DRAFT High Dynamic Range D-Cinema Addendum

DRAFT Version 0.96

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Digital Cinema Initiatives, LLC, Member Representatives Committee

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Introduction

With the publication by Digital Cinema Initiatives, LLC, (DCI) of version 1.0 of the Digital Cinema System Specification in July 2005, DCI recognized that digital cinema had the potential to significantly improve the movie-going experience for the public. In the over fifteen years since, technological developments and innovation have realized that potential in many areas of picture and sound reproduction. Now, further advances in High Dynamic Range (HDR) capabilities in both reflective projectors and emissive displays offer new opportunities to enhance the theatrical motion picture experience.

DCI believes that these new HDR opportunities require a rational, empirical basis for setting image parameters. To this end, DCI has conducted numerous picture experiments and tests, employing both lay and expert viewers. The requirements in this addendum are the considered results of these investigations, applicable to both reflective and emissive image devices. The DCI member companies believe that their utilization will provide real and achievable benefits to theater audiences, theater owners, filmmakers and distributors.

The proper presentation of a High Dynamic Range Digital Cinema Distribution Master (HDR-DCDM) requires the definition of an HDR Reference Display and controlled environment. This specification defines the HDR Reference Display and specifies the tolerances around the critical image parameters for Review Rooms and Exhibition Theaters so that consistent and repeatable color quality can be achieved.

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1 Scope

This specification defines the HDR Reference Display and its controlled environment, along with the acceptable tolerances around critical image parameters for Review Room and Exhibition Theater applications. The HDR Reference Display may be an HDR projection system, or a Cinema Direct View Display as constrained in DCI's *Direct View Display D-Cinema Addendum*.

The goal is to provide a means for achieving consistent and repeatable color image quality. The HDR Reference Display is a practical device. The nominal parameters are based on industry experience and have been demonstrated by commercially available HDR Displays in controlled environments. Two levels of tolerances are specified, a tighter tolerance for Review Rooms[1] where critical color judgments are made, and a wider tolerance for satisfactory reproduction in Exhibition Theaters used for general public exhibition.

This document shall be integrated into DCI's Digital Cinema System Specification.

[1] The use of the term "Review Room" includes the mastering environment where creative color decisions are made on a displayed image.

2 Normative References

The following standards contain provisions which, through reference in this text, constitute provisions of this specification. At the time of publication, the editions indicated were valid. This specification is subject to revision, and parties to agreements based on this specification are encouraged to investigate the possibility of applying the most recent edition of the documents indicated below.

DCI Direct View Display D-Cinema Addendum

ISO 11664-1, Colorimetry -- Part 1: CIE standard colorimetric observers

ISO 11664-3, Colorimetry -- Part 3: CIE tristimulus values

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

ISO/CIE 11664-6, Colorimetry -- Part 6: CIEDE2000 Colour-difference formula

SMPTE ST 377:2004, Material Exchange Format (MXF) — File Format Specification

SMPTE RP 431-2, Reference Projector and Environment for D-Cinema Quality

SMPTE ST 428-1, D-Cinema Distribution Master (DCDM) — Image Characteristics

SMPTE ST 429-16, Additional Composition Metadata and Guidelines

SMPTE ST 431-1, Screen Luminance Level, Chromaticity and Uniformity for D-Cinema Quality

SMPTE ST 2084, High Dynamic Range Electro-Optical Transfer Function of Mastering Reference Displays

3 Terms and Definitions

For the purposes of this document, the following terms and definitions apply.

3.1 Edit Unit

The smallest unit of D-Cinema content that can be successfully edited while maintaining the integrity of the content. *The edit unit value must be an integer multiple of the duration of a single D-Cinema frame.* In most cases, the edit unit value is the same as frame duration, but in certain applications, the value can be >1 (for example, Stereoscopic D-Cinema requires an edit unit value twice that of the frame duration).

3.2 Minimum Active Black Level

The Minimum Active Black Level of a HDR Reference Display is the lowest luminance level above code value 0 reproduced within the specified uniformity tolerance.

3.3 Double Prime Notation

The double prime notation (e.g., X'') is used to indicate a value encoded using the SMPTE ST 2084 EOTF.

