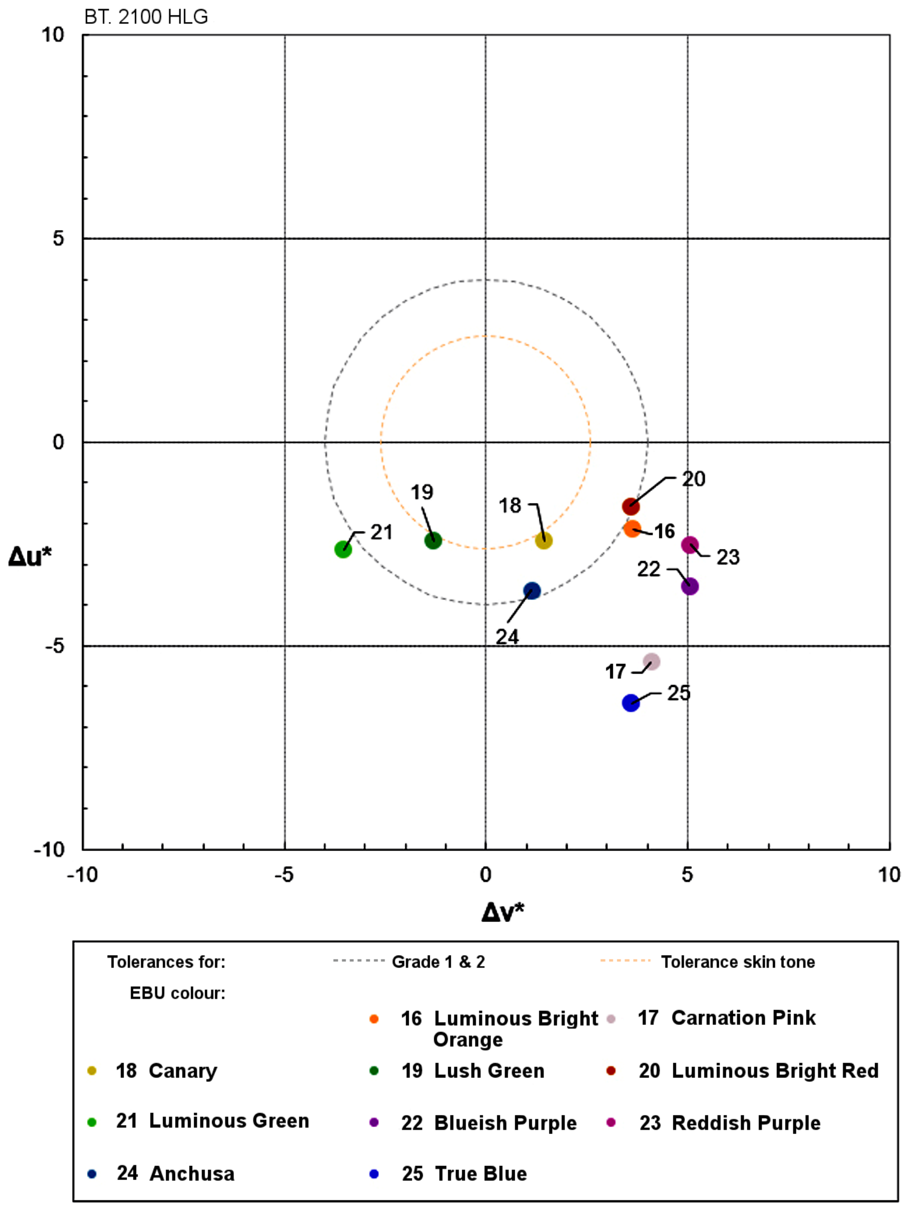


Figure 45: Deviation from the standard EBU test colours 16-25 (example)

3.7 Colour temperature and uniformity

3.7.1 Definition of uniformity

Uniformity is defined as the evenness of light output and chromaticity over the picture area.

3.7.2 Measurement conditions – colour temperature

The input test signal is a test pattern having an HDR-reference white frame (at 203.15 cd/m^2). Test patterns EBU_3-1 to EBU_3-13 in the correct measurement mode HLG or PQ, where only one patch at a time is illuminated, may be used. All measurements are made parallel to a line perpendicular to the centre of the display.

__Measurement points:__ 1 to 13.

__Measurement equipment:__ Tristimulus meter or spectroradiometer equipment.

3.7.3 Presentation of the Measurement results for colour temperature

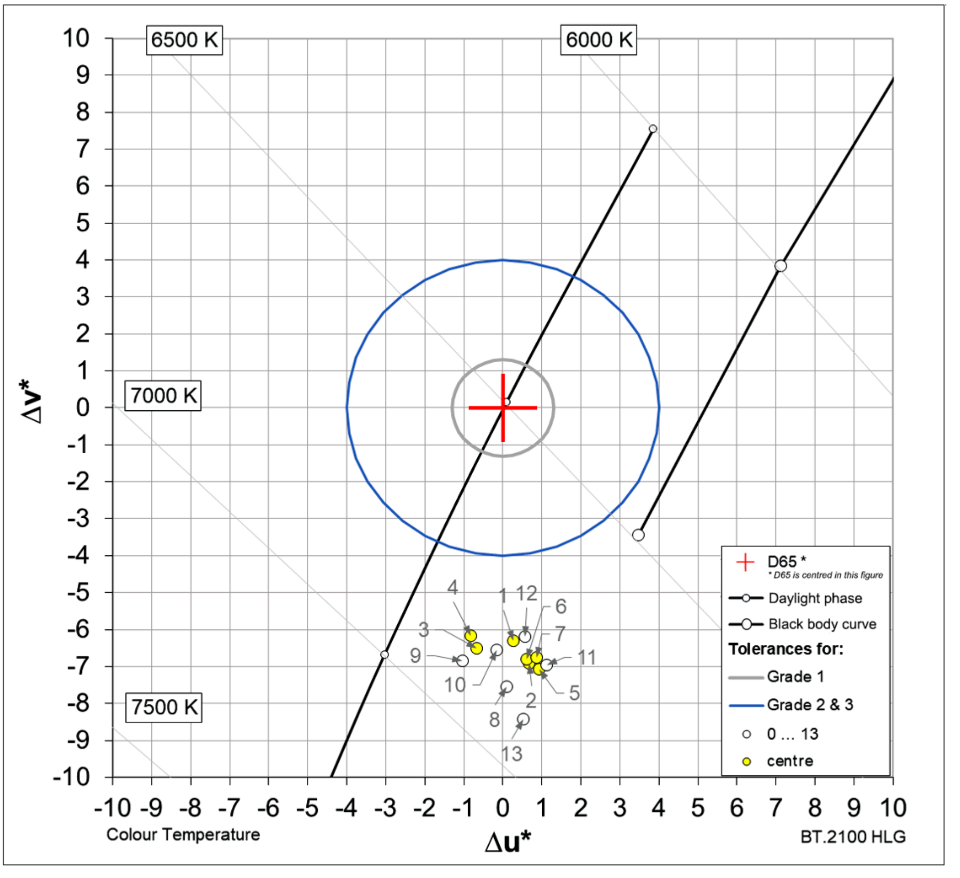


Figure 46: Colour Temperature measurement results presentation (Example)

3.7.4 Measurement procedure: Luminance large area uniformity

Measurements are to be carried out at all thirteen standardised positions within the screen area and may be made at the same time as the chrominance measurements. The display should be driven with HDR reference white video signal across the whole frame. Suitable signals are Test pattern EBU_3-1 to EBU_3-13 in the correct measurement mode HLG or PQ.

Measurement points: 1 to 13.

Measurement equipment: Tristimulus meter or spectroradiometer equipment.

Presentation of results: Luminance (Y).

Table 25: Luminance large area uniformity measurement results (example)

		Luminance (Y)		
	Test point	cd/m²	% of point 1	
centre	1	203.785	100	
	2	195.266	95.8	
	3	191.150	93.8	
	4	194.819	95.6	
	5	194.411	95.4	
	6	197.875	97.1	
	7	203.786	100.00	
	8	185.852	91.2	
	9	186.667	91.6	
	10	187.278	91.9	
	11	190.335	93.4	
	12	196.449	96.4	
	13	184.629	90.6	BT.2100 HLG

Tolerance of mean luminance (%)	±5	Reference
Maximum Luminance Deviation (%)	-9.4	Measured

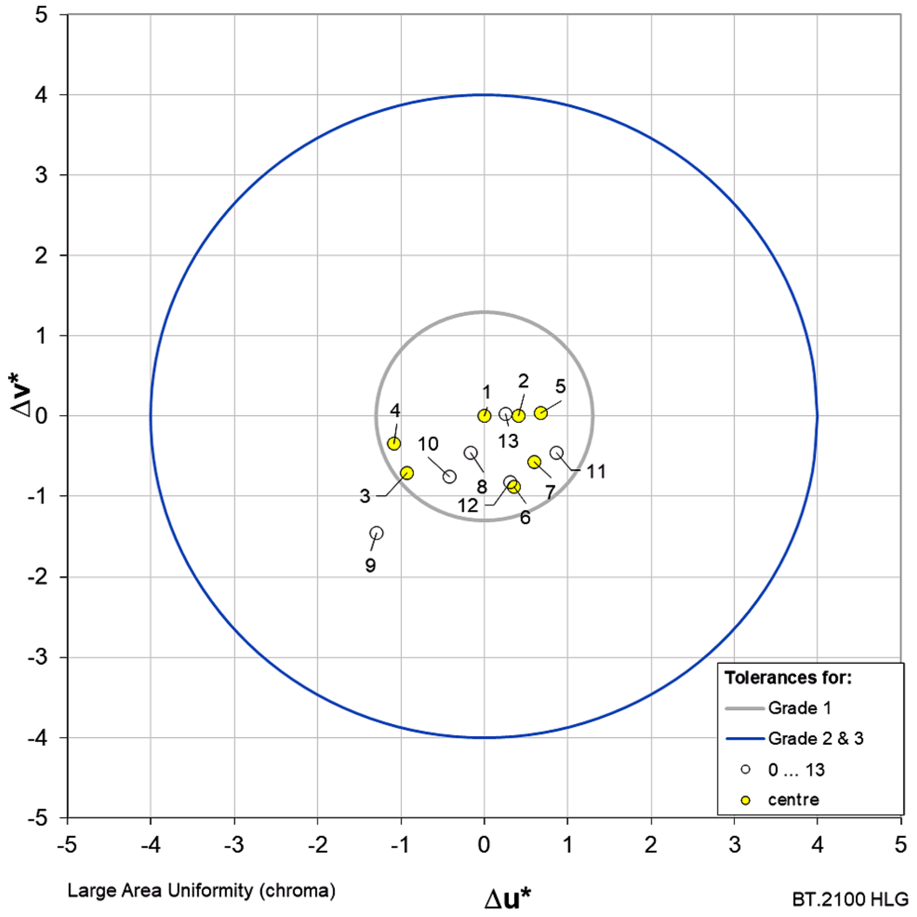


Figure 47: Uniformity
(centre of the tolerance circles: measurement point 1)

3.7.5 Measurement procedure: Luminance small area uniformity

This measurement is done using an array light measurement device (LMD) over the entire display screen. The output is a pseudo-colour image showing the relative luminance level of small areas. The visual analysis of this image can provide information about the localisation of non-uniformity areas, rate of luminance variations, and presence of periodic and fixed patterns. The uniformity score is computed using the standard deviation as in:

$$\text{Uniformity (\%)} = 100 * \left(1 - \frac{\sigma}{\bar{x}}\right), \text{ with } \sigma = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(x_i - \bar{x})}$$

and where $\{x_1, x_2, \ldots, x_N\}$ are the luminance samples, $\bar{x}$ is the mean value of the luminance samples and N is the number of luminance samples.

