HDR Demystified

EMERGING UHDTV SYSTEMS

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The CE industry is currently migrating from High Definition TV (HDTV) to Ultra High Definition TV (UHDTV). In addition to higher resolution, UHDTV benefits greatly from additional visual quality enhancements like Higher Dynamic Range (HDR) and Wide Color Gamut (WCG).

These enhanced features have been received very positively by consumers, and CE manufacturers are moving very quickly to introduce equipment to the market with various levels of UHD capability. This fast movement in the industry has left many of us confused about UHDTV capabilities, proposed system features, system compatibility, and standards.

In this preliminary draft document, we attempt to shed some light on High Dynamic Range and Wide Color Gamut, the two significant features of UHDTV that will affect how we test and calibrate the image accuracy of these new generation TVs.

We cover the different industry proposals related to HDR and WCG and we briefly discuss how CalMAN display calibration software addresses these new technologies.

UHDTV Capabilities

The new UHDTV system comprises a number of advanced technologies. Those technologies include:

High Resolution Video – Higher spatial resolution was the first promoted feature of UHDTV. A UHD TV's native resolution will be 3840x2160 pixels. This is four times the total number of pixels produced by HDTV at 1920x1080. However, the visible resolution improvement over HDTV could be less pronounced in a home environment, due to the limitations of human visual acuity, screen size, and home viewing distances.

High Dynamic Range (HDR) – The dynamic range of a TV refers to its luminance, the maximum and minimum amount of light the TV is capable of producing.

High Dynamic Range is the capability to represent a large luminance variation in the video signal, i.e., from very dark values (0.00005 cd/m2) to very bright values (greater than 1000 cd/m2). Existing systems, now referred to as Standard Dynamic Range (SDR), support luminance values only in the range of 0.0002 to 100 cd/m2.

HDR creates brighter whites, darker blacks, and brighter colors that better match images we see in the real world. The enhanced image quality due to HDR is appreciable under virtually any viewing condition.

Wide Color Gamut (WCG) – A TV's color gamut indicates the level of saturation and number of colors that a TV can produce. Wide Color Gamut indicates the capability of displaying images with a wider range of colors than have been supported by conventional systems.

Video systems up to now have been based on the BT.709 and BT.601 color spaces, which contain only a small percentage (about 33.5%) of all 1976 CIE visible chromaticity values. This legacy color space leaves a large set of visible colors that cannot be rendered on SDTV or HDTV displays.

Note: The NTSC color gamut was never used, even for the NTSC system, and is totally irrelevant.

Larger color spaces, such as DCI-P3 and BT.2020 can represent a much larger set of visible colors (about 41.8% and 57.3% respectively). Displays capable of producing a majority of these color spaces can render more colorful and realistic content.

The UHD spec will call for a wider color gamut, creating more vivid colors and more detailed color gradation than with HDTVs.

High Dynamic Range (HDR)

High dynamic range will potentially provide the most significant UHD picture quality improvement over HDTV. HDR provides a more lifelike range of image light levels than previously possible.

The average picture level (APL) of UHD images will remain fairly consistent with HDTV images, but the black level detail will be enhanced and the highest luminance levels will occur only in specular highlights within the HDR images.

The contrast range and light levels in specular highlights will increase dramatically, coming closer to reproducing the rich contrast, tonal details, and bright picture highlights that we see in the real world. HDR, along with wide color gamut, enables a more natural saturation of bright colors, without the artificially muted saturation inherent in the BT.709 HDTV system (figure 1).

Figure 1: HDR produces bright highlights, but it also yields brighter, natural colors and improved shadow detail. Image credit: Scott Wilkinson, AVS Forum post

High Dynamic Range Photography – The first experience many of us had with HDR was with a smartphone camera that provided an HDR function. HDR photography is about overcoming the limitations of consumer image sensors to increase an image's exposure range. It typically does this by automatically capturing three images, at different exposures, then combining the best exposed parts of the three images into a single HDR photo. This results in a captured image with increased tonal detail in both the dark and bright areas of the photo. However, there is no expanded range; it does not make the dark areas of the photo darker or the bright areas of the photo brighter.

HDR photography entirely involves optimizing the image exposure capture process, basically to tone map an HDR image into an SDR container. It does not increase an image's dynamic range, nor does it involve the method with which the image is transmitted to a display device or the method with which the image is rendered on the display.

High Dynamic Range TV – HDR TV is not about overcoming limitations on the capture end, as with consumer photography. Professional film and digital video cameras have long had greater dynamic range than the 6 exposure stops (or a few more with camera s-curves and grading correction) supported by the BT.709 HDTV SDR system. (An exposure stop is a doubling or halving of light.) Most digital cinema cameras today can capture at least 14 stops of exposure range, but this wide dynamic range is not currently preserved, even for cinema presentation. HDR grading for the home can be delivered with 8-10 stops of exposure range.

HDR TV is also not primarily about overcoming limitations on the playback end. Late model TVs have become capable of displaying much brighter images than the current BT.709 HDTV luminance spec of 100 cd/m2 (now commonly known as nits).

Even before the push to HDR, many TVs with LED backlights could produce brighter colors than the BT.709 standard and could produce peak luminance levels over 400 nits. Current displays can produce greater dynamic range than the current specifications for the content distribution chain can handle. Trends suggest that HDR-capable consumer TVs should be able to produce "specular highlights" with luminance of 1,000-1,500 nits or brighter in the next few years.

