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SMPTE STANDARD

High Dynamic Range Electro-Optical Transfer Function of Mastering Reference Displays

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Foreword

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SMPTE ST 2084 was prepared by Technology Committee 10E.

Intellectual Property

At the time of publication no notice had been received by SMPTE claiming patent rights essential to the implementation of this Engineering Document. However, attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. SMPTE shall not be held responsible for identifying any or all such patent rights.

Introduction

This section is entirely informative and does not form an integral part of this Engineering Document.

This standard defines an electro-optical transfer function (EOTF) with a high luminance range capability of 0 to 10,000 cd/m^2. Because this EOTF is referenced to absolute luminance, the display is assumed to be operating in a specified reference viewing environment, two examples of which are given in Annex B of this document.

The EOTF does not impart a preferred rendering appearance for any particular viewing environment. Image modifications needed for viewer contrast, colorfulness, highlight details, and visible detail in shadows at any particular output level must be chosen as part of the mastering process.

This EOTF is intended to enable the creation of video images with an increased luminance range; not for creation of video images with overall higher luminance levels. For consistency of presentation across devices with different output brightness, average picture levels in content would likely remain similar to current luminance levels; i.e. mid-range scene exposures would produce currently expected luminance levels appropriate to video or cinema. With this EOTF, the upper range of scene exposures would not need to be highly compressed as in traditional video and images with increased realism and sense of presence can be presented.

The reference EOTF is specified by an equation with four independent parameters. With a foundation based on human visual perception, this EOTF creates an efficient mapping from digital code values containing as few as 10 bits to a large, absolute luminance range of 0 to 10,000 cd/m^2. System implementations that utilize this EOTF will be able to represent a luminance level of 10,000 cd/m^2 at their native white point, but can not represent that luminance level at all other chromaticity points. An example of this would be an XYZ system implementation, which could represent 10,000 cd/m^2 at the equal energy white point E, but could only represent about 9187 cd/m^2 at D65.

The reference EOTF and its inverse represent an efficient encoding system for high luminance range data. Though an idealized display device could follow this EOTF exactly, in real world displays the EOTF can be thought of as a nominal target. Actual displays can vary from the absolute curve due to output limitations and effects of non-ideal viewing environments.

1 Scope

This standard specifies an EOTF characterizing high-dynamic-range reference displays used primarily for mastering non-broadcast content. This standard also specifies an Inverse-EOTF derived from the EOTF.

2 Conformance Notation

Normative text is text that describes elements of the design that are indispensable or contains the conformance language keywords: "shall", "should", or "may". Informative text is text that is potentially helpful to the user, but not indispensable, and can be removed, changed, or added editorially without affecting interoperability. Informative text does not contain any conformance keywords.

All text in this document is, by default, normative, except: the Introduction, any section explicitly labeled as "Informative" or individual paragraphs that start with "Note:"

The keywords "shall" and "shall not" indicate requirements strictly to be followed in order to conform to the document and from which no deviation is permitted.

The keywords, "should" and "should not" indicate that, among several possibilities, one is recommended as particularly suitable, without mentioning or excluding others; or that a certain course of action is preferred but not necessarily required; or that (in the negative form) a certain possibility or course of action is deprecated but not prohibited.

The keywords "may" and "need not" indicate courses of action permissible within the limits of the document.

The keyword "reserved" indicates a provision that is not defined at this time, shall not be used, and may be defined in the future. The keyword "forbidden" indicates "reserved" and in addition indicates that the provision will never be defined in the future.

A conformant implementation according to this document is one that includes all mandatory provisions ("shall") and, if implemented, all recommended provisions ("should") as described. A conformant implementation need not implement optional provisions ("may") and need not implement them as described.

Unless otherwise specified, the order of precedence of the types of normative information in this document shall be as follows: normative prose shall be the authoritative definition; tables shall be next; followed by formal languages; then figures; and then any other language forms.

3 Terms

The following terms are described only as used in this context of this document:

3.1
Color Value

A number corresponding to the amount of a specific color component (such as R, G, B, or Y) for an image element.

3.2
Digital Code Value

Digital representation of an image signal value. Usually representative of a nonlinear color value.