Measurement points: over the entire display screen.

Measurement equipment: Array LMD or DLSR camera using a method proposed by the CBC [14].

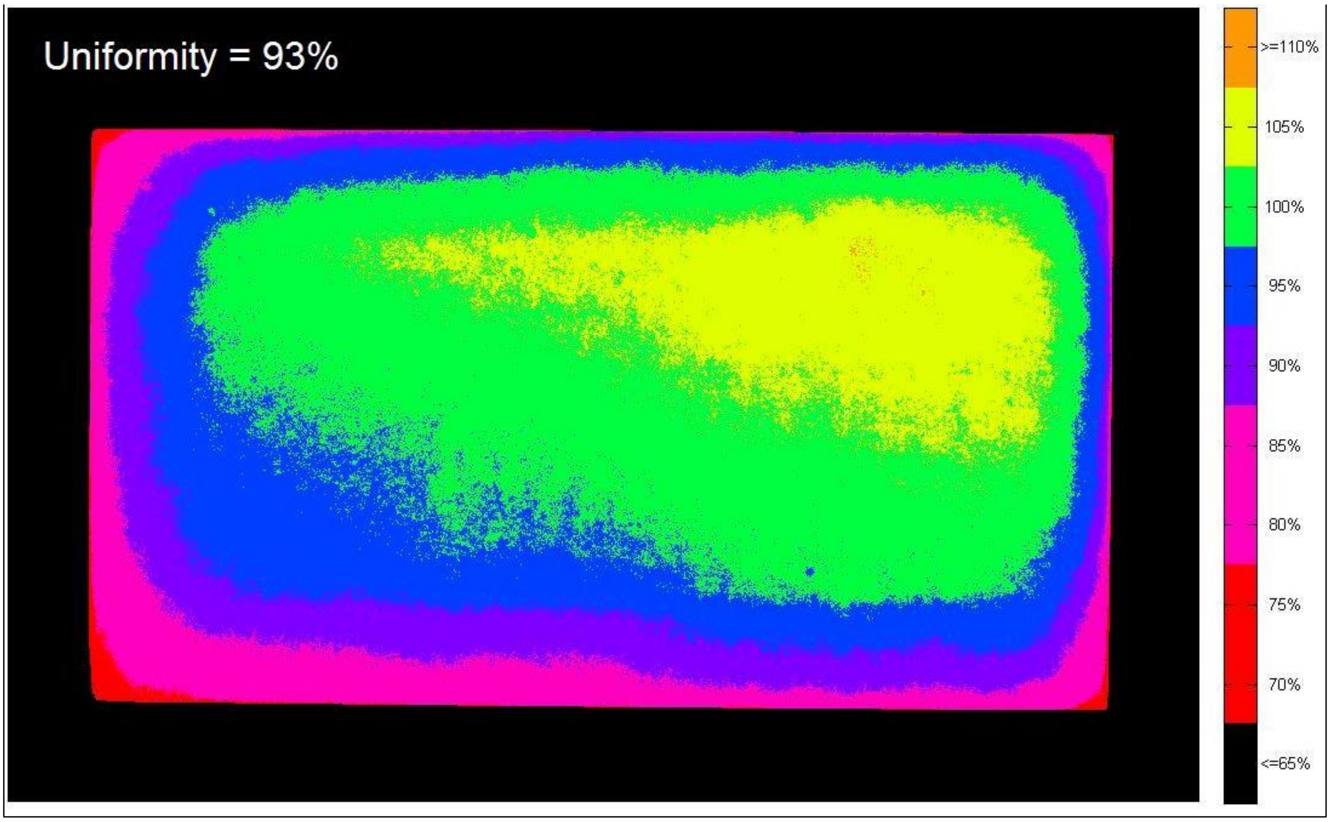


Figure 48: Uniformity measurement result presentation (example)

3.8 Viewing-angle dependency

See § 2.8.

3.9 Motion artefacts

See § 2.9

3.10 Screen resolution

Whilst the manufacturers' data should indicate conformance with the requirement, a visual check of conformance can be performed by conducting a set of tests using (e.g.) Test pattern EBU_7 in 1920x1080 and, for UHD monitors, 3840x2160 versions.

Presentation of results:

Table 26: Screen resolution visual check results presentation (example)

Resolution:	Manufacturers Data:	'x'	Confirmed: Yes ¤ , No ¤

3.11 Image scaling and overscan

Test pattern EBU_7 will also enable the visual confirmation of the scaling quality or overscan.

A valid conclusion of this test might be that the monitor is not suitable for monitoring signals that have a pixel structure that does not scale well to the native resolution of the display.

3.12 Delay time

A variety of methods can be used to measure the delay between the arrival of the electrical signal and its appearance on the screen. A scanning display will have a different characteristic from a display that reads a whole frame before displaying it.

For the following measurements, test signals EBU_9-top and EBU_9-centre are used. These contain nine lines in 1080p (18 lines in 2160p) of nominal peak white in a single frame (i.e., a white flash in an otherwise black signal). The transition between black and white is at the top of the screen (EBU_9-top) for the first measurement and at the middle of the centre line (EBU_9-centre) for the second measurement.

Manufacturers are requested to explicitly state the delay time relating to the top line of the screen, and so the delay at this point on the screen should be measured:

Note: *The delay reported should be the time between the arrival of the timing transition in the serial electrical signal at the monitor input and the moment at which the light output from the screen has risen to 50% of its final value.*

The most important issue is that of lip-sync and to assess this, a second test position at the centre (both vertically and horizontally), of the screen is used.

Note: *The delay reported should be the time between the arrival of the timing transition in the serial electrical signal representing the middle line of the image at the monitor input and the moment at which the light output from the screen has risen to 50% of its final value.*

Any variation between these two measurements is interesting as part of the understanding of the delay characteristic of the screen.

The usual test method to detect the light output from the screen will involve the use of a photodiode that only covers a few display lines. The time delay between the electrical and optical signals is determined on an oscilloscope. Since the delays concerned are of the order of ms, the ramp-up of the photo diode detector (of the order of hundreds of μs) as the 5 lines are illuminated in sequence is not significant. Any A-to-D or D-to-A converters that are included in the test arrangement should be tested to confirm that they have negligible delay, or that their delay is accounted for.

A block diagram showing the possible arrangement of the equipment is shown below. For systems that utilise quad-3G-SDI, a single 3G-SDI link may be used in the measurement process.

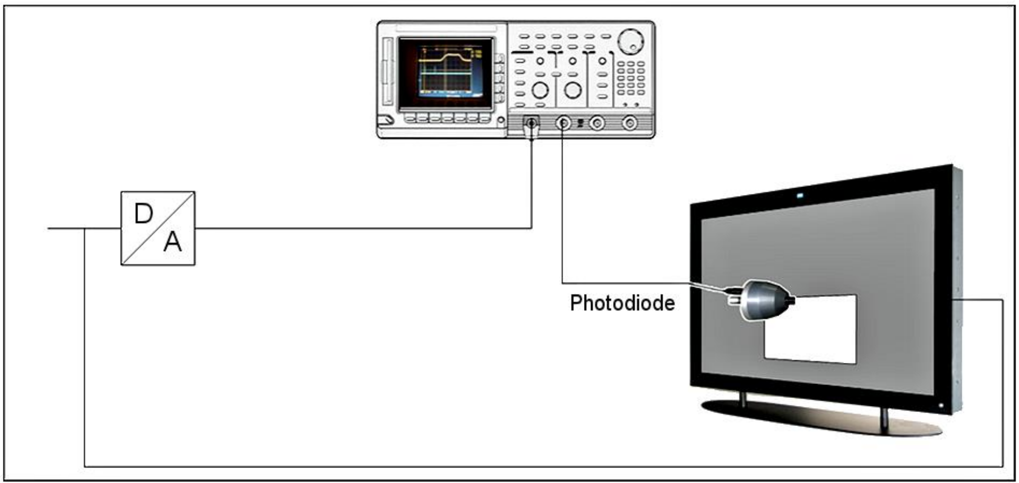


Figure 49: Arrangement of equipment for measurement of a/v delay

Table 27: Delay measurement results presentation (example)

Test signal:	1920x1080p/50	3840x2160p/50
Short delay display mode:	Top: delay: . . . . ms Centre: delay: . . . . ms	Top: delay: . . . . ms Centre: delay: . . . . ms
Normal display mode:	Top: delay: . . . . ms Centre: delay: . . . . ms	Top: delay: . . . . ms Centre: delay: . . . . ms

3.13 Mura (imperfections in LCD, LED and OLED panels)

See § 2.13.

Note: ‘Mura’ is a defect that looks like a small-scale crack with very small changes in luminance or colour. ‘Mura’ is likely to be noticeable in the flat portions of images even if the size of the Mura is very small. Mura will be revealed in a small area uniformity test.

3.14 Stability

Stability of black level, white level and colour temperature should be measured regularly over the first 30 minutes. Results for black and white levels should be normalised to 100% and plotted against time. Colour temperature variations with time should be plotted on a diagram like Figure 46. Any variation in black level visible using PLUGE should be reported.

3.15 Pixel defects

A high-resolution photograph (or a series of photographs covering the whole the screen area) on which it is possible to resolve the individual sub-pixels, should be taken on 10% and 50% signal level grey frames, to check for both bright and dark stuck or dead pixels. Pixel defects, classified according to ISO 13406 2 [15], should be reported.

Pixels that are stuck on or that are stuck at a high luminance level are detected by displaying a black frame. Pixels that are stuck off or that are stuck at a low luminance level can be detected using 75% level red, green and blue frames.