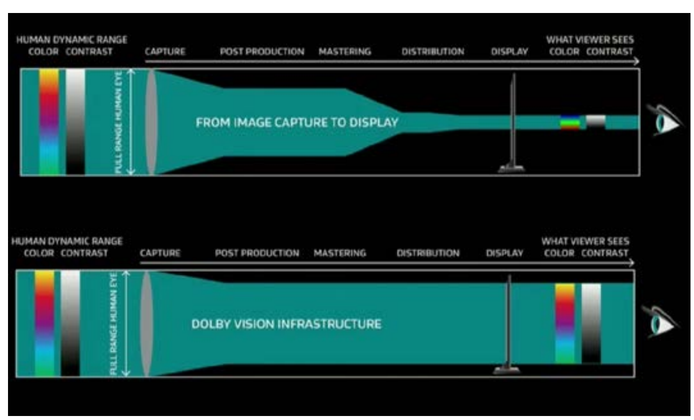

Figure 2: The original dynamic range of captured content will be able to be substantially preserved by a new HDR TV system, compared to the current SDR TV system. Image credit: Dolby

Dual modulation backlights and zone LED backlighting were both introduced prior to HDR and are prime enablers of HDR, but until now we couldn't fully take advantage of these technologies.

TVs with LED backlights, OLED displays, or quantum dots can also produce a wider range of colors, including more highly saturated colors, which also look brighter. To accurately render BT.709 images, HDTVs currently need to limit any of these enhanced capabilities.

The main challenges that need to be addressed to enable HDR TV are primarily the specifications and systems for the middle processes of mastering, encoding and delivering TV images to consumer display devices.

HDR TV Standards

Standards have been and continue to be formulated for every aspect of HDR content creation, transport, delivery, and display. The International Telecommunications Union (ITU), Society of Motion Picture and Television Engineers (SMPTE), Consumer Electronics Association (CEA), Motion Picture Experts Group (MPEG), and the Blu-ray Disc Association (BDA) have all developed standards relating to some aspect of UHDTV and HDR.

SMPTE – SMPTE ST2084:2014 (and CEA-861-3) standardizes an Electro-Optical Transfer Function (EOTF) for HDR that was developed by Dolby Labs to define the process by which digital code words are converted into visible light.

SMPTE – SMPTE standard ST2086:2014 defines static metadata; metadata that does not change during playback of the associated video content.

SMPTE standard ST2094, which is being considered in committee, along with CEA-861-G/HDMI 2.x, will define content-dependent (dynamic) metadata.

ITU – ITU-R Recommendation BT.2020 defines a wide gamut color space, among other aspects of a UHDTV system.

ITU-R Report BT.2381-0 (07/2015), Requirements for High Dynamic Range Television (HDR-TV) Systems, is a summary of performance criteria that should be met by a newly implemented HDR TV delivery system that includes the criterion of backward compatibility of HDR content with SDR displays.

CTA – The Consumer Technology Association (CTA), formerly the Consumer Electronics Association (CEA), has defined the following minimum guidelines for a TV, monitor, or projector to be referred to as an HDR-Compatible Display:

- Includes at least one interface that supports HDR signaling.
- Receives and processes static HDR metadata. (An HDMI input needs to be HDMI 2.0a to pass HDR metadata.)
- Receives and processes the HDR10 Media Profile from IP, HDMI or other video delivery sources. This requires HDMI 2.0a. Other media profiles may additionally be supported.
- Applies an appropriate Electro-Optical Transfer Function (EOTF) before rendering the image.

UHD Alliance – The UHD Alliance is a multi-industry alliance that formed to promote UHD standards development and UHD branding and certification. The alliance members include all major production studios, content distributors, and display manufacturers.

The UHD Alliance has defined an ULTRA HD PREMIUM certification and logo for devices, content and services that meet the following minimum UHD specs.

- **Resolution**: 3840x2160 for content, distribution, and playback displays.
- **Color bit depth**: 10 bits minimum for content and distribution, 10 bits for playback displays.
- **Color representation**: BT.2020 for content, distribution, and playback displays.
- **Mastering display**; transfer function: SMPTE ST2084 inverse EOTF; color space: minimum 100% of P3; peak luminance more than 1,000 nits; black level: less than 0.03 nits.
- **Content transfer function**: SMPTE ST2084
- **Playback display**; transfer function: SMPTE ST2084 EOTF; color space: minimum 90% of P3; peak luminance more than 1,000 nits and black level less than 0.05 nits OR peak

luminance more than 540 nits and black level less than 0.0005 nits

One goal of the UHD Alliance is that UHD content will be backwards compatible with SDR displays. This is a key challenge for HDR delivery systems.

BDA - The Blu-ray Disc Association has released its new Ultra HD Blu-ray Disc specification, which includes provision for base layer HDR10 video and optional Dolby Vision.

HDR Transfer Function

The image content of a video signal is defined by what is seen on the mastering reference display, since colorists adjust and make decisions on the appearance of the content based on the look of the reference display.

In the case of live production, this may be performed by a creative at a camera control unit or by the application of a simple look-up table (LUT) for tone mapping. For off-line production, this usually involves artistic color grading of the content in a post-production suite.

The reference display's EOTF determines how video signal values are converted to linear light values. Since the production of both live and off-line content is guided by a reference display, the EOTF of the reference display always defines the content.