3.3
Electro-Optical Transfer Function (EOTF)

Relationship between the nonlinear color values provided to a display device and the linear color values produced by the device.

3.4
High Dynamic Range

A term used to describe an image or imaging device that spans or is capable of spanning a range of luminance levels greater than the range of luminance levels spanned by traditional imaging systems. This standard assumes a peak luminance level limited to 10,000 cd/m^2.

3.5
Linear Color Value

Color Value abbreviated as L, normalized to the range [0,1], that is directly proportional to the optical output of a display device, and which is not directly proportional to the encoded signal representation.

3.6
Nonlinear Color Value

Color Value abbreviated as N, normalized to the range [0,1], that is directly proportional to the encoded signal representation, and which is not directly proportional to the optical output of a display device.

4 Reference EOTF

4.1 Linearization and Scaling

The EOTF transforms a nonlinear color value N into an optical output value C. The EOTF transform shall be split into two steps: a linearization equation followed by a level calibration equation as defined in Sections 4.2 and 4.3.

4.2 EOTF Linearization Equation

The linear color values proportional to the desired optical output denoted by L are related to the nonlinear color values proportional to an input signal denoted by N. This relationship shall be defined by the EOTF linearization equation:

Equation 4.1

$$L = \left(\frac{max\left[\left(N^{1/m_2} - c_1\right), 0\right]}{c_2 - c_3 N^{1/m_2}} \right)^{1/m_1}$$

where

N denotes a nonlinear color value

L denotes the corresponding linear color value

m_1 is the number $2610/4096 \times \frac{1}{4} = 0.1593017578125$

m_2 is the number $2523/4096 \times 128 = 78.84375$

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

c_2 is the number $2413/4096 \times 32 = 18.8515625$

c_2 is the number $2392/4096 \times 32 = 18.6875$

4.3 EOTF Level Calibration Equation

The EOTF linearization equation 4.1 was constructed to align with human visual contrast sensitivities over a specific range of luminance values, therefore the absolute optical output shall be defined as:

Equation 4.2

$$C = 10{,}000\ L$$

where

L denotes the linear color value

C denotes the corresponding optical output value

C represents luminance in candelas per square meter (cd/m^2) when

all three component values of a linear additive tristimulus system are equal to L

or

a system contains a linear luminance component value Y that is equal to L, and any other color components are set to their native white point

These relationships simply state: When a system is set to make an output at the system's native white point at some normalized level L lying in the range 0 to 1, the target optical output C in cd/m^2 of the ideal reference display is 0 cd/m^2 to 10,000 cd/m^2.

4.4 Mastering Reference Viewing Environments

A reference display using the EOTF equations 4.1 and 4.2 and operating in a defined mastering reference viewing environment can contribute to visual consistency. Some examples of mastering reference viewing environments are presented in Annex B.

5 Reference Inverse-EOTF

5.1 Linearization and Scaling

An Inverse-EOTF transform converts an optical output value C to a nonlinear color value N. The inverse EOTF transform shall be split into two steps: a normalization equation followed by a nonlinear encoding equation as defined in Sections 5.2 and 5.3.

5.2 Inverse-EOTF Normalization Equation

The Inverse-EOTF normalization equation shall be defined as follows:

Equation 5.1

$$L = C/10{,}000$$

where

C denotes an optical output value

L denotes the corresponding linear color value

C represents the luminance in candelas per square meter (cd/m^2) when

all three component values of a linear additive tristimulus system are equal to L

or

a system contains a linear luminance component value Y that is equal to L, and any other color components are set to their native white point

5.3 Inverse-EOTF Nonlinear Encoding Equation

The Inverse-EOTF nonlinear encoding equation shall be defined as follows:

Equation 5.2

$$N = \left(\frac{c_1 + c_2 L^{m_1}}{1 + c_3 L^{m_1}}\right)^{m_2}$$

where

L denotes a linear color value

N denotes the corresponding nonlinear color value

m_1 is the number $2610/4096 \times \frac{1}{4} = 0.1593017578125$

m_2 is the number $2523/4096 \times 128 = 78.84375$

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

c_2 is the number $2413/4096 \times 32 = 18.8515625$

c_3 is the number $2392/4096 \times 32 = 18.6875$

Annex A
(Informative)

Example Digital Representations

A.1 Digital Representations

Three example digital representations are shown which encode nonlinear component values into digital code values. The first representation utilizes all available code values, while the second and third representations are constructed such that reserved code values for traditional video signaling purposes are not used, while maintaining range consistency among multiple bit depths between 10 and 16 bits per component.