3.16 Ringing and handling of under- and over-shoots

A visual check at a viewing distance of 1H is made using Test pattern EBU_10. Any visible ringing or overshoots generated by the display should be reported.

If sub-black and super-white patches of a test signal (for example PLUGE) are not reproduced, this should be reported, since it indicates that overshoots present in the signal may be disguised.

3.17 Treatment of illegal signals

Hyperbolic zone plates such as those in test pattern EBU_7 provide a useful indication of the behaviour of a display in handling frequency components beyond the theoretical channel limit.

A test pattern that includes illegal colours should be used to check how the display handles such colours.

Note that signals can be within the range standardised for YCbCr but when matrixed to RGB do not fall within the 10-bit code value range – these are defined as out-of-range colours.

3.18 Image sticking (long-term after-image)

The luminance levels are measured on a mid- grey frame (test pattern EBU_12-grey) at measurement locations 9 and 12. A test pattern having light grey on the left-hand side of the screen and dark grey on the right (and with a gentle transition at the join – Test pattern EBU_12-burn) is displayed for 1 hour. Then the mid grey frame is displayed for 1 hour. At the end of that time the measurements are repeated, and the results tabulated.

> ***Warning***: *Users should seek confirmation from manufacturers that they consent to this test being applied to their products. The EBU accepts no responsibility should any test cause damage to equipment!*

If image sticking or burn-in appears to be an issue, the user might, in consultation with the manufacturer, consider conducting a test such as that specified in VESA FPDM2 [4], section 305-2. Problems with image retention are discussed in EBU R 129 [16].

3.19 Signal interfaces

Measurements of conformance to interface standards may be undertaken as specified in the relevant interface standards documents.

3.20 Acoustic Noise

See § 2.20.

3.21 Crosstalk and Streaking

Flat panel display devices can exhibit crosstalk between line or column circuitry, between power supply and line or column circuitry or from induced current in circuitry by external influences such as Electro-Magnetic Interference. The perceived visual artefact caused by crosstalk is known as streaking.

The UHD Crosstalk Test pattern (EBU_13) is used for this test, see Figure 50. For each location, 1 to 9, the luminance is measured. The mean average of positions 2 - 9 is calculated and shall be within the tolerance given in Table 28. This test shall be graded as a Pass or Fail.

Table 28: Crosstalk tolerances

Monitor Lw	HLG		PQ	
	Min Grey L	Max Grey L	Min Grey L	Max Grey L
600	19.36	22.53	24.32	28.31
1000	24.32	28.31	24.32	28.31
1500	29.15	33.93	24.32	28.31
2000	33.15	28.58	24.32	28.31
3000	39.73	46.23	24.32	28.31
4000	45.17	52.57	24.32	28.31

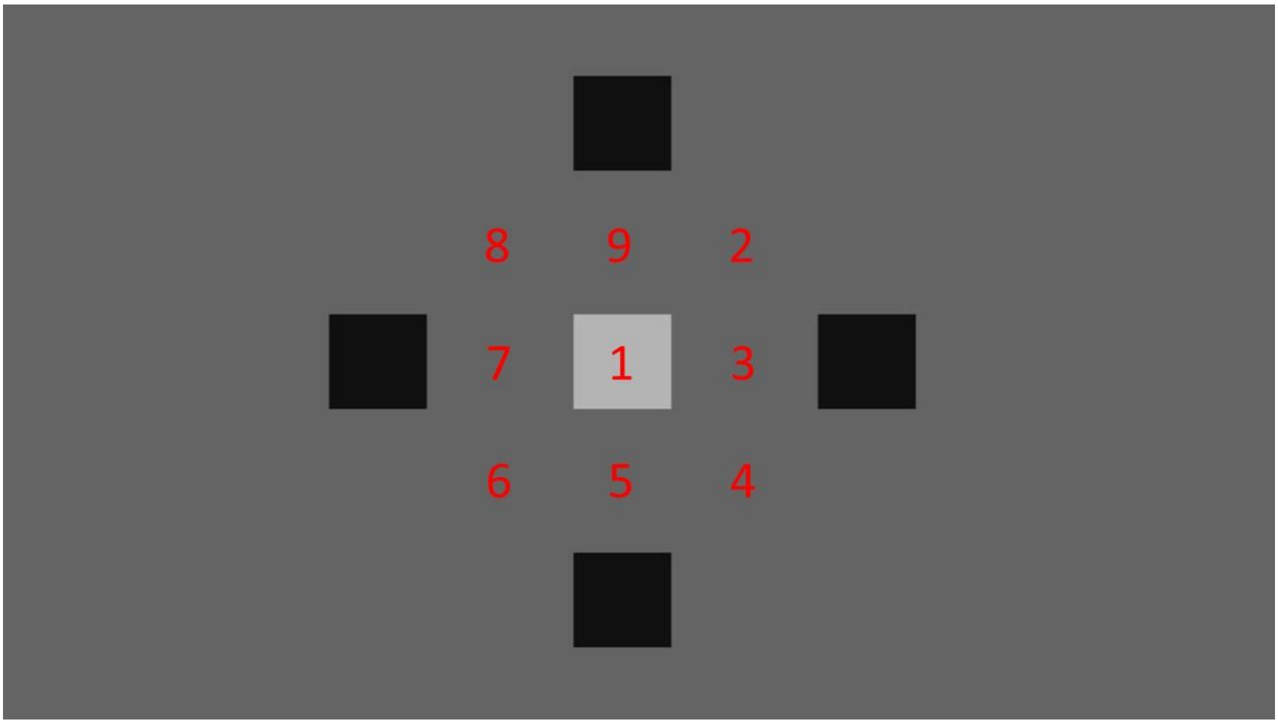


Figure 50: Crosstalk test pattern with areas 1 to 9 to measure

4. References

For references to a specific version of a document, the reader is encouraged to investigate the availability of the most recent edition[9].

[1] EBU Tech 3320 v4.1, *User requirements for Video Monitors in Television Production*, EBU, September 2019, tech.ebu.ch/publications/tech3320

[2] EBU R 103 v2.0, *Video Signal Tolerance in Digital Television Systems*, EBU, May 2020, tech.ebu.ch/publications/r103

[3] EBU Tech 3373, *Colour Bars for use in the Production of Hybrid-Log Gamma (HDR) UHDTV*, EBU, March 2020, tech.ebu.ch/publications/tech3373

[4] *Information Display Measurements Standard* (IDMS) v1.03, SID/VESA, International Committee for Display Metrology, June 2021, sidfiles.egnyte.com/dl/sk85eRizaG/20120522_IDMSv1p03.pdf_

[5] ITU-R BT.2035, *A reference viewing environment for evaluation of HDTV program material or completed programmes*, ITU, July 2012, https://www.itu.int/rec/R-REC-BT.2035-0-201307-I

[6] ITU-R BT.2100-2, *Image parameter values for high dynamic range television for use in production and international programme exchange*, ITU, July 2018, www.itu.int/rec/R-REC-BT.2100

[7] ITU-R BT.814-4, *Specifications of PLUGE test signals and alignment procedures for setting of brightness and contrast of displays*, ITU, July 2018, www.itu.int/rec/R-REC-BT.814

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[9] IEC 60107-1:1997, *Methods of measurement on receivers for television broadcast transmission - Part 1: General considerations - Measurements at radio and video frequencies*, IEC, April 1994

[10] ITU-R BT.709-5, *Parameter values for the HDTV standards for production and international programme exchange*, ITU, April 2014, www.itu.int/rec/R-REC-BT.709

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[12] EBU Tech 3237, *Methods of measurement of the colorimetric fidelity of television cameras*, EBU, May 1983, tech.ebu.ch/publications/tech3237

[13] EBU Tech 3237s1, *Methods of measurement of the colorimetric fidelity of television cameras - Supplement 1*, EBU, November 1989, tech.ebu.ch/publications/tech3237s1

[14] *Display measurement - a simple approach to small-area luminance uniformity testing*, Poulin, F., Caron, M., EBU Technical Review, 2009 Q2, EBU, tech.ebu.ch/docs/techreview/trev_2009-Q2.pdf

[15] ISO 13406-2, *Ergonomic requirements for work with visual displays based on flat panels -- Part 2: Ergonomic requirements for flat panel displays*, ISO, January 2001

[16] EBU R 129 v2.0, *Advice on avoiding 'image retention' on displays*, EBU, November 2018, tech.ebu.ch/publications/r129

[17] *Community reaction criteria for external noises*, Kosten and Van Os, National Physical Laboratory Symposium, No. 12, 1962, p. 377, London H.M.S.O.

[18] EBU Tech 3325s2, EOTF tolerances for HLG and PQ measurements using EBU Tech 3325, EBU, July 2021, tech.ebu.ch/publications/tech3325s2

[19] *Measuring Colour*, Hunt and Pointer, 4th Edition, Wiley IS&T Series in Imaging Science and Technology, Wiley, Chichester UK, 2011

[20] ISO/CIE 11664-5:2016, *Colorimetry-Part 5: CIE 1976 L*u*v* colour space and u', v' uniform chromaticity scale diagram*, ISO, September 2016

[21] SMPTE RP 177:1993, *Derivation of Basic Television Color Equations*, SMPTE, Nov 1993

[22] ITU-R BT.2020, *Parameter values for ultra-high-definition television systems for production and international programme exchange*, ITU, October 2015, https://www.itu.int/rec/R-REC-BT.2020

[9] Links to EBU publications normally point to the related web page, which provides links to all available versions of the publication (e.g.: tech.ebu.ch/publications/tech3320). Links to the publication files themselves, may either be to the latest publication (e.g.: tech.ebu.ch/docs/tech/tech3320.pdf), or to a specific version (e.g.: tech.ebu.ch/docs/tech/tech3320v1_0.pdf). Note the inclusion of version information in the URL in the second case.

Annex 1: Calculation procedures for Electro-Optical Transfer Function

For SDR:

L = Screen luminance in cd/m²

L_W = Screen luminance for white (measurement: luminance at CV 940 or V = 1)

L_B = Screen luminance for black (measurement: luminance at CV 64 or V = 0)

V = Input video signal (normalized, black at V = 0, to white at V = 1. For ITU-R BT.709, 10-bit digital code value “CV”: V = (CV-64)/(940-64)

⇨ Measured EOTF = $\frac{\log(L - L_B) - \log(L_W)}{\log V}$

For HDR (HLG and PQ):

As the transfer functions for HDR are complex and cannot be represented by a single numerical figure, a supplement to this document in the form of an **Excel spreadsheet** [18] is provided to calculate the applicable tolerance in transfer function for HLG and PQ.