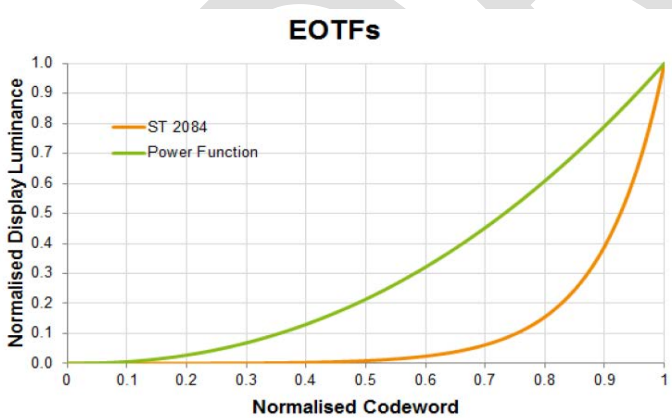

Figure 3: ST2084 HDR EOTF vs. legacy gamma power function. Image credit: IBC/Litwic et.al.

The legacy BT.709 and BT.1886 power law gamma curves are a quantization of relative brightness. These curves are relative luminance, allowing each playback display to map a video signal's maximum code word to the peak luminance of that specific display.

The traditional gamma curves (e.g. BT.709 or BT.1886) were based on CRT physics and are similar to human perception at relatively low light levels. They cover luminance values up to 100 nits.

When conventional EOTFs are stretched beyond a few hundred nits, even with a 10-bit signal, they start to produce image contouring, due to the inefficient way they use bits relative to the human visual system.

The SMPTE ST2084 EOTF curve is a 10 or 12-bit quantization of absolute brightness. It is an absolute luminance function, requiring the EOTF of the playback display to exactly match the EOTF of the mastering reference display.

The ST2084 EOTF was designed with headroom for future expansion and covers a range of luminance from 0.00005 nits up to 10,000 nits (figure 3). ST2084 maps each video signal code word to the same absolute luminance and chromaticity in every display (i.e. 10-bit code word 691 always maps to 500 nits). This allows each playback display to exactly match the luminance and chromaticity of the mastering reference display.

This HDR EOTF, standardized as SMPTE ST2084, is based on the contrast sensitivity function of the human eye, as measured by Barten and referenced in ITU-R Report BT.2246-5. It is called a perceptual quantizer (PQ) curve.

Since SMPTE ST2084 corresponds closely to the human perceptual model, it makes the most efficient use of signal bits throughout the entire luminance range. An ST2084 encoded signal can represent luminance levels up to 10,000 nits at the cost of relatively few extra code words (figure 3). A majority of the ST2084 codes represent lower luminance levels, to complement the human visual system's greater contrast sensitivity at lower luminance levels and to minimize visible banding at those lower levels. Half of the HDR codes are in the SDR range, meaning that 10-bit HDR doubles the number of code values in the SDR range, compared to traditional 8-bit video.

If a display system were to simply reproduce a linear representation of the scene light, it would produce low contrast, washed out images. This is because scenes that are viewed at brightness levels much lower than the original scene are perceived to have much lower contrast than the original scene

To optimize the images, an S-curve function is used to map scene light to display light. This Optical to Optical Transfer Function (OOTF - often referred to as rendering intent or system gamma) compresses/clips the extreme highlights and dark areas and contrast enhances the mid-range light levels with a gamma >1 characteristic (typically 1.1 to 1.6).

The SMPTE ST2084 PQ system, which is defined by its EOTF, was designed to have the OOTF applied in the camera or the production process (figure 4).

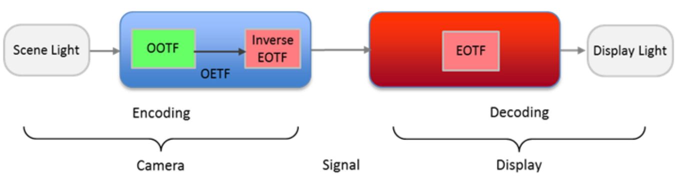

Figure 4: In an ST2084 PQ system, the OOTF (rendering intent) is applied in the production process. Image credit: ITU

HDR Metadata

SMPTE ST2086 defines static metadata that is supported by HDMI 2.0a, and is included with mastered HDR content to convey the color volume of the mastering display and the luminance of the content. This is described by the chromaticity of the red, green, and blue display primaries and white point of the mastering display, plus its black level and peak luminance level. ST2086 also conveys the following luminance attributes of the mastered content (calculated in linear light domain):

- MaxCLL (Maximum Content Light Level)

  The MaxCLL cd/m^2 level is the luminance of the brightest pixel in the content.

- MaxFALL (Maximum Frame-Average Light Level)

  The average luminance of all pixels in each frame is first determined (frame-average maxRGB). The MaxFALL cd/m^2 level is then the maximum value of frame-average maxRGB for all frames in the content.

SMPTE ST2094 (pending) will define content-dependent (dynamic) metadata, to be supported in HDMI 2.1. Dynamic metadata will convey frame-by-frame or scene-by-scene Color Remapping Information (CRI), developed by Technicolor, which will enable color transformation to be variable along the content timeline.

Samsung has also proposed a standard for content-dependent dynamic metadata and color volume mapping of HDR content to displays with a smaller dynamic range and narrower color gamut (more below on color volume mapping).

Wide Color Gamut (WCG)

From CES 2016, it appears that almost all UHD content that is HDR will also be wide color gamut. Wide color gamut describes content or displays with the capability of representing a larger volume of colors than have been supported by existing color standards.