A.2 Full Range Code Value Mapping

Full range digital code values are computed as follows:

Equation A.1

$$CV_F = Floor\left((2^b - 1)\ N + 0.5\right)$$

where

N is the nonlinear color value from zero to unity

CV_F is the resulting full range digital code value

b takes a value between 10 to 16 inclusive, corresponding to the number of bits per code word

The unary function $Floor$ yields the largest integer not greater than its argument.

This scaling places the extrema of N at code words 0h(0) and 3FFh(1023) in a 10-bit representation, code words 0h(0) and FFFh(4095) in a 12-bit representation, code words 0h(0) and 3FFFh(16,383) in a 14-bit representation, or code words 0h(0) and FFFFh(65,535) in a 16-bit representation.

A.3 Inverse Full Range Code Value Mapping

Normalized nonlinear color values N are computed from their full range digital code values as follows:

Equation A.2

$$N = CV_F/(2^b - 1)$$

where

CV_F is the component's full range digital code value

N is the nonlinear color value from zero to unity

b takes a value between 10 to 16 inclusive, corresponding to the number of bits per code word

A.4 Reserved Code Values

For some serial digital interfaces currently in use, such as SMPTE ST 292-1, code values having the 8 most-significant bits all zero or all one — for example, 10-bit codes 000_h(0) through 003_h(3) and $3FC_h$(1020) through $3FF_h$(1023) in the case of a 10-bit system, or 12-bit codes 000_h(0) through $00F_h$(15) and $FF0_h$(4080) through FFF_h(4095) in the case of a 12-bit system — are employed for synchronizing purposes and are excluded from video or ancillary data/signals. By extension, equivalent ranges for 14-bit and 16-bit systems would also be excluded from use for picture information.

The excluded values are:

System Bit Depth	Low Excluded Values	High Excluded Values
10-bit systems	000_h(0) through 003_h(3)	$3FC_h$(1020) through $3FF_h$(1023)
12-bit systems	000_h(0) through $00F_h$(15)	$FF0_h$(4080) through FFF_h(4095)
14-bit systems	0000_h(0) through $003F_h$(63)	$3FC0_h$(16,320) through $3FFF_h$(16,383)
16-bit systems	0000_h(0) through $00FF_h$(255)	$FF00_h$(65,280) through $FFFF_h$(65,535)

A.5 SDI Range Code Value Mapping

SDI range digital code values are computed as follows:

Equation A.3

$$CV_S = Floor(1015\, D\, N + 4\, D + 0.5)$$

where

N is the nonlinear color value from zero to unity

CV_S is the resulting SDI range digital code value

$D = 2^{b-10}$

b takes a value between 10 to 16 inclusive, corresponding to the number of bits per code word

The unary function $Floor$ yields the largest integer not greater than its argument.

This scaling places the extrema of N at code words 04h(4) and 3FBh(1019) in a 10-bit representation, code words 10h(16) and FECh(4076) in a 12-bit representation, code words 40h(64) and 3FB0h(16,304) in a 14-bit representation, or code words 100h(256) and FEC0h(65,216) in a 16-bit representation.

A.6 Inverse SDI Range Code Value Mapping

Normalized nonlinear color values N are computed from their SDI range digital code values as follows:

Equation A.4

$$N = (CV_S - 4\,D)/1015\,D$$

where

CV_S is the component's SDI range digital code value

N is the nonlinear color value from zero to unity

$D = 2^{b-10}$

b takes a value between 10 to 16 inclusive, corresponding to the number of bits per code word

A.7 Narrow Range Code Value Mapping

Narrow range digital code values are computed as follows:

Equation A.5

$$CV_N = Floor(876\,D\,N + 64\,D + 0.5)$$

where

N is the nonlinear color value from zero to unity

CV_N is the resulting narrow range digital codevalue

$D = 2^{b-10}$

b takes a value between 10 to 16 inclusive, corresponding to the number of bits per code word

The unary function $Floor$ yields the largest integer not greater than its argument.