3.4 HDR Digital Cinema Distribution Master (HDR-DCDM)

The HDR Digital Cinema Distribution Master (HDR-DCDM) is a DCDM that contains images and subtitles that are graded to be played on an HDR playback system, adhering to an Electro-Optical Transfer Function (EOTF) complying with SMPTE ST 2084.

3.5 HDR Digital Cinema Package (HDR-DCP)

The HDR Digital Cinema Package (HDR-DCP) is a DCP that is made from the HDR-DCDM. When unpackaged, decrypted and decoded, the image is visually indistinguishable from the original HDR-DCDM image.

4 Input Requirements

The HDR Reference Display shall support the HDR-DCDM, with full-range 12 bit image data formatted for SMTPE ST-2084 EOTF with CIE XYZ colorimetry at 2048x1080 or 4096x2160 image structures and frame rates as described in Table 1.

Support for Stereoscopic 3D is optional on HDR Reference Displays. If the HDR Reference Display supports Stereoscopic 3D, the display shall support the image structures and frame rates as described in Table 1 under "2K 3D". "Required" in this category applies only to displays in which 3D is implemented.

Table 1 Edit units per second requirements for HDR Reference Display

Edit Unit/Sec	2K 2D	2K 3D	4K 2D
24	Required	Required	Required
48	Required	Required	Required
60	Required	Required	Required
96	Required		
120	Required		

4.1 Signaling HDR in DCP Packaging

HDR content is identified by the presence of an HDR flag in both MXF and CPL metadata, which indicates that the EOTF is SMPTE ST 2084.

For MXF picture track files that carry HDR essence, this fact shall be signaled using the "Transfer Characteristic" property of the MXF "Generic Picture Essence Descriptor" to indicate the EOTF is SMPTE ST 2084. The UL value to be used shall be 06.0E.2B.34.04.01.01.0D.04.01.01.01.01.0A.00.00.

Composition Playlists containing picture track files that carry HDR essence shall signal this fact using SMTPE ST 429-16 Metadata as follows:

Scope:	http://www.dcimovies.com/schemas/2018/HDR-Metadata
Name:	Image Encoding Parameters
Property Name:	EOTF
Property Value:	ST 2084

Below is an example excerpt from such a Composition:

```
<ExtensionMetadata scope="http://www.dcimovies.com/schemas/2018/HDR-Metadata">
 <Name>Image Encoding Parameters</Name>
 <PropertyList>
  <Property>
   <Name>EOTF</Name>
   <Value>ST 2084</Value>
  </Property>
 </PropertyList>
</ExtensionMetadata>
```

4.2 Device Behavior

Devices shall display content in HDR mode when presented with a Composition Playlist and MXF Transfer Characteristic containing these signals.

5 Standard Dynamic Range (SDR) Mode

A HDR system in SDR Mode shall display SDR content in a manner that emulates the SDR display on which the content was mastered (SDR Mode). A HDR system in SDR Mode shall not reproduce black level values lower than 0.01 cd/m^2. In SDR Mode, the luminance tracking shall conform to SMPTE RP 431-2, with the exception that screen black level shall be displayed at luminance levels above 0.01 cd/m^2.

6 Initial Conditions

The display shall be turned on and allowed to thermally stabilize for 20 to 30 minutes prior to all measurements. The room lights shall be turned off, with the exception of the minimal lighting provided for working or safety reasons.

The display shall be calibrated to the target image parameters before final measurements are made.

7 Environment

7.1 Ambient Luminance

An HDR Reference Display can be either a projector or a Cinema Direct View Display. Stray light reflected from the screen or display should be minimized. Black, non-reflective finishes on all surfaces, along with recessed lighting, should be used.

With the device turned off, measure the luminance of the center of the screen. For both Review Rooms and Exhibition Theaters, the ambient light level measured in the center of the screen should be less than or equal to 0.005 cd/m^2. Safety regulations and the placement of exit lights or access lights may result in a higher ambient light level, but it should be noted that this will reduce the contrast of the resulting image.

7.2 Reference Viewing Position for Color Grading

The reference viewing position for color grading shall be at a viewing distance of 1.5 to 3.5 screen heights (for constant height presentation), or if constant width is used for both 2.39:1 and 1.85:1 aspect ratios, then this viewing distance refers to the height of the 1.85:1 picture. Lighting on work surfaces or consoles should be masked and filtered to eliminate any spill onto the display.