To use this Excel spreadsheet, enter the peak luminance and black level measurements and a plot of code value vs. expected luminance is created with acceptable tolerances. Please plot your recorded values on the relevant HLG or PQ plot and ensure they lie within the displayed tolerance limits.

Annex 2: Calculation procedures for Chromaticities

Chromaticity coordinates in the CIE 1931 colour space can be obtained for each primary from the tristimulus values:

$$x = \frac{X}{X+Y+Z} \qquad y = \frac{Y}{X+Y+Z} \qquad z = \frac{Z}{X+Y+Z}$$

The third coordinate, z, is not required since x + y + z = 1. For television purposes, it is more customary to use coordinates in the CIE 1976 colour space, derived either by transformation from x and y or, more-directly, from the tristimulus values:

$$u' = \frac{4x}{-2x+12y+3} = \frac{4X}{X+15Y+3Z} \qquad v' = \frac{9y}{-2x+12y+3} = \frac{9Y}{X+15Y+3Z}$$

For the calculation of colour reproduction errors and the presentation of white-uniformity results, these coordinates should also be transformed into CIELuv units. This system is preferred because it more-closely relates objective measurements to subjective experience. The units are:

General formula:

$L_{a/n}^* = 116(Y_a/Y_n)^{1/3} - 16$ for $Y_a/Y_n > 0.008856$

$L_{a/n}^* = 903.3\ (Y_a/Y_n)$ for $Y_a/Y_n \leq 0.008856$

$u_a^* = 13\ L_{a/n}^*\ (u'_a - u'_n)$

$v_a^* = 13\ L_{a/n}^*\ (v'_a - v'_n)$

Y_n, u'_n and v'_n are the luminance and chromacities of the reference white. The *a* index is for the desired calculation point (can be substituted by *m*, *w*, *D65* or *ref* in function of which L*, u* or v* is desired)

$\Delta u_m^* = u_m^* - u_{ref}^*$

$\Delta u_m^* = u_m^* - u_{ref}^*$

$\Delta u_m^* = 13\ L_{m/n}^*\ (u'_m - u'_n) - 13\ L_{ref/n}^*\ (u'_{ref} - u'_n)$

Δv_m^* is calculated in the same way,
where *m* is for the measured chromaticity, and *ref* is the reference from which Δu_m^* is calculated.

For tolerances to be applied to the white point:

- *ref* is *D65* with chromaticity coordinates $u'_{D65} = 0.1978$ and $v'_{D65} = 0.4683$.
- *m* becomes *w* for measured white
- n is D65
- For Grade 1 monitors Y_n is taken as 100 cd/m², for Grade 2, 200 cd/m², and for Grade 3 as 250 cd/m².
- For Grade 1 HDR monitors Y_n is taken as 1000 cd/m², for Grade 2 HDR, 600 cd/m², and for Grade 3 HDR as 500 cd/m².
- The generalized formula
  $\Delta u_w^* = u_w^* - u_{D65}^* = 13\ L_{w/D65}^*\ (u'_w - u'_{D65}) - 13\ L_{D65/D65}^*\ (u'_{D65} - u'_{D65})$
  $\rightarrow \Delta u_w^* = 13\ L_{w/D65}^*\ (u'_w - u'_{D65}) - 0$
  can therefore be simplified as:
  $\Delta u_w^* = 13\ L_{w/D65}^*\ (u'_w - u'_{D65})$
  and similarly:
  $\Delta v_w^* = 13\ L_{w/D65}^*\ (v'_w - v'_{D65})$

For grey-scale tracking calculations:

- *ref* is the measured white point and becomes *w*
- *m* becomes *g* for grey scale
- *n* is the measured white point, *w*
- The generalized formula
  $\Delta u_g^* = u_g^* - u_w^* = 13\, L_{g/w}^*\, (u'_g - u'_w) - 13\, L_{w/w}^*\, (u'_w - u'_w)$
  $\rightarrow \Delta u_g^* = u_g^* - u_w^* = 13\, L_{g/w}^*\, (u'_g - u'_w) - 0$
  can therefore be simplified as:
  $\Delta u_g^* = 13\, L_{g/w}^*\, (u'_g - u'_w)$
  and similarly:
  $\Delta v_g^* = 13\, L_{g/w}^*\, (v'_g - v'_w)$

For test colour and primary reproduction calculations:

- *ref* is the expected test colour and becomes *ex*
- *m* becomes *c* for colour
- *n* is the measured white point, *w*
- The generalized formula is
  $\Delta u_c^* = u_c^* - u_{ex}^* = 13\, L_{c/w}^*\, (u'_c - u'_w) - 13\, L_{ex/w}^*\, (u'_{ex} - u'_w)$
- To remove the effect of EOTF error of the display
  $L_{ex/w}^*$ *could* be replaced by $L_{c/w}^*$ (not useable for calculating ΔE^*_{uv} because then $\Delta L^* = 0$ as per definition!) the generalized formula
  $\Delta u_c^* = 13\, L_{c/w}^*\, (u'_c - u'_w) - 13\, L_{ex/w}^*\, (u'_{ex} - u'_w)$
  $\rightarrow L_{ex/w}^*$ replaced by $L_{c/w}$
  $\rightarrow \Delta u_c^* = 13\, L_{c/w}^*\, (u'_c - u'_w) - 13\, L_{c/w}^*\, (u'_{ex} - u'_w)$
  $\rightarrow \Delta u_c^* = 13\, L_{c/w}^*\, [(u'_c - u'_w) - (u'_{ex} - u'_w)]$
  $\rightarrow \Delta u_c^* = 13\, L_{c/w}^*\, (u'_c - u'_{ex})$
  and can therefore be simplified (when ignoring the error in L*) as:
  $\Delta u_c^* = 13\, L_{c/w}^*\, (u'_c - u'_{ex})$
  and similarly:
  $\Delta v_c^* = 13\, L_{c/w}^*\, (v_c' - v_{ex}')$

Deltas:

$\Delta u^*v^* = \sqrt{(\Delta u^{*2} + \Delta v^{*2})}$

$\Delta E^*_{uv} = \sqrt{(\Delta L^{*2} + \Delta u^{*2} + \Delta v^{*2})}$

For further information, please refer to §§ 3.8 - 3.10 in [19] and to [20].

Annex 3: How the Code Values for test patterns were calculated

General

- L_{ref} = Reference White
  => At E' = HLG $OETF^{-1}$ = 0.75 -> F_D = OOTF = 203.152145937545 cd/m²
  => At E' = HLG $OETF^{-1}$ = 0.99999999506613 ≈ 1 -> F_D = OOTF = 1000 cd/m²
- L_{ref} for PQ is the same as for HLG75 (203.152145937545 cd/m²)!

  The resulting Code Value is 594 which correlates with E' [0:1] = 0.5806452
- L_w = Nominal Peak Luminance
- Y_{exp} = Y = L · L_{ref} = Expected Luminance in cd/m²
- PQ SDI full range:
  PQ is intended to be used in full range (e.g., code value 0 to 1023 in a 10-bit system). But in an SDI-based infrastructure the Time Reference Signals (TRC) use CV 0 to 3 and 1020 to 1023 (10 bit) and thus no active video shall be used in these ranges (protected values).

  Therefore, only the "permitted range" as described in SMPTE RP 2077:2013 is used where the transfer function below CV 4 and above CV 1019 is cut off, but the curve shape in the range of CV 4 and 1019 remains unchanged compared to CV_{Full}. See also EBU R 103 [2].
- The PQ narrow range is defined between Code Values 64 (Black) and 940 (White). The curve in PQ narrow range is thus compressed into the smaller Code Value range of narrow range compared to PQ full range.

Matrices

Two versions of the matrices are provided below: the "long-version" with all 16 decimals, and a "short-version" with 4 decimals. Using the "short-version" may lead to small inaccuracies in the code value calculations. For the calculation of the values in this document the long versions have been used, unless otherwise stated.

Attention! *Never use the "short-version" of one matrix and let Excel or Matlab calculate its inverse Matrix. This will cause major inaccuracies. If you would like to let your programme calculate the Inverse, always use the "long-version".*

NPM709

709-Matrix

X_R =	0.4123907992659590	X_G =	0.3575843393838780	X_B =	0.1804807884018340
Y_R =	0.2126390058715100	Y_G =	0.7151686787677560	Y_B =	0.0721923153607337
Z_R =	0.0193308187155919	Z_G =	0.1191947797946260	Z_B =	0.9505321522496610

709-Matrix (calculated with high precision and then rounded to four decimals)

X_R =	0.4124	X_G =	0.3576	X_B =	0.1805
Y_R =	0.2126	Y_G =	0.7152	Y_B =	0.0722
Z_R =	0.0193	Z_G =	0.1192	Z_B =	0.9505

Inverse NPM_{709} or NPM_{709}^{-1}

Inverse 709-Matrix

R_X =	3.2409699419045200	R_Y =	-1.5373831775700900	R_Z =	-0.4986107602930030
G_X =	-0.9692436362808800	G_Y =	1.8759675015077200	G_Z =	0.0415550574071756
B_X =	0.0556300796969936	B_Y =	-0.2039769588889770	B_Z =	1.0569715142428800

Inverse 709-Matrix (calculated with high precision and then rounded to four decimals)

R_X =	3.2410	R_Y =	-1.5374	R_Z =	-0.4986
G_X =	-0.9692	G_Y =	1.8760	G_Z =	0.0416
B_X =	0.0556	B_Y =	-0.2040	B_Z =	1.0570

NPM_{2020}

2020-Matrix

X_R =	0.6369580483012910	X_G =	0.1446169035862080	X_B =	0.1688809751641720
Y_R =	0.2627002120112670	Y_G =	0.6779980715188710	Y_B =	0.0593017164698620
Z_R =	0.0000000000000000	Z_G =	0.0280726930490874	Z_B =	1.0609850577107900

2020-Matrix (calculated with high precision and then rounded to four decimals)

X_R =	0.6370	X_G =	0.1446	X_B =	0.1689
Y_R =	0.2627	Y_G =	0.6780	Y_B =	0.0593
Z_R =	0	Z_G =	0.0281	Z_B =	1.0610

Inverse NPM_{2020} or NPM_{2020}^{-1}

Inverse 020-Matrix

R_X =	1.7166511879712700	R_Y =	-0.3556707837763930	R_Z =	-0.2533662813736600
G_X =	-0.6666843518324890	G_Y =	1.6164812366349400	G_Z =	0.0157685458139111
B_X =	0.0176398574453109	B_Y =	-0.0427706132578085	B_Z =	0.9421031212354740