This scaling places the extrema of N at code words 40h(64) and 3ACh(940) in a 10-bit representation, code words 100h(256) and EB0h(3760) in a 12-bit representation, code words 400h(1024) and 3AC0h(15,040) in a 14-bit representation, or code words 1000h(4096) and EB00h(60,160) in a 16-bit representation.

A.8 Inverse Narrow Range Code Value Mapping

Normalized nonlinear color values N are computed from their narrow range digital code values as follows:

Equation A.6

$$N = (CV_N - 64\,D)/876\,D$$

where

CV_N is the component's narrow range digital code value

N is the nonlinear color value from zero to unity

$D = 2^{b-10}$

b takes a value between 10 to 16 inclusive, corresponding to the number of bits per code word

A.9 Clamping Function for Inverse Code Value Mapping

Though the nonlinear code values N are normalized to the range [0,1], it is often useful for practical systems to be able to process values below zero or above one. In the digital representations for SDI Range and Narrow Range signals, it is possible for actual code words to represent these negative or greater than one values. In these cases it can be valuable to add a clamping function to explicitly limit the nonlinear code values to the [0,1] range.

A.10 Inverse SDI Range Code Value Mapping with Clamping

Normalized and clamped nonlinear color values N are computed from their SDI range digital code values as follows:

Equation A.7

$$N = min\{max[(CV_S - 4\,D)/1015\,D\,,0]\,,1\}$$

where

CV_S is the component's SDI range digital code value

N is the nonlinear color value restricted to zero to unity

$D = 2^{b-10}$

b takes a value between 10 to 16 inclusive, corresponding to the number of bits per code word

A.11 Inverse Narrow Range Code Value Mapping with Clamping

Normalized and clamped nonlinear color values N are computed from their narrow range digital code values as follows:

Equation A.8

$$N = min\{max[(CV_S - 64\,D)/876\,D\,,0]\,,1\}$$

where

CV_N is the component's narrow range digital code value

N is the nonlinear color value restricted to zero to unity

$D = 2^{b-10}$

b takes a value between 10 to 16 inclusive, corresponding to the number of bits per code word

Annex B
(Informative)

Example Reference Viewing Environments

B.1 Consistency with Traditional Program Production Environments

It is desirable for programs using the high dynamic range EOTF to be created under the same ambient lighting conditions as those using traditional EOTFs. This will allow the same facility to produce content for both traditional and high dynamic range formats by simply switching the EOTF response of their reference display. This methodology will also allow for legacy content to be directly inserted into new high dynamic range programs without affecting the original creative intent of the legacy content. Two example reference environments will be described in the following sections for HDTV and cinema applications.

B.2 Reference Viewing Environment for HDTV

Section 1 of Annex 1 of Recommendation ITU-R BT.2035 describes reference viewing conditions for HDTV, including room illumination of 10 Lux, chromaticity of background as D_{65}, and a luminance of background of 8 to 12 cd/m^2 (based on Section 1.1.c and Section 3.2). Non-cinema reference displays utilizing the high dynamic range EOTF would operate under these same three conditions.

B.3 Reference Viewing Environment for Digital Cinema

Section 6 of SMPTE RP 431-2 describes reference viewing conditions for digital cinema, including black, non-reflective finishes on all surfaces, recessed lighting which is appropriately masked and filtered, and an ambient light level reflected by the screen of less than 0.01 cd/m^2. Cinema reference displays utilizing the high dynamic range EOTF would operate under these same three conditions.

Annex C
(Informative)

Example Inverse-EOTF Use Case

To clarify the inclusion of an Inverse-EOTF in the scope of this document, the following example use case is provided. In mastering systems for producing episodic content, typically a color correction system provides the input for the mastering reference display. The color correction system will normally operate with linear floating point signals internally, and these signals must be converted from linear values to the nonlinear values expected by the display device. If the display device implements the EOTF defined in this document, then the color correction system uses the Inverse-EOTF to produce a direct linear to nonlinear conversion for presentation to the display.

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SMPTE RP 431-2:2011, D-Cinema Quality — Reference Projector and Environment

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