8 HDR Mode Image Parameters

All image parameters shall be measured as light from the screen or display, with the measurements made from the reference viewing position in the Review Room, or from the center of the normal seating area in an Exhibition Theater.

8.1 Luminance Uniformity

The variance in measured luminance across the display shall not exceed the specified tolerances in Table A.1.

8.2 Calibration White Point and Luminance

When the HDR Reference Display is sent a full frame image with the code values 2060 X′′, 2081 Y′′, 2116 Z′′, the chromaticity coordinates of the displayed image shall be x = 0.3127, y = 0.3291. These code values shall produce a displayed luminance of 100.1 cd/m² within the specified tolerances in Table A.1.

When the HDR Reference Display is sent a full frame image with code values 2524 X′′, 2546 Y′′, 2583 Z′′, the chromaticity coordinates of the displayed image shall be x = 0.3128, y = 0.3290. These code values shall produce a displayed luminance of 299.6 cd/m² within the specified tolerances in Table A.1.

Behavior of code values representing output luminance exceeding 299.6 cd/m² is undefined.

Other “creative” white points are possible and can be accommodated, albeit with some marginal differences in peak luminance. Refer to Table A.4 for examples of alternative creative white points.

8.3 Minimum Active Black Level

Minimum Active Black Level shall be 0.005 cd/m², and shall not exceed the specified tolerances in Table A.1. Behavior of code values representing output luminance below 0.005 cd/m² but greater than zero is undefined.

When the HDR Reference Display is sent a full frame images with the code values 60 X′′, 62 Y′′, 65 Z′′, the chromaticity coordinates of the displayed image shall be x = 0.3095, y = 0.3296. These code values shall produce a displayed luminance of 0.005 cd/m² within the specified tolerances in Table A.1.

Minimum active black level shall be measured without the contribution of ambient light.

8.4 White Chromaticity Uniformity

The variance in displayed chromaticity across the display shall not exceed the specified tolerances in Table A.1.

8.5 Electro-Optical Transfer Function

8.5.1 Encoding Function

The encoding transfer function shall be defined in terms of output-referred CIE XYZ tristimulus values produced by the HDR Reference Display unit. The HDR transfer functions are specified using 12bit CIE XYZ Encoding Primaries and ST 2084 EOTF, as shown below:

$$CV_{X''} = floor\left(\frac{1}{2} + \mathrm{k}_1 \cdot \left(\frac{c_1 + c_2\left(\frac{X}{k_0}\right)^{m_1}}{1 + c_3\left(\frac{X}{k_0}\right)^{m_1}}\right)^{m_2}\right)$$

$$CV_{Y''} = floor\left(\frac{1}{2} + \mathrm{k}_1 \cdot \left(\frac{c_1 + c_2\left(\frac{Y}{k_0}\right)^{m_1}}{1 + c_3\left(\frac{Y}{k_0}\right)^{m_1}}\right)^{m_2}\right)$$

$$CV_{Z''} = floor\left(\frac{1}{2} + \mathrm{k}_1 \cdot \left(\frac{c_1 + c_2\left(\frac{Z}{k_0}\right)^{m_1}}{1 + c_3\left(\frac{Z}{k_0}\right)^{m_1}}\right)^{m_2}\right)$$

where:

$$\mathrm{k}_0 = 10{,}000 \qquad \mathrm{m}_1 = \frac{2610}{4096} \cdot \frac{1}{4} \qquad \mathrm{c}_2 = \frac{2413}{4096} \cdot 32$$

$$\mathrm{k}_1 = 4095 \qquad \mathrm{m}_2 = \frac{2523}{4096} \cdot 128 \qquad \mathrm{c}_3 = \frac{2392}{4096} \cdot 32$$

$$\mathrm{c}_1 = \mathrm{c}_3 - \mathrm{c}_2 + 1$$

The unary function $floor()$ yields the largest integer not greater than its argument.

Note: If the data is transported over some interfaces (like Serial Digital Interface), code values 0-15 and 4080-4095 are reserved (illegal) code values and these code values will be clipped.