Inverse 2020-Matrix (calculated with high precision and then rounded to four decimals)

R_X =	1.7167	R_Y =	-0.3557	R_Z =	-0.2534
G_X =	-0.6667	G_Y =	1.6165	G_Z =	0.0158
B_X =	0.0176	B_Y =	-0.0428	B_Z =	0.9421

BT.709 SDR (Tech 3325)

709-SDR	with EOTF 2.35 according to Tech 3325; L_{ref} = 100 cd/m²; L_w = 100 cd/m²	
u' v' L	given values	as defined in EBU Tech 3325
x y z	$x = 9u' / (6u' - 16v' + 12)$ $y = 4v' / (6u' - 16v' + 12)$ $z = 1 - x - y$	ISO 11664-5, Annex A, Equation A.6 ISO 11664-5, Annex A, Equation A.7 ISO 11664-3, Equation 9
X Y Z	$X = x \cdot (Y/y)$ $Y = L \cdot L_{ref} = Y_{exp}$ $Z = (1-x-y) \cdot (Y/y)$	ISO 11664-5, Annex A, Equation A.8 ISO 11664-5, Annex A, Equation A.9
$X_{[norm]}$, $Y_{[norm]}$, $Z_{[norm]}$	$X_{[norm]} = X / L_w$ $Y_{[norm]} = Y / L_w = L \cdot (L_{ref}/L_w)$ $Z_{[norm]} = Z / L_w$	
R G B	$R = R_X \cdot X_{[norm]} + R_Y \cdot Y_{[norm]} + R_Z \cdot Z_{[norm]}$ $G = G_X \cdot X_{[norm]} + G_Y \cdot Y_{[norm]} + G_Z \cdot Z_{[norm]}$ $B = B_X \cdot X_{[norm]} + B_Y \cdot Y_{[norm]} + B_Z \cdot Z_{[norm]}$	Inverse NPM_{709} (16-digit version)
range [0:1]	Cut R G B below 0 and above 1	
R' G' B'	$R' = R^{(1/2.35)}$ $G' = G^{(1/2.35)}$ $B' = B^{(1/2.35)}$	ITU-R BT.2087, M2 $E' = E^{(1/\gamma)}$ with γ=2.35
Y' C'_B C'_R	$Y' = 0.2126 \cdot R' + 0.7152 \cdot G' + 0.0722 \cdot B'$ $C'_B = \frac{B'-Y'}{1.8556}$ $C'_R = \frac{R'-Y'}{1.5748}$	ITU-R BT.709-6, chapter 3.3 (use four-digit version, not NPM_{709})
$CV_{Y'}$ $CV_{C'B}$ $CV_{C'R}$ (Code Value for 10 bit)	$CV_{Y'} = Round\ (876 \cdot Y' + 64)$ $CV_{C'B} = Round\ (896 \cdot C'_B + 512)$ $CV_{C'R} = Round\ (896 \cdot C'_R + 512)$	ITU-R BT.2100-2, table 9

BT.2020 SDR

2020-SDR	with EOTF 2.4; L_{ref} = 100 cd/m²; L_W = 100 cd/m²	
u' v' L	given values	as defined in EBU Tech 3325
x y z	$x = 9u' / (6u' - 16v' + 12)$ $y = 4v' / (6u' - 16v' + 12)$ $z = 1 - x - y$	ISO 11664-5, Annex A, Equation A.6 ISO 11664-5, Annex A, Equation A.7 ISO 11664-3, Equation 9
X Y Z	$X = x \cdot (Y/y)$ $Y = L \cdot L_{ref} = Y_{exp}$ $Z = (1-x-y) \cdot (Y/y)$	ISO 11664-5, Annex A, Equation A.8 ISO 11664-5, Annex A, Equation A.9
$X_{[norm]}$, $Y_{[norm]}$, $Z_{[norm]}$	$X_{[norm]} = X / L_W$ $Y_{[norm]} = Y / L_W = L \cdot (L_{ref}/L_W)$ $Z_{[norm]} = Z / L_W$	
R G B	$R = R_X \cdot X_{[norm]} + R_Y \cdot Y_{[norm]} + R_Z \cdot Z_{[norm]}$ $G = G_X \cdot X_{[norm]} + G_Y \cdot Y_{[norm]} + G_Z \cdot Z_{[norm]}$ $B = B_X \cdot X_{[norm]} + B_Y \cdot Y_{[norm]} + B_Z \cdot Z_{[norm]}$	Inverse NPM_{2020} (16-digit version)
range [0:1]	Cut R G B below 0 and above 1	
R' G' B'	$R' = R^{(1/2.4)}$ $G' = G^{(1/2.4)}$ $B' = B^{(1/2.4)}$	ITU-R BT.2087, M2 $E' = E^{(1/\gamma)}$ with γ=2.4
Y' C'B C'R	$Y' = 0.2627 \cdot R' + 0.6780 \cdot G' + 0.0593 \cdot B'$ $C'_B = \frac{B'-Y'}{1.8814}$ $C'_R = \frac{R'-Y'}{1.4746}$	ITU BT.2100, table 6 (use four-digit version, not NPM_{2020})
$cv_{Y'}$ $cv_{C'B}$ $cv_{C'R}$ (Code Value for 10 bit)	$cv_{Y'} = \text{Round}(876 \cdot Y' + 64)$ $cv_{C'B} = \text{Round}(896 \cdot C'_B + 512)$ $cv_{C'R} = \text{Round}(896 \cdot C'_R + 512)$	ITU-R BT.2100-2, table 9

BT.2100 HLG

HLG	L_{ref} = 1000 cd/m²; L_w = 1000 cd/m²; γ = 1.2	ITU-R BT.2100, Note 5f, Footnote 2: $\gamma = 1.2 \cdot \kappa^{\log_2\left(\frac{L_W}{1000}\right)}\ where\ \kappa = 1.111$
u' v' L	given values	as defined in EBU Tech 3325
x y z	x = 9u' / (6u' - 16v' + 12) y = 4v' / (6u' - 16v' + 12) z = 1 - x - y	ISO 11664-5, Annex A, Equation A.6 ISO 11664-5, Annex A, Equation A.7 ISO 11664-3, Equation 9
X Y Z	X = x · (Y/y) Y = L · L_{ref} = Y_{exp} Z = (1-x-y) · (Y/y)	ISO 11664-5, Annex A, Equation A.8 ISO 11664-5, Annex A, Equation A.9
$X_{[norm]}$, $Y_{[norm]}$, $Z_{[norm]}$	$X_{[norm]}$ = X / L_W $Y_{[norm]}$ = Y / L_W = L · (L_{ref}/L_W) = Y_D $Z_{[norm]}$ = Z / L_W	
R_D G_D B_D	$R_D = R_X \cdot X_{[norm]} + R_Y \cdot Y_{[norm]} + R_Z \cdot Z_{[norm]}$ $G_D = G_X \cdot X_{[norm]} + G_Y \cdot Y_{[norm]} + G_Z \cdot Z_{[norm]}$ $B_D = B_X \cdot X_{[norm]} + B_Y \cdot Y_{[norm]} + B_Z \cdot Z_{[norm]}$	Inverse NPM_{2020} (16-digit version)
R_S G_S B_S	$R_S = (Y_D)^{(1-\gamma)/\gamma} * R_D$ $G_S = (Y_D)^{(1-\gamma)/\gamma} * G_D$ $B_S = (Y_D)^{(1-\gamma)/\gamma} * B_D$	ITU-R BT.2100-2, note 5i with α set to 1.0 cd/m²
range [0:1]	Cut R_S G_S B_S below 0 and above 1	ITU-R BT.2100-2, table 5, HLG Reference OOTF
Y_S	$Y_S = Y_R \cdot R_S + Y_G \cdot G_S + Y_B \cdot B_S$	NPM_{2020} Ys is useful for the inverse calculation Also note that: $Y_D = (Y_S)^{\gamma}$
R' G' B'	E' = OETF [E] = $\begin{cases} \sqrt{3E} & 0 \le E \le 1/12 \\ a \cdot \ln(12 \cdot E - b) + c & 1/12 < E \le 1 \end{cases}$	ITU-R BT.2100-2, table 5, HLG Reference OETF
range [0:1]	Cut R' G' B' below 0 and above 1	ITU-R BT.2100-2, table 5, HLG Reference OETF

$Y'\ C'_B\ C'_R$	$Y' = 0.2627 \cdot R' + 0.6780 \cdot G' + 0.0593 \cdot B'$ $C'_B = \frac{B'-Y'}{1.8814}$ $C'_R = \frac{R'-Y'}{1.4746}$	ITU-R BT.2100, table 6 (use four-digit version, not NPM_{2020})
$CV_{Y'}\ CV_{C'B}\ CV_{C'R}$ (Code Value for 10 bit)	$CV_{Y'}$ = Round $(876 \cdot Y' + 64)$ $CV_{C'B}$ = Round $(896 \cdot C'_B + 512)$ $CV_{C'R}$ = Round $(896 \cdot C'_R + 512)$	ITU-R BT.2100-2, table 9

BT.2100 HLG 75%

HLG75	$L_{ref} = 203.1521\ cd/m^2$; $L_w = 1000\ cd/m^2$; $\gamma = 1.2$	ITU-R BT.2100, Note 5f, Footnote 2: $\gamma = 1.2 \cdot \kappa^{log_2\left(\frac{L_w}{1000}\right)}\ where\ \kappa = 1.111$
u' v' L	given values	as defined in EBU Tech 3325
x y z	$x = 9u' / (6u' - 16v' + 12)$ $y = 4v' / (6u' - 16v' + 12)$ $z = 1 - x - y$	ISO 11664-5, Annex A, Equation A.6 ISO 11664-5, Annex A, Equation A.7 ISO 11664-3, Equation 9
X Y Z	$X = x \cdot (Y/y)$ $Y = L \cdot L_{ref} = Y_{exp}$ $Z = (1-x-y) \cdot (Y/y)$	ISO 11664-5, Annex A, Equation A.8 ISO 11664-5, Annex A, Equation A.9
$X_{[norm]}, Y_{[norm]}, Z_{[norm]}$	$X_{[norm]} = X / L_w$ $Y_{[norm]} = Y / L_w = L \cdot (L_{ref}/L_w) = Y_D$ $Z_{[norm]} = Z / L_w$	
$R_D\ G_D\ B_D$	$R_D = R_X \cdot X_{[norm]} + R_Y \cdot Y_{[norm]} + R_Z \cdot Z_{[norm]}$ $G_D = G_X \cdot X_{[norm]} + G_Y \cdot Y_{[norm]} + G_Z \cdot Z_{[norm]}$ $B_D = B_X \cdot X_{[norm]} + B_Y \cdot Y_{[norm]} + B_Z \cdot Z_{[norm]}$	Inverse NPM_{2020} (16-digit version)
$R_S\ G_S\ B_S$	$R_S = (Y_D)^{(1-\gamma)/\gamma} * R_D$ $G_S = (Y_D)^{(1-\gamma)/\gamma} * G_D$ $B_S = (Y_D)^{(1-\gamma)/\gamma} * B_D$	ITU-R BT.2100-2, note 5i with α set to 1.0 cd/m^2
range [0:1]	Cut $R_S\ G_S\ B_S$ below 0 and above 1	ITU-R BT.2100-2, table 5, HLG Reference OOTF