Wide color gamut enables more true-to-life hues and saturation levels, especially in very bright and very dark image areas. It allows you to see more lifelike color representations of vividly colored objects like flowers and eggplants, sports jerseys, or stained glass.

To produce a wider color gamut, a display needs to have higher saturation, narrow spectral bandwidth RGB primary colors that measure closer to the edges of the CIE Chromaticity Diagram (figure 5). The edge colors on the diagram are pure, monochromatic, 100% saturated colors; created by light energy that is concentrated at a single wavelength.

The current color gamut standard for HDTV is specified by ITU-R Rec. BT.709. As seen in figure 5, the P3 color gamut that is currently specified by the DCI for cinema presentation is significantly larger than the BT.709 HDTV gamut. The recently specified color space for HDR, ITU-R Rec. BT.2020, with absolutely pure RGB primary colors, is the ultimate limit of the UHDTV system.

The BT.2020 color space is a large container for color gamut information, but the size of the container does not define the color gamut of any particular content. The color gamut volume within the BT.2020 container, as specified by HDR metadata, can be any gamut content that is no larger than the BT.2020 color space container. As wide color gamut is being implemented within the UHDTV system, the DCI P3 gamut (legacy cinema content) is a popular content gamut.

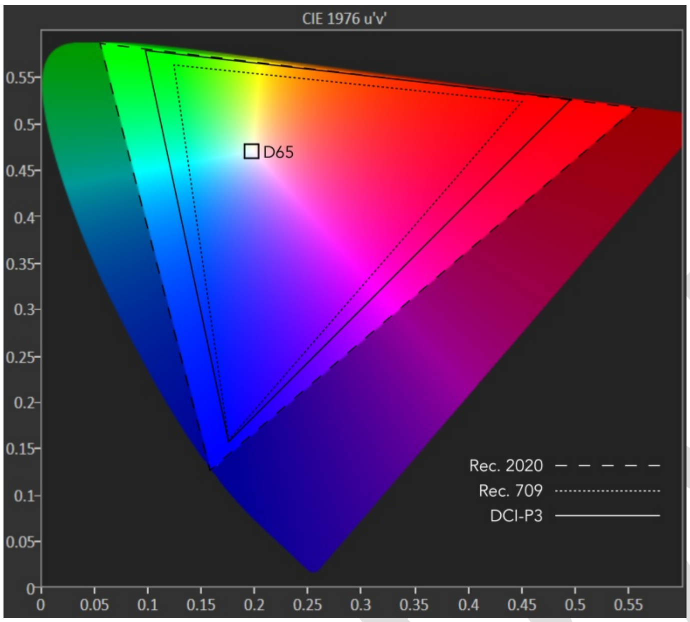

Figure 5: The BT.2020 color gamut is the goal for UHD TV. The P3 gamut is currently used for cinema theater presentations and will be an intermediate gamut for UHD content. The BT.709 color gamut, with much lower saturation colors, is the current HDTV standard. Image credit: W3C

Until recently, RGB LED and RG phosphor-doped LED backlights have been the principal source of highly saturated primary colors, getting close to the P3 gamut. OLED emissive displays, primarily from LG, are now available with color gamuts also very close to the P3 gamut.

Quantum Dot red and green nanocrystals, which emit light at very narrow bandwidths when excited by blue LED photon energy, are now beyond DCI-P3 and are getting narrower and wider as the technology matures.

Laser light sources, as recently implemented in the Dolby Cinema and IMAX Laser projection systems, produce narrow bandwidth, highly saturated colors and are able to precisely reproduce the BT.2020 color gamut.

Pointer's gamut is an approximation of the gamut of 4,000 diffuse surface colors found in nature, as seen by the human eye and measured by Dr. Michael R. Pointer in 1980 (figure 6). Every color that can be reflected by the surface of an object of any natural or man-made material is inside Pointer's gamut.

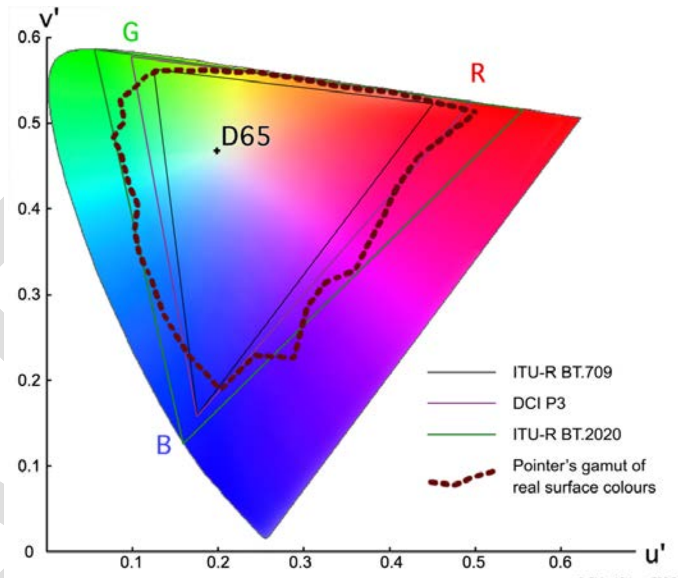

Figure 6: Pointer's gamut, containing the colors of all real surfaces, is mostly contained within the BT.2020 color gamut. Image credit: BBC

As indicated in figure 6, BT.2020 covers 99.9% of Pointer's gamut. Hence, there are very few naturally occurring colors that could not be described within the BT.2020 color space. So, BT.2020 would appear to be a sufficient color space for television systems to display realistic images (including neon lights, LED lights, and computer generated images).