8.5.2 Decoding Function

The following equations can be used to compute X, Y and Z from a set of code values:

$$X = k_0 \left(\frac{max\left[\left(\frac{CV_{X''}}{k_1} \right)^{\frac{1}{m_2}} - c_1, 0 \right]}{c_2 - c_3 \left(\frac{CV_{X''}}{k_1} \right)^{\frac{1}{m_2}}} \right)^{\frac{1}{m_1}}$$

$$Y = k_0 \left(\frac{max\left[\left(\frac{CV_{Y''}}{k_1} \right)^{\frac{1}{m_2}} - c_1, 0 \right]}{c_2 - c_3 \left(\frac{CV_{Y''}}{k_1} \right)^{\frac{1}{m_2}}} \right)^{\frac{1}{m_1}}$$

$$Z = k_0 \left(\frac{max\left[\left(\frac{CV_{Z''}}{k_1} \right)^{\frac{1}{m_2}} - c_1, 0 \right]}{c_2 - c_3 \left(\frac{CV_{Z''}}{k_1} \right)^{\frac{1}{m_2}}} \right)^{\frac{1}{m_1}}$$

8.5.3 Tracking Performance

EOTF tracking performance shall be measured at the code-values described in Table A.2 and Table A.3 with the tolerances identified in Table A.1.

8.6 Color Volume

In an additive display, the color volume is a cuboid with vertices determined by the XYZ coordinates of the three color primaries, the white point, and the black point. The color primaries and white point in Table A.1 define the minimum color volume for an HDR Reference Display.

8.7 Color Accuracy

Within the minimum color volume, all colors shall be accurately reproduced. Table A.1 defines tolerances that can be used to verify the color primaries of the minimum color volume. Table A.4 provides exact chromaticity and luminance values for a set of test code values that fall within these tolerances.

ANNEX A: Normative HDR Mode Tables

The HDR Reference Display image parameters and tolerances for the displayed image in Review Rooms and Exhibition Theaters, as measured from the display and including the room ambient light, are summarized in Table A.1. Where the nominal parameters are specified as minimums, it is understood that these parameters shall not be constrained from future improvements as the technology improves.

Tolerances for Electro-Optical Transfer Function distortion (measured as a percentage error) are calculated as follows:

Percentage error = 100*((measured luminance – target luminance) / target luminance)

where target luminance is derived by decoding the input code value using the decoding equation in Section 8.5.2, using the ranges and tolerances specified in Table A.1.

Table A.1 Image Parameters and Tolerances for HDR Reference Display

Section	Parameter	Nominal	HDR Reference Projector		HDR Direct View Display	
			Review Room Tolerance	Theater Tolerance	Review Room Tolerance	Theater Tolerance
9.1, 9.2	Luminance, center, Peak Luminance, White-1 D65	300.0 cd/m^2 (87.6 fL)	± 6.0 cd/m^2	± 6.0 cd/m^2	± 6.0 cd/m^2	± 6.0 cd/m^2
	Luminance, Screen Average, White-1 D65	300.0 cd/m^2 (87.6 fL)	N/A	N/A	± 6.0 cd/m^2	± 6.0 cd/m^2
	Luminance, sides	300.0 cd/m^2 (87.6 fL)	85% to 100% of center	75% to 100% of center	± 6.0 cd/m^2	± 6.0 cd/m^2
	Luminance, corners	300.0 cd/m^2 (87.6 fL)	85% to 100% of center	Not Specified	± 6.0 cd/m^2	± 6.0 cd/m^2
9.3	Minimum Active Black Level	0.005 cd/m^2 (0.0003 fL)	± 0.0002 cd/m^2	± 0.0002 cd/m^2	± 0.0002 cd/m^2	± 0.0002 cd/m^2
9.4	White chromaticity, center, Peak Luminance, White-1 D65	x = 0.3127 y = 0.3290	± 0.002 x ± 0.002 y	± 0.006 x ± 0.006 y	± 0.002 x ± 0.002 y	± 0.006 x ± 0.006 y
	White chromaticity uniformity, corners (tolerance from center)	± 0.000 x ± 0.000 y	± 0.008 x ± 0.008 y	± 0.015 x ± 0.015 y	± 0.008 x ± 0.008 y	± 0.015 x ± 0.015 y
9.5	Electro-Optical Transfer Function	Per SMPTE ST 2084	< 0.02 cd/m^2 ± 5%; 0.02 - 300 cd/m^2 ± 2%	< 0.02 cd/m^2 ± 5%; 0.02 - 300 cd/m^2 ± 2%	< 0.02 cd/m^2 ± 5%; 0.02 - 300 cd/m^2 ± 2%	< 0.02 cd/m^2 ± 5%; 0.02 - 300 cd/m^2 ± 2%
9.6	Color Volume	The volume in XYZ space defined by the black point and the following points expressed in (Y,x,y), representing a 300 nits P3D65 color volume: Red (68.69, 0.6800, 0.3200), Green (207.52, 0.2650, 0.6900), Blue (23.79, 0.1500, 0.0600), Peak White (300, 0.3127, 0.3290)	N/A	N/A	N/A	N/A
9.7	Color Accuracy	The following points are expressed in (x,y): Red (0.6800, 0.3200), Green (0.2650, 0.6900), Blue (0.1500, 0.0600)	Red (0.6800 ± .01, 0.3200 ± .01), Green (0.2650 ± .02, 0.6900 ± .02), Blue (0.1500 + 0.01/- 0.03, 0.0600 + 0.02/- 0.04)	Red (0.6800 ± .01, 0.3200 ± .01), Green (0.2650 ± .02, 0.6900 ± .02), Blue (0.1500 + 0.01/- 0.03, 0.0600 + 0.02/- 0.04)	Red (0.6800 ± .01, 0.3200 ± .01), Green (0.2650 ± .02, 0.6900 ± .02), Blue (0.1500 + 0.01/- 0.03, 0.0600 + 0.02/- 0.04)	Red (0.6800 ± .01, 0.3200 ± .01), Green (0.2650 ± .02, 0.6900 ± .02), Blue (0.1500 + 0.01/- 0.03, 0.0600 + 0.02/- 0.04)