Y_S	$Y_S = Y_R \cdot R_S + Y_G \cdot G_S + Y_B \cdot B_S$	NPM_{2020} Ys is useful for the inverse calculation Also note that: $Y_D = (Y_S)^{\gamma}$
R' G' B'	E' = OETF [E] = $\begin{cases} \sqrt{3E} & 0 \leq E \leq 1/12 \\ a \cdot \ln(12 \cdot E - b) + c & 1/12 < E \leq 1 \end{cases}$	ITU-R BT.2100-2, table 5, HLG Reference OETF
range [0:1]	Cut R' G' B' below 0 and above 1	ITU-R BT.2100-2, table 5, HLG Reference OETF
$Y' C'_B C'_R$	$Y' = 0.2627 \cdot R' + 0.6780 \cdot G' + 0.0593 \cdot B'$ $C'_B = \frac{B'-Y'}{1.8814}$ $C'_R = \frac{R'-Y'}{1.4746}$	ITU-R BT.2100, table 6 (use four-digit version, not NPM_{2020})
$CV_{Y'}$ $CV_{C'B}$ $CV_{C'R}$ (Code Value for 10 bit)	$CV_{Y'}$ = Round (876 · Y' + 64) $CV_{C'B}$ = Round (896 · C'_B + 512) $CV_{C'R'}$ = Round (896 · C'_R + 512)	ITU-R BT.2100-2, table 9

BT.2100 PQ (permitted range)

PQ 100	L_{ref} = 10.000 cd/m²; L_w = 10.000 cd/m²;	
u' v' L	given values	as defined in EBU Tech 3325
x y z	x = 9u' / (6u' - 16v' + 12) y = 4v' / (6u' - 16v' + 12) z = 1 - x - y	ISO 11664-5, Annex A, Equation A.6 ISO 11664-5, Annex A, Equation A.7 ISO 11664-3, Equation 9
X Y Z	X = x · (Y/y) Y = L · L_{ref} = Y_{exp} Z = (1-x-y) · (Y/y)	ISO 11664-5, Annex A, Equation A.8 ISO 11664-5, Annex A, Equation A.9
$X_{[norm]}$, $Y_{[norm]}$, $Z_{[norm]}$	$X_{[norm]} = X / L_w$ $Y_{[norm]} = Y / L_w = L \cdot (L_{ref}/L_w) = Y_D$ $Z_{[norm]} = Z / L_w$	

R_D G_D B_D	$R_D = R_X \cdot X_{[norm]} + R_Y \cdot Y_{[norm]} + R_Z \cdot Z_{[norm]}$ $G_D = G_X \cdot X_{[norm]} + G_Y \cdot Y_{[norm]} + G_Z \cdot Z_{[norm]}$ $B_D = B_X \cdot X_{[norm]} + B_Y \cdot Y_{[norm]} + B_Z \cdot Z_{[norm]}$	Inverse NPM_{2020} (16-digit version)
range [0:1]	Cut Rd Gd Bd below 0 and above 1	
R' G' B'	$E' = OETF[E] = EOTF^{-1}[OOTF[E]]$ $= EOTF^{-1}[F_D] = \left(\frac{c1 + c2 * Y^{m1}}{1 + c3 * Y^{m1}}\right)^{m2}$	ITU-R BT.2100-2, table 4, Reference PQ OETF Note: fill in R_d, G_D, B_D in Y
range [0:1]	Cut R' G' B' below 0 and above 1	ITU-R BT.2100-2, table 4, Reference PQ OETF
Y' C'_B C'_R	$Y' = 0.2627 \cdot R' + 0.6780 \cdot G' + 0.0593 \cdot B'$ $C'_B = \frac{B' - Y'}{1.8814}$ $C'_R = \frac{R' - Y'}{1.4746}$	ITU-R BT.2100, table 6 (use four-digit version, not NPM_{2020})
CV_{full}	$cv_{Y'} = Round(1023 * Y')$ $cv_{C'B} = Round(1023 * C'_B + 512)$ $cv_{C'R'} = Round(1023 * C'_R + 512)$	ITU-R BT.2100-2, table 9 Full-range (CV_{full})
$cv_{Y'}$ $cv_{C'B}$ $cv_{C'R}$ (Code Value for 10 bit) SDI full range	$cv_Y = Clamp(4, 1019, cv_Y)$ $c_{C'B} = Clamp(4, 1019, cv_{C'B})$ $c_{C'R} = Clamp(4, 1019, cv_{C'R})$ with: Clamp(4, 1019, x) = | 4, if x e [4,1019] | 4, if x < 4 | 1019, if x > 1019	SMPTE RP 2077:2013, equation 1 Permitted range

BT.2100 PQ 58% (permitted range)

PQ-58	L_{ref} = 203.1521 cd/m²; L_w = 10.000 cd/m²;	L_{ref} is the same as for HLG75!
u' v' L	given values	as defined in EBU Tech 3325
x y z	x = 9u' / (6u' - 16v' + 12) y = 4v' / (6u' - 16v' + 12) z = 1 - x - y	ISO 11664-5, Annex A, Equation A.6 ISO 11664-5, Annex A, Equation A.7 ISO 11664-3, Equation 9
X Y Z	$X = x \cdot (Y/y)$ $Y = L \cdot L_{ref} = Y_{exp}$ $Z = (1\text{-}x\text{-}y) \cdot (Y/y)$	ISO 11664-5, Annex A, Equation A.8 ISO 11664-5, Annex A, Equation A.9
$X_{[norm]}$, $Y_{[norm]}$, $Z_{[norm]}$	$X_{[norm]} = X / L_w$ $Y_{[norm]} = Y / L_w = L \cdot (L_{ref}/L_w) = Y_D$ $Z_{[norm]} = Z / L_w$	
R_D G_D B_D	$R_D = R_X \cdot X_{[norm]} + R_Y \cdot Y_{[norm]} + R_Z \cdot Z_{[norm]}$ $G_D = G_X \cdot X_{[norm]} + G_Y \cdot Y_{[norm]} + G_Z \cdot Z_{[norm]}$ $B_D = B_X \cdot X_{[norm]} + B_Y \cdot Y_{[norm]} + B_Z \cdot Z_{[norm]}$	Inverse NPM_{2020} (16-digit version)
range [0:1]	Cut Rd Gd Bd below 0 and above 1	
R' G' B'	$E' = OETF[E] = EOTF^{-1}[OOTF[E]]$ $= EOTF^{-1}[F_D] = \left(\frac{c1 + c2 * Y^{m1}}{1 + c3 * Y^{m1}}\right)^{m2}$	ITU-R BT.2100-2, table 4, Reference PQ OETF Note: fill in R_d, G_D, B_D in Y
range [0:1]	Cut R' G' B' below 0 and above 1	ITU-R BT.2100-2, table 4, Reference PQ OETF
Y' C'B C'R	$Y' = 0.2627 \cdot R' + 0.6780 \cdot G' + 0.0593 \cdot B'$ $C'_B = \frac{B' - Y'}{1.8814}$ $C'_R = \frac{R' - Y'}{1.4746}$	ITU-R BT.2100, table 6 (use four-digit version, not NPM_{2020})
CV_{full}	$cv_{Y'}$ = Round (1023 * Y') $cv_{C'B}$ = Round (1023 * C'_B + 512) $cv_{C'R'}$ = Round (1023 * C'_R + 512)	ITU-R BT.2100-2, table 9 Full range (CV_{full})

$CV_{Y'}$ $CV_{C'B}$ $CV_{C'R}$ (Code Value for 10 bit) SDI full range	cv_Y = Clamp(4, 1019, cv_Y) $c_{C'B}$ = Clamp(4, 1019, $cv_{C'B}$) $c_{C'R}$ = Clamp(4, 1019, $cv_{C'R}$) with: Clamp(4, 1019, x) = | 4, if x e [4,1019] | 4, if x < 4 | 1019, if x > 1019	SMPTE RP 2077:2013, equation 1 Permitted range

BT.2100 PQ 1000nit (permitted range)

PQ @1000nits	L_{ref} = 1000 cd/m²; L_w = 10.000 cd/m²;	L_{ref} = 1000 cd/m² for being visually comparable to HLG with the same max. luminance of 1000 cd/m² (used for the new EBU-colours EBU-16 to EBU-25)
↓		
u' v' L	given values	as defined in EBU Tech 3325
↓		
xyz	x = 9u' / (6u' - 16v' + 12) y = 4v' / (6u' - 16v' + 12) z = 1 - x - y	ISO 11664-5, Annex A, Equation A.6 ISO 11664-5, Annex A, Equation A.7 ISO 11664-3, Equation 9
↓		
XYZ	X = x · (Y/y) Y = L · L_{ref} = Y_{exp} Z = (1-x-y) · (Y/y)	ISO 11664-5, Annex A, Equation A.8 ISO 11664-5, Annex A, Equation A.9
↓		
$X_{[norm]}$, $Y_{[norm]}$, $Z_{[norm]}$	$X_{[norm]}$ = X / L_w $Y_{[norm]}$ = Y / L_w = L · (L_{ref}/L_w) = Y_D $Z_{[norm]}$ = Z / L_w	
↓		
R_D G_D B_D	$R_D = R_X \cdot X_{[norm]} + R_Y \cdot Y_{[norm]} + R_Z \cdot Z_{[norm]}$ $G_D = G_X \cdot X_{[norm]} + G_Y \cdot Y_{[norm]} + G_Z \cdot Z_{[norm]}$ $B_D = B_X \cdot X_{[norm]} + B_Y \cdot Y_{[norm]} + B_Z \cdot Z_{[norm]}$	Inverse NPM_{2020} (16-digit version)
↓		
range [0:1]	Cut Rd Gd Bd below 0 and above 1	
↓		
R' G' B'	E' = OETF [E] = $EOTF^{-1}$[OOTF[E]] $= EOTF^{-1}[F_D] = \left(\frac{c1 + c2 * Y^{m1}}{1 + c3 * Y^{m1}}\right)^{m2}$	ITU-R BT.2100-2, table 4, Reference PQ OETF Note: fill in R_d, G_D, B_D in Y

range [0:1]	Cut R' G' B' below 0 and above 1	ITU-R BT.2100-2, table 4, Reference PQ OETF
$Y'\ C'_B\ C'_R$	$Y' = 0.2627 \cdot R' + 0.6780 \cdot G' + 0.0593 \cdot B'$ $C'_B = \frac{B'-Y'}{1.8814}$ $C'_R = \frac{R'-Y'}{1.4746}$	ITU-R BT.2100, table 6 (use four-digit version, not NPM_{2020})
CV_{full}	$cv_{Y'}$ = Round (1023 * Y') $cv_{C'B}$ = Round (1023 * C'_B + 512) $cv_{C'R'}$ = Round (1023 * C'_R + 512)	ITU-R BT.2100-2, table 9 Full-range (CV_{full})
$cv_{Y'}\ cv_{C'B}\ cv_{C'R}$ (Code Value for 10 bit) SDI full range	cv_Y = Clamp(4, 1019, cv_Y) $c_{C'B}$ = Clamp(4, 1019, $cv_{C'B}$) $c_{C'R}$ = Clamp(4, 1019, $cv_{C'R}$) with: Clamp(4, 1019, x) = | 4, if x e [4,1019] | 4, if x < 4 | 1019, if x > 1019	SMPTE RP 2077:2013, equation 1 Permitted range