The chromaticities of the BT.2020 color space are plotted in figure 7, as compared to the smaller HDTV BT.709 color gamut.

The BT.2020 primaries, which are represented at the very edges of the CIE Diagram, are maximum saturation pure colors, created by extremely narrow spectral slices of light energy. As with all other consumer color standards, BT.2020 specifies a D65 white point.

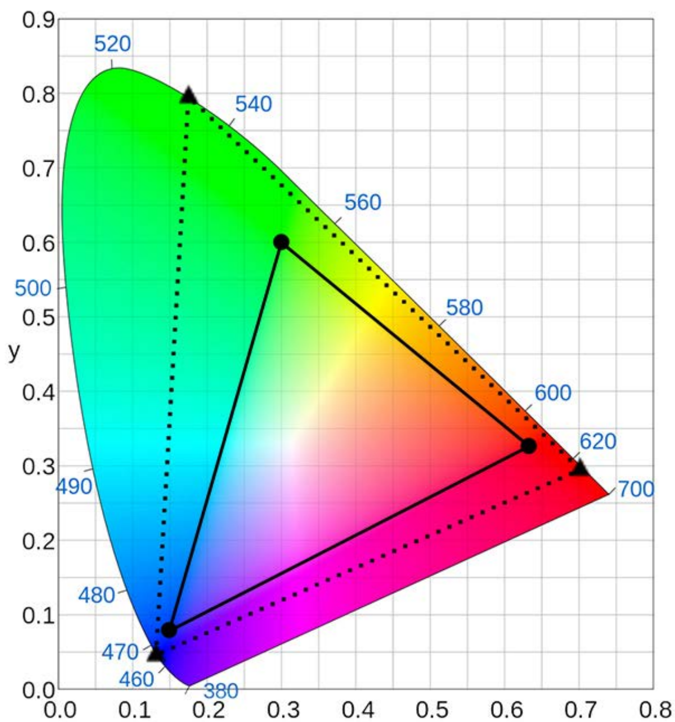

Figure 7: BT.2020 (dotted) vs. BT.709 (solid) color gamut chromaticities, as plotted on 1931 CIE Chromaticity Diagram. Image credit: Geoffrey Morrison/CNET, Sakurambo

The BT.2020 color space container can represent BT.709, P3, or any gamut up to and including the full BT.2020 spec. Figure 8 shows the color gamut of BT.709 content, as it would be represented within the larger BT.2020 container.

If a playback display is BT.2020 compatible, content with any smaller color gamut, but represented within the BT.2020 color space container, will be rendered with its original saturation and hue. The large color volume specification of BT.2020 allows the color gamuts of each combination of video content and playback display to be utilized to the fullest extent possible.

Color Volume Mapping

High dynamic range and wider color spaces are becoming linked by standards bodies into what is often referred to as color volume (figure 8). The higher the luminance range and the wider the color space, the larger the overall color volume.

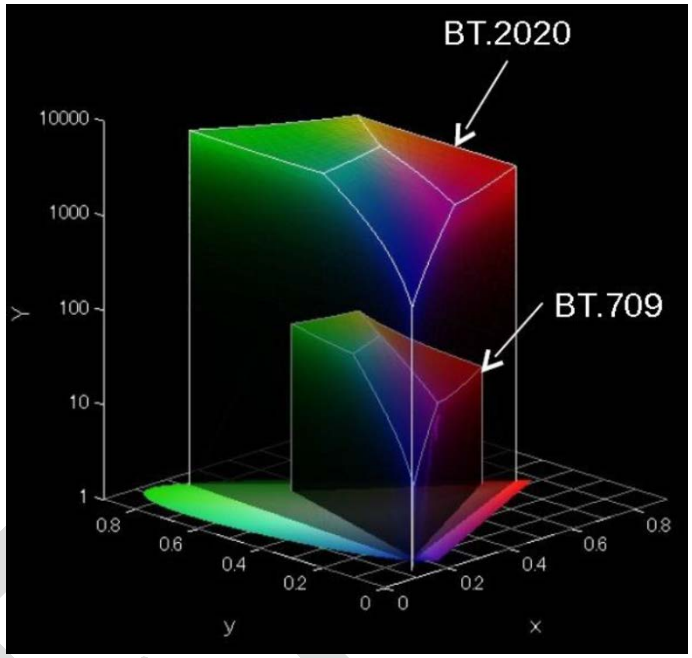

Figure 8: The color volume of the new BT.2020 color gamut, compared to the current BT.709 color gamut. Image credit: Sony

Color volume mapping denotes the process of mapping content that was created on a large color volume mastering display down to a playback display that has a reduced color volume ('color gamut' often evokes a 2D area). In some HDR systems, this mapping is being called "display adaptation" or "display tuning."

Luminance - The peak luminance of a playback HDR display will often be lower than the peak luminance of the reference display that was used to master video content that is being played back. In this case, the higher content luminance can be tone mapped to the lower dynamic range of the playback display, with a luminance roll-off of the brightest highlights that avoids hard clipping. Tone mapping needs to be done in a fashion that minimizes the perceptual effects of the luminance roll-off.

Chromaticity - The primary colors of a playback HDR display will often be less saturated than the primaries of the reference HDR display that was used to master video content. In this case, the wider content gamut can be gamut mapped to the narrower gamut of the playback display. Gamut mapping needs to be done in a perceptual fashion to maintain relative saturation differences but also not desaturate lower saturation images and wash out the image.