Table A.2 Black-to-white gray step-scale test pattern code values, luminance values, and chromaticity coordinates
All measurements are made in the center of the Screen.

	Input Code Values			Output Chromaticity Coordinates		Output Luminance
Step Number	**X′′**	**Y′′**	**Z′′**	**x**	**y**	**Y,** cd/m²
1	472	481	496	0.3126	0.3292	0.50
2	603	614	632	0.3122	0.3292	1.00
3	758	771	792	0.3121	0.3293	2.00
4	1000	1015	1040	0.3124	0.3291	5.00
5	1211	1227	1255	0.3128	0.3288	10.00
6	1444	1462	1492	0.3128	0.3291	20.00
7	1783	1803	1836	0.3126	0.3292	50.01
8	2060	2081	2116	0.3127	0.3291	100.10
9	2350	2372	2408	0.3127	0.3292	200.21
10	2524	2546	2583	0.3128	0.3290	299.64

Table A.3 Black-to-dark gray step-scale test pattern code values, luminance values, and chromaticity coordinates
All measurements are made in the center of the Screen.

	Input Code Values			Output Chromaticity Coordinates		Output Luminance
Step Number	**X′′**	**Y′′**	**Z′′**	**x**	**y**	**Y,** cd/m²
1	60	62	65	0.3095	0.3296	0.0050
2	74	76	79	0.3134	0.3302	0.0075
3	86	88	92	0.3133	0.3281	0.0100
4	105	108	112	0.3124	0.3309	0.0151
5	121	124	129	0.3129	0.3293	0.0202
6	157	161	167	0.3125	0.3300	0.0352
7	185	189	196	0.3138	0.3291	0.0501
8	221	226	234	0.3131	0.3296	0.0752
9	250	255	265	0.3129	0.3279	0.0998
10	332	339	351	0.3121	0.3289	0.1997

Table A.4 Color Accuracy color patch code values, luminance values, and chromaticity coordinates.
The accuracy with which these colors shall be displayed is shown in Table A.1

	Input Code Values			**Output Chromaticity Coordinates**		**Output Luminance**
Patch	**X′′**	**Y′′**	**Z′′**	**x**	**y**	**Y,** cd/m²
Red-1	2234	1925	68	0.6787	0.3202	68.13
Green-1	1988	2387	1327	0.2651	0.6899	207.35
Blue-1	1871	1525	2565	0.1501	0.0602	23.86
Cyan-1	2218	2434	2583	0.1998	0.3320	231.33
Magenta-1	2383	2049	2565	0.3362	0.1515	92.58
Yellow-1	2423	2510	1327	0.4380	0.5357	275.80
Red-2	2169	1899	1058	0.6401	0.3300	63.83
Green-2	2110	2402	1674	0.3001	0.6001	214.73
Blue-2	1834	1491	2524	0.1501	0.0602	21.70
Cyan-2	2280	2443	2576	0.2245	0.3288	236.21
Magenta-2	2322	2016	2533	0.3213	0.1541	85.39
Yellow-2	2432	2513	1731	0.4190	0.5054	277.72
White-1 D65	2524	2546	2583	0.3128	0.3290	299.64
White-2 D60	2509	2530	2534	0.3217	0.3376	288.81
White-3 D55	2493	2513	2478	0.3319	0.3476	277.72