BT.2100 PQ (narrow range)

PQ @1000nits	L_{ref} = 10000 cd/m²; L_w = 10000 cd/m²;	
u' v' L	given values	as defined in EBU Tech 3325
xyz	x = 9u' / (6u' - 16v' + 12) y = 4v' / (6u' - 16v' + 12) z = 1 - x - y	ISO 11664-5, Annex A, Equation A.6 ISO 11664-5, Annex A, Equation A.7 ISO 11664-3, Equation 9
XYZ	X = x · (Y/y) $Y = L \cdot L_{ref} = Y_{exp}$ Z = (1-x-y) · (Y/y)	ISO 11664-5, Annex A, Equation A.8 ISO 11664-5, Annex A, Equation A.9

$X_{[norm]}$, $Y_{[norm]}$, $Z_{[norm]}$	$X_{[norm]} = X / L_W$ $Y_{[norm]} = Y / L_W = L \cdot (L_{ref}/L_W) = Y_D$ $Z_{[norm]} = Z / L_W$	
$R_D\ G_D\ B_D$	$R_D = R_X \cdot X_{[norm]} + R_Y \cdot Y_{[norm]} + R_Z \cdot Z_{[norm]}$ $G_D = G_X \cdot X_{[norm]} + G_Y \cdot Y_{[norm]} + G_Z \cdot Z_{[norm]}$ $B_D = B_X \cdot X_{[norm]} + B_Y \cdot Y_{[norm]} + B_Z \cdot Z_{[norm]}$	Inverse NPM_{2020} (16-digit version)
range [0:1]	Cut Rd Gd Bd below 0 and above 1	
R' G' B'	$E' = OETF[E] = EOTF^{-1}[OOTF[E]]$ $= EOTF^{-1}[F_D] = \left(\frac{c1 + c2 * Y^{m1}}{1 + c3 * Y^{m1}}\right)^{m2}$	ITU-R BT.2100-2, table 4, Reference PQ OETF Note: fill in R_d, G_D, B_D in Y
range [0:1]	Cut R' G' B' below 0 and above 1	ITU-R BT.2100-2, table 4, Reference PQ OETF
$Y'\ C'_B\ C'_R$	$Y' = 0.2627 \cdot R' + 0.6780 \cdot G' + 0.0593 \cdot B'$ $C'_B = \frac{B' - Y'}{1.8814}$ $C'_R = \frac{R' - Y'}{1.4746}$	ITU-R BT.2100, table 6 (use four-digit version, not NPM_{2020})
CV_{narrow} (Code Value	$cv_{Y'} = Round(876 * Y' + 64)$ $cv_{C'B} = Round(896 * C'_B + 512)$ $cv_{C'R} = Round(896 * C'_R + 512)$	ITU-R BT.2100-2, table 9 Narrow-range (CV_{narrow})

BT.2100 PQ 58% (narrow range)

$PQ\text{-}58_{narrow}$	L_{ref} = 203.1521 cd/m²; L_W = 10.000 cd/m²;	L_{ref} is the same as for HLG 75!
u' v' L	given values	as defined in EBU Tech 3325
xyz	$x = 9u' / (6u' - 16v' + 12)$ $y = 4v' / (6u' - 16v' + 12)$ $z = 1 - x - y$	ISO 11664-5, Annex A, Equation A.6 ISO 11664-5, Annex A, Equation A.7 ISO 11664-3, Equation 9
XYZ	$X = x \cdot (Y/y)$ $Y = L \cdot L_{ref} = Y_{exp}$ $Z = (1-x-y) \cdot (Y/y)$	ISO 11664-5, Annex A, Equation A.8 ISO 11664-5, Annex A, Equation A.9

Step	Calculation	Reference
$X_{[norm]}$, $Y_{[norm]}$, $Z_{[norm]}$	$X_{[norm]} = X / L_W$ $Y_{[norm]} = Y / L_W = L \cdot (L_{ref}/L_W) = Y_D$ $Z_{[norm]} = Z / L_W$	
$R_D\ G_D\ B_D$	$R_D = R_X \cdot X_{[norm]} + R_Y \cdot Y_{[norm]} + R_Z \cdot Z_{[norm]}$ $G_D = G_X \cdot X_{[norm]} + G_Y \cdot Y_{[norm]} + G_Z \cdot Z_{[norm]}$ $B_D = B_X \cdot X_{[norm]} + B_Y \cdot Y_{[norm]} + B_Z \cdot Z_{[norm]}$	Inverse NPM_{2020} (16-digit version)
range [0:1]	Cut Rd Gd Bd below 0 and above 1	
R' G' B'	$E' = OETF[E] = EOTF^{-1}[OOTF[E]]$ $= EOTF^{-1}[F_D] = \left(\frac{c1 + c2 * Y^{m1}}{1 + c3 * Y^{m1}}\right)^{m2}$	ITU-R BT.2100-2, table 4, Reference PQ OETF Note: fill in R_d, G_D, B_D in Y
range [0:1]	Cut R' G' B' below 0 and above 1	ITU-R BT.2100-2, table 4, Reference PQ OETF
$Y'\ C'_B\ C'_R$	$Y' = 0.2627 \cdot R' + 0.6780 \cdot G' + 0.0593 \cdot B'$ $C'_B = \frac{B' - Y'}{1.8814}$ $C'_R = \frac{R' - Y'}{1.4746}$	ITU-R BT.2100, table 6 (use four-digit version, not NPM_{2020})
CV_{narrow} (Code Value	$cv_{Y'} = Round(876 * Y' + 64)$ $cv_{C'B} = Round(896 * C'_B + 512)$ $cv_{C'R} = Round(896 * C'_R + 512)$	ITU-R BT.2100-2, table 9 Narrow-range (CV_{narrow})

BT.2100 PQ1000nit (narrow range)

Step	Calculation	Reference
PQ @1000nits	$L_{ref} = 1000\ cd/m^2$; $L_W = 10.000\ cd/m^2$;	$L_{ref} = 1000\ cd/m^2$ for being visually comparable to HLG with the same max. luminance of $1000\ cd/m^2$ (used for the new EBU-colours EBU-16 to EBU-25)
u' v' L	given values	as defined in EBU Tech 3325
xyz	$x = 9u' / (6u' - 16v' + 12)$ $y = 4v' / (6u' - 16v' + 12)$ $z = 1 - x - y$	ISO 11664-5, Annex A, Equation A.6 ISO 11664-5, Annex A, Equation A.7 ISO 11664-3, Equation 9

XYZ	$X = x \cdot (Y/y)$ $Y = L \cdot L_{ref} = Y_{exp}$ $Z = (1\text{-}x\text{-}y) \cdot (Y/y)$	ISO 11664-5, Annex A, Equation A.8 ISO 11664-5, Annex A, Equation A.9
$X_{[norm]}$, $Y_{[norm]}$, $Z_{[norm]}$	$X_{[norm]} = X / L_W$ $Y_{[norm]} = Y / L_W = L \cdot (L_{ref}/L_W) = Y_D$ $Z_{[norm]} = Z / L_W$	
$R_D\ G_D\ B_D$	$R_D = R_X \cdot X_{[norm]} + R_Y \cdot Y_{[norm]} + R_Z \cdot Z_{[norm]}$ $G_D = G_X \cdot X_{[norm]} + G_Y \cdot Y_{[norm]} + G_Z \cdot Z_{[norm]}$ $B_D = B_X \cdot X_{[norm]} + B_Y \cdot Y_{[norm]} + B_Z \cdot Z_{[norm]}$	Inverse NPM_{2020} (16-digit version)
range [0:1]	Cut Rd Gd Bd below 0 and above 1	
R' G' B'	$E' = OETF[E] = EOTF^{-1}[OOTF[E]]$ $= EOTF^{-1}[F_D] = \left(\frac{c1 + c2 * Y^{m1}}{1 + c3 * Y^{m1}}\right)^{m2}$	ITU-R BT.2100-2, table 4, Reference PQ OETF Note: fill in R_d, G_D, B_D in Y
range [0:1]	Cut R' G' B' below 0 and above 1	ITU-R BT.2100-2, table 4, Reference PQ OETF
$Y'\ C'_B\ C'_R$	$Y' = 0.2627 \cdot R' + 0.6780 \cdot G' + 0.0593 \cdot B'$ $C'_B = \frac{B'-Y'}{1.8814}$ $C'_R = \frac{R'-Y'}{1.4746}$	ITU-R BT.2100, table 6 (use four-digit version, not NPM_{2020})
CV_{narrow} (Code Value for 10 bit)	$CV_{Y'} = Round\ (876 * Y' + 64)$ $CV_{C'B} = Round\ (896 * C'_B + 512)$ $CV_{C'R} = Round\ (896 * C'_R + 512)$	ITU-R BT.2100-2, table 9 Narrow-range (CV_{narrow})

Annex 4: Matrix to convert between BT.709 and BT.2020

The exact matrix with high precision (all 16 digits) shall be used to get exact values or when calculating the inverse matrix. If you use the matrix with values rounded to four decimals as it is written down in some specifications, you will get an inverse matrix that is not precise enough for further calculations.