Luminance and Chromaticity - Because of the perceptual interaction of luminance and chromaticity, when a lower dynamic range display rolls off the top end of higher luminance content, that also affects the chromaticity of brighter pixels, and both need to be taken into account in a display's color volume mapping strategy.

For tone mapping and gamut mapping to be achieved in the playback display, the display needs to be informed by static metadata of the luminance and chromaticity attributes of both the mastering display and the content. These attributes are represented by the static metadata fields that are defined in the SMPTE ST2086 standard.

However, if color volume mapping is performed without scene-by-scene content information, the mapping will be based only on the brightest scene and the widest gamut scene in the content. The majority of the content will have greater compression of dynamic range and color gamut than would be necessary.

Dynamic metadata allows a compatible display to map the content to a smaller color volume only as needed, when the content exceeds the capability of the playback display. The perception model can change dynamically, based on the luminance and gamut requirements of each scene.

Color volume mapping is more important the more difference there is between the mastering display and the playback display and will be an essential part of the future proofing of HDR technology. It ensures that playback displays that can do accurate mapping will still show content well when mastering displays are at or near the BT.2020 gamut limits, with many thousands of nits.

ICtCp Color Representation

Y'C'bC'r is SDR's legacy color-opponent based encoding scheme that separates luma from chroma information for the purposes of chroma subsampling. With the large color volume that results from high dynamic range and wider color gamut, the shortcomings in using Y'C'bC'r to map luminance, hue, and saturation differences from one color volume to another have become magnified, also yielding larger color crosstalk encoding errors and amplification of noise near the edges of the RGB color space. The shortcomings are due to the perceptual crosstalk between the Y', C'b, and C'r signal channels.

As saturation changes in this color space, the luminance changes and the hue shifts, especially in the blue region. Because the Y'C'bC'r space is not constant luminance, saturated colors (especially red and blue) are rendered too bright. Also, as Y'C'bC'r chroma is subsampled to 4:2:2 or 4:2:0, quantization errors due to bit depth limitations are introduced in the chroma.

The BT.2020 standard provides the Y'cC'bcC'rc constant luminance format as an alternative to Y'C'bC'r (see ITU-R Report BT.2246-5). This format resolves the issue of chroma leakage into the Y'c luma signal, yielding improved tone mapping and luminance encoding. It does not, however, solve the problem of luminance leakage into the C'bc and C'rc signals.

Dolby has proposed the use of an alternate ICtCp color representation, approved by ITU-R SG 6, that better conforms to the neural processing characteristics of the human visual system than either Y'C'bC'r or Y'cC'bcC'rc. ICtCp is a color-opponent space that represents color in terms of an Intensity (black-white) channel (I), a Tritan (blue-yellow) channel (Ct), and a Protan (red-green) channel (Cp). As saturation changes in the ICtCp color space, luminance and hue remain almost constant; no crosstalk.

The ICtCp color representation results in constant intensity, hue linearity, and perceptual uniformity. This yields efficient encoding of high dynamic range and wide gamut color difference signals with lower quantization error, as well as more accurate color volume mapping

HDR TV Delivery Systems

A number of systems have been proposed for delivering HDR content to consumer displays. These HDR systems, which combine existing and proposed standards, are outlined here and discussed individually in the following sections.

System 1: **HDR10**; uses ST2084 EOTF, a single content layer with static metadata; not compatible with SDR TVs; specified by CTA for HDR-compatible TVs and mandated for Ultra HD Blu-ray.

System 2: **Dolby Vision**; uses ST2084 EOTF, a base content layer with static metadata, and an enhanced content layer with dynamic metadata; optionally compatible with HDR10 TVs and SDR TVs; optional for Ultra HD Blu-ray.

System 3: **BBC/NHK**; uses a hybrid log-gamma (HLG) EOTF with no metadata; playback on HLG-compatible HDR TVs or SDR TVs.

System 4: **Technicolor/Philips**; uses ST2084 EOTF, a single content layer with metadata; optional for Ultra HD Blu-ray; compatible with SDR TVs through an external decoder device (e.g. STB or BD player).

System 1: HDR10

The MPEG group studied HDR requirements and concluded that the HEVC Main 10 profile compression (H.265) provided the efficiency and signal quality needed for HDR delivery. Other industry groups also determined that an optimum implementation of a 10-bit 4:2:0 format base video signal would meet the requirements for delivering HDR and WCG.

Based on these conclusions, the Blu-ray Disc Association (BDA), the High-Definition Multimedia Interface (HDMI) Forum, and the UHD Alliance (UHDA) adopted a delivery format, based on HEVC Main 10, for the compression and delivery of HDR and WCG content. This base-level HDR delivery format is now commonly referred to as “HDR10.” The CTA (former CEA) mandated the HDR10 media profile in their HDR-compatible display spec.

This HDR10 open platform version of HDR is not yet a complete standard. It is a collection of technologies and specifications, but it is incomplete as an end-to-end system (more below).

Linear light image data from a camera is first subject to some form of live or off-line grading, as judged by the visual results on an HDR-compatible mastering display (figure 9). The color volume of the content is always represented within a BT.2020 color space container.