ANNEX B: Subjective Parameters (Informative)

The following parameters are also important to picture quality, but because they are difficult to measure with today's readily available instrumentation, they are generally assessed subjectively.

Instrumentation designers are encouraged to design and manufacture equipment that can be used to translate subjective parameters into objective performance characterization.

B.1 Grayscale Tracking

Using the black-to-white gray step-scale test pattern, the entire step-scale appears neutral without any visible color non-uniformity. The black-to-white gray step-scale test pattern is centered on the display and occupies a rectangle sized 20% of the screen height by 80% of the screen width. The background is defined by code values [1000 1015 1040], which define a luminance of 5.0 cd/m^2 and chromaticity coordinates x = 0.3124 y = 0.3291. Each step is 8% of the screen width and is defined by the code values in Table A.2.

Using the black-to-dark gray step-scale test pattern, the entire step-scale appears neutral without any visible color non-uniformity. The black-to-dark gray step-scale test pattern is centered on the display and occupies a rectangle sized 20% of the screen height by 80% of the screen width. The background is defined by code values

[122 124 129], which define a luminance of 0.020 cd/m2 and chromaticity coordinates x = 0.3129 y = 0.3293. Each step is 8% of the screen width and is defined by the code values in Table A.3.

B.2 Contouring

Contouring is the appearance of steps or bands where only a continuous or smooth gradient is expected. Because contouring is a function of many variables, it is important to look at a series of test patterns with shallow gradations to simulate naturally occurring gradations in images.

Examples include horizons, particularly at sunset or sunrise, and the natural falloff around high intensity spotlights, particularly if diffused by atmosphere or lens filtration. These test pattern ramps have a step width of no less than 4 pixels with an increment of one code value per step and are placed on a background equal to the minimum value in the ramp, so that the eye is adapted for maximum sensitivity.

Since dynamic fades to black are widely used in real-world content, a dynamic test pattern that fades slowly to black is another useful approach.

Each image is viewed in the proper environment as defined in Section 6, and ought not to exhibit any contouring (step in luminance), or color deviation from the neutral gray.

ANNEX C: D65 Color Primaries, White Point and Color Conversions (Informative)

The color image encoding parameters for today's HDR Reference Displays and the corresponding color conversion steps to convert from P3D65 R'G'B' to X''Y''Z'' and from X''Y''Z'' to P3D65 RGB are shown here as an example for implementation[2].

C.1 Color Primaries

Table C.1 Chromaticity Coordinates of Primaries

Encoding Primaries
R (x, y) = (0.6800, 0.3200)
G (x, y) = (0.2650, 0.6900)
B (x, y) = (0.1500, 0.0600)

x, y refers to the chromaticity coordinates defined by the CIE.

C.2 White Reference

Table C.2 Chromaticity Coordinates of White Reference

White Reference
(x, y) = (0.3127,0.3290)

x, y refers to the chromaticity coordinates defined by the CIE.

[2] P3D65 is defined in SMPTE ST 2113.

C.3 Luminance

The Reference White Luminance is 300 cd/m^2.

C.4 Color Conversion R'G'B' to X''Y''Z''

Color conversion from R'G'B' to X''Y''Z'' typically involves the following five-step process:

1) To the R'G'B' code values, apply the inverse-quantization process to convert the image's integer code values to a non-linear R'G'B' signal in the range [0.0,1.0] from the code value's integer range, 12bit full-range code values range from [0,4095] and 16 bit full-range code values range from [0,65535].

2) To the non-linear R'G'B' signal, apply ST 2084 EOTF to convert non-linear R'G'B' signal to linear RGB signal.

3) To the linear RGB signal, apply the RGB to XYZ primary conversion matrix to convert linear RGB to linear XYZ.