There are two ways to get the exact values:

1. Matrix calculation that follows SMPTE RP 177 [21] (there described for ITU-R BT.709-Matrix)
2. Use of the formula given in ITU-R BT.2390-7, chapter 11, equations 6 to 14

In Detail:

Calculation according to SMPTE RP 177

Mathematics for BT.2020 (for BT.709 see SMPTE RP 177)[10]

Given:

- Chromaticity's for D65:
  $x_W = 0.3127$
  $y_W = 0.3290$
  $z_W = 1 - (x_W + y_W) = 0.3583$

  - A set of reference primaries:
    $x_R = 0.708$; $y_R = 0.292$; $z_R = 1 - (x_R + y_R) = 0$
    $x_G = 0.170$; $y_G = 0.797$; $z_G = 1 - (x_G + y_G) = 0.033$
    $x_B = 0.131$; $y_B = 0.046$; $z_B = 1 - (x_B + y_B) = 0.823$

Calculate primary-matrix and white-vector:

$$P = \begin{bmatrix} x_R & x_G & x_B \\ y_R & y_G & y_B \\ z_R & z_G & z_B \end{bmatrix} = \begin{bmatrix} 0.708 & 0.170 & 0.131 \\ 0.292 & 0.797 & 0.046 \\ 0 & 0.033 & 0.823 \end{bmatrix}; \; W = \begin{bmatrix} x_W/y_W \\ 1 \\ z_W/y_W \end{bmatrix} = \begin{bmatrix} 0.950455927051672 \\ 1 \\ 1.08905775075988 \end{bmatrix}$$

Compute the coefficients C_i:

$$\begin{bmatrix} C_R \\ C_G \\ C_B \end{bmatrix} = P^{-1} \cdot W = \begin{bmatrix} 0.899658260312558 \\ 0.850687668154167 \\ 1.28916774934483 \end{bmatrix}$$

Build diagonal-matrix from the coefficients C_i:

$$C = \begin{bmatrix} C_R & 0 & 0 \\ 0 & C_G & 0 \\ 0 & 0 & C_B \end{bmatrix} = \begin{bmatrix} 0.899658260312558 & 0 & 0 \\ 0 & 0.850687668154167 & 0 \\ 0 & 0 & 1.28916774934483 \end{bmatrix}$$

[10] ITU-R BT.709 [10] specifies primaries for a single worldwide HDTV system, whilst. ITU-R BT.2020 [22] specifies primaries for a single worldwide UHDTV system. Neither specifies any tolerances.

Compute the final normalized primary matrix NPM:

$$NPM = \begin{bmatrix} X_R & X_G & X_B \\ Y_R & Y_G & Y_B \\ Z_R & Z_G & Z_B \end{bmatrix} = P \cdot C = \begin{bmatrix} x_R & x_G & x_B \\ y_R & y_G & y_B \\ z_R & z_G & z_B \end{bmatrix} \cdot \begin{bmatrix} C_R & 0 & 0 \\ 0 & C_G & 0 \\ 0 & 0 & C_B \end{bmatrix}$$

NPM relates television linear RGB signals to CIE XYZ tristimulus values:

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} X_R & X_G & X_B \\ Y_R & Y_G & Y_B \\ Z_R & Z_G & Z_B \end{bmatrix} \cdot \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

$$= \begin{bmatrix} 0.636958048301291 & 0.1446169035862080 & 0.168880975164172 \\ 0.262700212011267 & 0.6779980715188710 & 0.059301716469862 \\ 0.000000000000000 & 0.0280726930490874 & 1.060985057710790 \end{bmatrix} \cdot \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

Calculation according to BT.2390-7, chapter 11

Then the matrix elements of NPM are derived as follows:

$$X_R = \frac{((y_G*z_B - y_B*z_G)*x_W + (x_B*z_G - x_G*z_B)*y_W + (x_G*y_B - x_B*y_G)*z_W)*x_R}{(x_R*(y_G*z_B - y_B*z_G) - x_G*(y_R*z_B - y_B*z_R) + x_B*(y_R*z_G - y_G*z_R))*y_W} \quad (6)$$

$$X_G = \frac{((y_B*z_R - y_R*z_B)*x_W + (x_R*z_B - x_B*z_R)*y_W + (x_B*y_R - x_R*y_B)*z_W)*x_G}{(x_R*(y_G*z_B - y_B*z_G) - x_G*(y_R*z_B - y_B*z_R) + x_B*(y_R*z_G - y_G*z_R))*y_W} \quad (7)$$

$$X_B = \frac{((y_R*z_G - y_G*z_R)*x_W + (x_G*z_R - x_R*z_G)*y_W + (x_R*y_G - x_G*y_R)*z_W)*x_B}{(x_R*(y_G*z_B - y_B*z_G) - x_G*(y_R*z_B - y_B*z_R) + x_B*(y_R*z_G - y_G*z_R))*y_W} \quad (8)$$

$$Y_R = \frac{((y_G*z_B - y_B*z_G)*x_W + (x_B*z_G - x_G*z_B)*y_W + (x_G*y_B - x_B*y_G)*z_W)*y_R}{(x_R*(y_G*z_B - y_B*z_G) - x_G*(y_R*z_B - y_B*z_R) + x_B*(y_R*z_G - y_G*z_R))*y_W} \quad (9)$$

$$Y_G = \frac{((y_B*z_R - y_R*z_B)*x_W + (x_R*z_B - x_B*z_R)*y_W + (x_B*y_R - x_R*y_B)*z_W)*y_G}{(x_R*(y_G*z_B - y_B*z_G) - x_G*(y_R*z_B - y_B*z_R) + x_B*(y_R*z_G - y_G*z_R))*y_W} \quad (10)$$

$$Y_B = \frac{((y_R*z_G - y_G*z_R)*x_W + (x_G*z_R - x_R*z_G)*y_W + (x_R*y_G - x_G*y_R)*z_W)*y_B}{(x_R*(y_G*z_B - y_B*z_G) - x_G*(y_R*z_B - y_B*z_R) + x_B*(y_R*z_G - y_G*z_R))*y_W} \quad (11)$$

$$Z_R = \frac{((y_G*z_B - y_B*z_G)*x_W + (x_B*z_G - x_G*z_B)*y_W + (x_G*y_B - x_B*y_G)*z_W)*z_R}{(x_R*(y_G*z_B - y_B*z_G) - x_G*(y_R*z_B - y_B*z_R) + x_B*(y_R*z_G - y_G*z_R))*y_W} \quad (12)$$

$$Z_G = \frac{((y_B*z_R - y_R*z_B)*x_W + (x_R*z_B - x_B*z_R)*y_W + (x_B*y_R - x_R*y_B)*z_W)*z_G}{(x_R*(y_G*z_B - y_B*z_G) - x_G*(y_R*z_B - y_B*z_R) + x_B*(y_R*z_G - y_G*z_R))*y_W} \quad (13)$$

$$Z_B = \frac{((y_R*z_G - y_G*z_R)*x_W + (x_G*z_R - x_R*z_G)*y_W + (x_R*y_G - x_G*y_R)*z_W)*z_B}{(x_R*(y_G*z_B - y_B*z_G) - x_G*(y_R*z_B - y_B*z_R) + x_B*(y_R*z_G - y_G*z_R))*y_W} \quad (14)$$

Matrix and Inverse Matrix (Informative)

NPM_{709}

709-Matrix

X_R =	0.4123907992659590	X_G =	0.3575843393838780	X_B =	0.1804807884018340
Y_R =	0.2126390058715100	Y_G =	0.7151686787677560	Y_B =	0.0721923153607337
Z_R =	0.0193308187155919	Z_G =	0.1191947797946260	Z_B =	0.9505321522496610

Inverse NPM_{709} (NPM^{-1})

Inverse 709-Matrix

R_X =	3.2409699419045200	R_Y =	-1.5373831775700900	R_Z =	-0.4986107602930030
G_X =	-0.9692436362808800	G_Y =	1.8759675015077200	G_Z =	0.0415550574071756
B_X =	0.0556300796969936	B_Y =	-0.2039769588889770	B_Z =	1.0569715142428800

NPM_{2020}

2020-Matrix

X_R =	0.6369580483012910	X_G =	0.1446169035862080	X_B =	0.1688809751641720
Y_R =	0.2627002120112670	Y_G =	0.6779980715188710	Y_B =	0.0593017164698620
Z_R =	0.0000000000000000	Z_G =	0.0280726930490874	Z_B =	1.0609850577107900

Inverse NPM_{2020} (NPM^{-1})

Inverse 2020-Matrix

R_X =	1.7166511879712700	R_Y =	-0.3556707837763930	R_Z =	-0.2533662813736600
G_X =	-0.6666843518324890	G_Y =	1.6164812366349400	G_Z =	0.0157685458139111
B_X =	0.0176398574453109	B_Y =	-0.0427706132578085	B_Z =	0.9421031212354740

Annex 5: Optional HDR test colours

More possible HDR test colours derived from a real production by the RAI in 2020.

These test colours are more "extreme" than some of the other HDR colours described in this document. The use of these test colours is optional.

		10-bit code values at monitor input			Expected monitor output			
HDR-colours @ HLG (Lref = 1000 cd/m²)								
Sample	**Description**	**D'_Y**	**D'_{CB}**	**D'_{CR}**	**Y_{exp} [cd/m²] (= $L \cdot L_{ref}$)**	**L [0:1]**	**u'**	**v'**
	White point	940	512	512	1000	1	0.1978	0.4683
RAI 1	Yellow Front Face	410	349	503	31	0.031	0.1835	0.5668
RAI 2	Green leaves 1	482	339	448	50	0.050	0.1387	0.5688
RAI 3	Green leaves 2	695	254	473	206	0.206	0.1468	0.5693
RAI 4	Yellow Venice Dark	510	297	577	59	0.059	0.2629	0.5563
RAI 5	Yellow Venice High	681	234	568	183	0.183	0.2528	0.5568
RAI 6	Skirt green WS	378	488	335	30	0.030	0.0744	0.5195
RAI 7	Skirt Azure WS	233	630	419	7	0.007	0.1200	0.3120
RAI 8	Florence Column Orange	559	261	663	108	0.108	0.3794	0.5410
RAI 9	Azure Girl WS	569	606	392	89	0.089	0.1345	0.3905
RAI 10	Blue Score Table	631	680	368	162	0.162	0.1401	0.2937
RAI 11	RAI Green Wall	404	524	338	34	0.034	0.0852	0.4858
RAI 12	Red Promo Venice	176	500	684	7	0.007	0.5324	0.4956
RAI 13	Green leaves3	211	436	455	5	0.005	0.0798	0.5832
RAI 14	Dark Skin	439	614	718	65	0.065	0.3805	0.4103