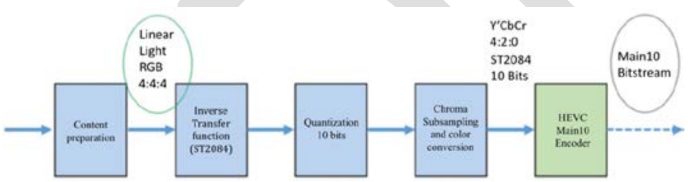

Figure 9: HDR10 content mastering process. Image credit: NGCodec

The RGB 4:4:4 image data is then encoded to video signal code words that best exploit human sight characteristics by using the SMPTE ST2084 PQ curve (figure 10).

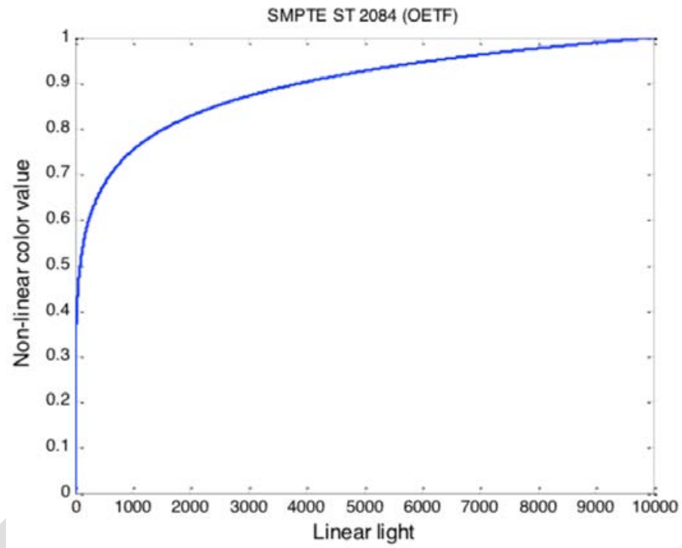

Figure 10: The SMPTE ST2084 inverse EOTF (PQ) curve is used to convert image data to video signal values in a manner that best exploits human sight characteristics. Image credit: SMPTE

The encoded data is then quantized to 10 bits per channel (figure 9). Color conversion and chroma sub-sampling is then performed to convert the signal to Y’Cb’Cr’, 4:2:0 before it is sent to an encoder for HEVC compression.

HDR10 Playback

- Minimum signal interface: HDMI 2.0a
- Playback color representation: ITU-R BT.2020
- Playback transfer function (EOTF): SMPTE ST2084
- Static metadata: SMPTE ST2086
- Playback bit depth: 10 bits

The playback process for an HDR10 display pretty much reverses the signal mastering process. The signal is decoded and the color conversion and sub-sampling are then reversed to recover an RGB 4:4:4 signal (figure 10).

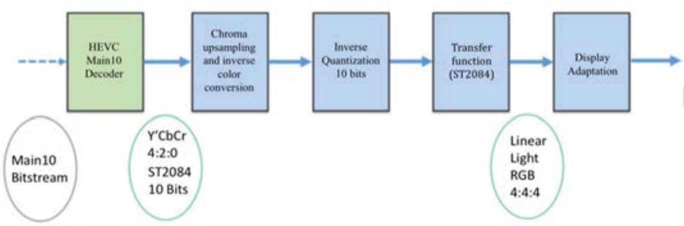

Figure 11: HDR10 content decoding process. Image credit: NGCodec

The signal is then applied to the SMPTE ST2084 playback transfer function (EOTF) to recover linear light values from the encoded video signal values.

The ST2086 metadata conveys the black level and peak luminance level of the mastering display, plus luminance attributes of the mastered content. If the color gamut of a playback display is narrower than that of the video content or if the peak luminance of the display is lower than that of the content, the content can be perceptually mapped to the narrower gamut or lower luminance display.

The playback display should follow ST2084 as much as possible for luminance, and then roll off smoothly from some point below the playback display's peak luminance to not clip the highest luminance levels in the mastered signal.

Because, with metadata, the playback display can know the peak luminance of the content, the playback display only needs to remap to the peak luminance of the content, not to the ST2084 10,000 nits maximum.

For HDR10, though, this perceptual luminance and gamut mapping is not defined. There is currently no industry standard for the method of color volume mapping an HDR signal's tonal range or color gamut to playback displays with a smaller dynamic range or narrower color gamut. The playback attributes of an HDR10 display can be tested, but there is currently no way to validate accurate image rendering of an HDR10 display against a standard.

Some current HDR10 displays seem to ignore parts of the ST2086 metadata, which is concerning.

System 2: Dolby Vision

The Dolby Labs HDR system, called Dolby Vision, is a proprietary HDR system requiring display manufacturer licensing. Dolby Vision is an end-to-end, scalable solution that is included in the specifications for 4K Ultra HD Blu-ray and can optionally provide compatibility with HDR10 and SDR displays.

Dolby developed RGB tunneling over HDMI, with the metadata embedded in the signal itself, to allow proprietary Dolby Vision 12-bit video and metadata to travel through HDMI 2.0 interfaces, without having to wait for the standardization of HDMI 2.0a.

Dolby Vision uses proprietary end-to-end dynamic metadata to precisely define image luminance and chromaticity. It conveys the black level and peak luminance level of the mastering display plus overall luminance attributes of the mastered content. It also conveys color volume attributes for each new scene.