4) To the linear XYZ signal, apply the ST 2084 Inverse-EOTF to convert from linear XYZ to non-linear X''Y''Z''.

5) To the non-linear X''Y''Z'' signal, apply the 12 bit full-range quantization process to convert non-linear X''Y''Z'' to 12 bit X''Y''Z'' code values.

The transfer function of the HDR Reference Display is explicitly specified by ST 2084. The actual coefficients of the color transform matrices depend on the color primaries of the Mastering HDR Reference Display (encoding side) and the Cinema HDR Display (decoding side), and their respective white points.

SMPTE ST 2084 is a defined standard, and 12-bit quantization is sufficient so a normalized PQ is not needed. Using a normalized PQ might impede the cross-utilization of assets in other formats.

The processing steps for converting 12 bit R'G'B' code values (which range from 0 to 4095) of the color-graded master to device-independent X''Y''Z'' are shown below.

This color space conversion can be implemented within the color corrector or applied in a separate batch process. The equations below combine step #1 (inverse quantization) and step #2 (ST 2084 EOTF):

$$R = k_0 \left(\frac{max\left[\left(\frac{CV_{R'}}{k_1}\right)^{\frac{1}{m_2}} - c_1, 0\right]}{c_2 - c_3\left(\frac{CV_{R'}}{k_1}\right)^{\frac{1}{m_2}}} \right)^{\frac{1}{m_1}}$$

$$G = k_0 \left(\frac{max\left[\left(\frac{CV_{G'}}{k_1}\right)^{\frac{1}{m_2}} - c_1, 0\right]}{c_2 - c_3\left(\frac{CV_{G'}}{k_1}\right)^{\frac{1}{m_2}}} \right)^{\frac{1}{m_1}}$$

$$B = k_0 \left(\frac{max\left[\left(\frac{CV_{B'}}{k_1}\right)^{\frac{1}{m_2}} - c_1, 0\right]}{c_2 - c_3\left(\frac{CV_{B'}}{k_1}\right)^{\frac{1}{m_2}}} \right)^{\frac{1}{m_1}}$$

where:

$$\mathrm{k_0} = 10{,}000 \qquad \mathrm{m_1} = \frac{2610}{4096} \cdot \frac{1}{4} \qquad \mathrm{c_2} = \frac{2413}{4096} \cdot 32$$

$$\mathrm{k_1} = 4095 \qquad \mathrm{m_2} = \frac{2523}{4096} \cdot 128 \qquad \mathrm{c_3} = \frac{2392}{4096} \cdot 32$$

$$\mathrm{c_1} = \mathrm{c_3} - \mathrm{c_2} + 1$$

The output (RGB) of this linearization is a floating point number that ranges from 0.0 to 10000.0. The 3x3 linear matrix is then applied to this signal, resulting in a linear XYZ signal with floating point values that range from 0.0 to 10000.0. To minimize quantization errors, this matrix should be implemented as a floating point calculation. The matrix is shown here to 14 significant digits.

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{pmatrix} 0.48657094864822 & 0.26566769316910 & 0.19821728523436 \\ 0.22897456406975 & 0.69173852183651 & 0.07928691409375 \\ 0 & 0.04511338185890 & 1.04394436890098 \end{pmatrix} * \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

Finally, the X’’Y’’Z’’ encoding transfer function is defined by the following expression which performs both step #4 (Inverse-EOTF) and step #5 (12bit Quantization). This equation does not compensate for the screen black level, so it represents an absolute encoding of the light levels independent of the screen black level.

$$CV_{X''} = floor\left(\frac{1}{2} + \mathrm{k_1} \cdot \left(\frac{c_1 + c_2\left(\frac{X}{k_0}\right)^{m_1}}{1 + c_3\left(\frac{X}{k_0}\right)^{m_1}} \right)^{m_2} \right)$$

$$CV_{Y''} = floor\left(\frac{1}{2} + \mathrm{k_1} \cdot \left(\frac{c_1 + c_2\left(\frac{Y}{k_0}\right)^{m_1}}{1 + c_3\left(\frac{Y}{k_0}\right)^{m_1}} \right)^{m_2} \right)$$

$$CV_{Z''} = floor\left(\frac{1}{2} + \mathrm{k}_1 \cdot \left(\frac{c_1 + c_2\left(\frac{Z}{k_0}\right)^{m_1}}{1 + c_3\left(\frac{Z}{k_0}\right)^{m_1}}\right)^{m_2}\right)$$

where:

$$\mathrm{k}_0 = 10{,}000 \qquad \mathrm{m}_1 = \frac{2610}{4096} \cdot \frac{1}{4} \qquad \mathrm{c}_2 = \frac{2413}{4096} \cdot 32$$

$$\mathrm{k}_1 = 4095 \qquad \mathrm{m}_2 = \frac{2523}{4096} \cdot 128 \qquad \mathrm{c}_3 = \frac{2392}{4096} \cdot 32$$

$$\mathrm{c}_1 = \mathrm{c}_3 - \mathrm{c}_2 + 1$$

The unary function $floor()$ yields the largest integer not greater than its argument.

C.5 Color Conversion X″Y″Z″ to P3D65 RGB

The X′′Y′′Z′′-to-P3D65 RGB processing steps for a Cinema HDR Display with the same color primaries as the HDR Reference Display are shown below and defined by the following steps:

1) Apply Inverse Quantization to the 12 bit X′′Y′′Z′′ code values, converting 12 bit X′′Y′′Z′′ code values to non-linear X′′Y′′Z′′ in the range [0.0,1.0]

2) Apply ST 2084 EOTF to non-linear X′′Y′′Z′′ values, converting non-linear X′′Y′′Z′′ to linear XYZ

3) Apply XYZ to RGB conversion to linear XYZ values

The equations below show step #1 (inverse quantization) and step #2 (ST 2084 EOTF) combined

$$X = k_0\left(\frac{max\left[\left(\frac{CV_{X''}}{k_1}\right)^{\frac{1}{m_2}} - c_1, 0\right]}{c_2 - c_3\left(\frac{CV_{X''}}{k_1}\right)^{\frac{1}{m_2}}}\right)^{\frac{1}{m_1}}$$

$$Y = k_0\left(\frac{max\left[\left(\frac{CV_{Y''}}{k_1}\right)^{\frac{1}{m_2}} - c_1, 0\right]}{c_2 - c_3\left(\frac{CV_{Y''}}{k_1}\right)^{\frac{1}{m_2}}}\right)^{\frac{1}{m_1}}$$

$$Z = k_0 \left(\frac{max\left[\left(\frac{CV_{Z''}}{k_1} \right)^{\frac{1}{m_2}} - c_1, 0 \right]}{c_2 - c_3 \left(\frac{CV_{Z''}}{k_1} \right)^{\frac{1}{m_2}}} \right)^{\frac{1}{m_1}}$$

where:

$$\mathrm{k_0} = 10{,}000 \qquad \mathrm{m_1} = \frac{2610}{4096} \cdot \frac{1}{4} \qquad \mathrm{c_2} = \frac{2413}{4096} \cdot 32$$

$$\mathrm{k_1} = 4095 \qquad \mathrm{m_2} = \frac{2523}{4096} \cdot 128 \qquad \mathrm{c_3} = \frac{2392}{4096} \cdot 32$$

$$\mathrm{c_1} = \mathrm{c_3} - \mathrm{c_2} + 1$$

Apply XYZ to P3D65 color encoding primaries transformation:

$$\begin{bmatrix} R \\ G \\ B \end{bmatrix} = \begin{pmatrix} 2.49349691194143 & -0.93138361791912 & -0.40271078445072 \\ -0.82948896956157 & 1.76266406031835 & 0.02362468584194 \\ 0.03584583024378 & -0.07617238926804 & 0.95688452400769 \end{pmatrix} * \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}$$

The resulting linear RGB light levels may end up being converted to other formats as the image data flows through the image/display processing operations involved in ultimately displaying the image to the viewer via the HDR display.

If other formats within the HDR display that may have a limited precision, it is important to preserve the visual fidelity/accuracy that is achievable with the 12 bit X′′Y′′Z′′ ST 2084 distribution format across the minimum gamut (luminance range and color volume) specified elsewhere in this document to ensure that additional fidelity isn’t loss.

ANNEX D: Bibliography (Informative)

SMPTE ST 372, Dual Link 1.5 Gb/s Digital Interface for 1920 × 1080 and 2048 × 1080 Picture Formats

SMPTE RP 177, Derivation of Basic Television Color Equations