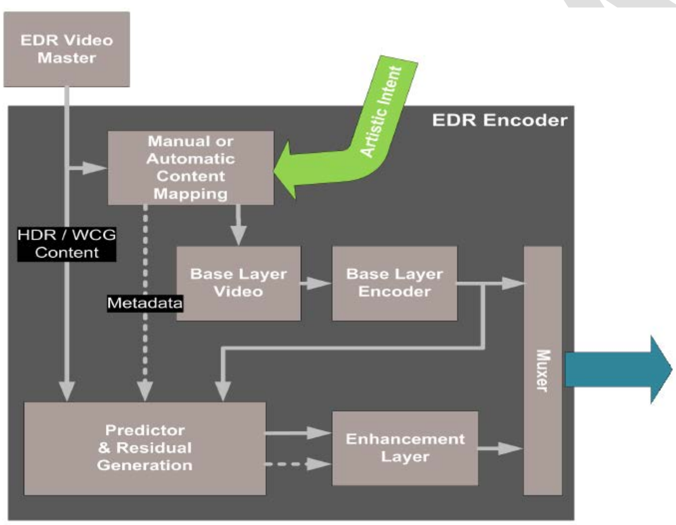

Figure 12: Dolby Vision content mastering process. Image credit: Dolby Labs

Dolby refers to images with higher dynamic range and wider color gamut than SDR as Extended Dynamic Range (EDR).

Dolby Vision offers the following choices to a Dolby Vision content creator. The choice as to which profile to use depends on whether the content distributor requires backward compatibility

- A dual-layer profile with a 10-bit base-layer of either SDR HDTV (not on Ultra HD Blu-ray) or HDR10 (optional on Ultra HD Blu-ray) for compatibility and a 2-bit enhancement layer for high dynamic range and wide color gamut. This comes at the cost of only a bit more bandwidth required for the enhancement layer.

  This system, which is more optimized for off-line production, transmits existing standards as a base layer, while an EDR enhancement layer provides information necessary to recreate the Dolby Vision EDR. The solution works with any spatial resolution, bit depth, color primaries, and color volumes up to 10,000 nits for either an 8-bit AVC base layer or an 8/10-bit HEVC base layer.

- A single layer 10-bit profile for real-time HDR content such as live broadcast or OTT applications. This non-backwards compatible solution provides greater bitrate efficiency. This single layer offers the ability to use dynamic metadata and, with the Dolby proprietary tunneling technology, retains the 12-bit mastering fidelity, even though the transport is 10-bit HEVC.

Much of the current Dolby Vision content is being mastered with the Dolby Pulsar reference display that has 4000 nits peak luminance, P3 color volume, and D65 white point.

Metadata is generated to describe the black level, peak luminance, and color volume of the mastering display, plus the maximum and average frame luminance of the content. Dynamic metadata is generated to describe the frame-by-frame luminance of the content and is used to map the content to the peak luminance of a particular playback display.

During EDR mastering, dynamic metadata for Dolby Vision is generated to reflect the relationship between the HDR and SDR versions of each video frame. This dynamic metadata is carried in the Dolby Vision enhancement layer.

Dolby Vision Playback

- Minimum signal interface: HDMI 1.4
- Playback color representation: ITU-R BT.2020
- Playback transfer function (EOTF): SMPTE ST2084
- Maximum playback luminance: 10,000 nits

All Dolby Vision playback devices are compatible with both single-layer and dual-layer profile content.

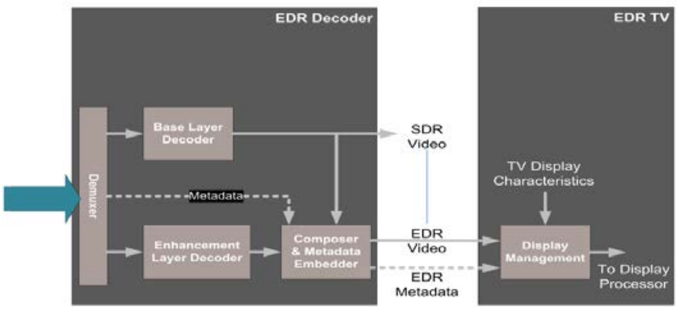

Figure 13: Dolby Vision content decoding process. Image credit: Dolby Labs

A Dolby Vision dual-layer stream with an SDR base-layer and an enhancement layer can be decoded, combining the SDR stream with the enhancement layer stream and dynamic metadata, to produce Dolby Vision HDR video, with dynamic metadata, to drive a Dolby Vision display. Or, the SDR stream can simply be decoded to produce SDR video to drive an SDR display.

A Dolby Vision dual-layer stream with an HDR10 base-layer and an enhancement layer can be decoded to produce Dolby Vision HDR video, HDR10 video, or SDR video.

In a Dolby Vision EDR decoder, the original mastered 12-bit PQ content is reconstructed by combining the 10-bit SDR or HDR10 stream, the 2-bit enhancement layer stream, and the dynamic metadata to produce 12-bit EDR video at the decoder output, with dynamic metadata.

A Dolby Vision display uses the dynamic metadata, along with the display characteristics, to map the EDR video to the capabilities of each particular playback display.

System 3: BBC/NHK HLG

The BBC of the UK and NHK of Japan have jointly proposed an HDR delivery system that is optimized more for real-time broadcast production.

The Hybrid Log Gamma (HLG) system has been approved as STD-B67 by ARIB, the Japanese organization that is the equivalent of ATSC in North America and DVB in Europe. The proposal has been submitted to the ITU and SMPTE for potential standardization.

The Hybrid Log Gamma name refers to the fact that the OETF is a hybrid curve that applies a standard gamma curve for darker pixels in the legacy SDR range and a logarithmic curve for higher brightness highlights (figure 14).

The hybrid OETF makes it possible to broadcast a single signal/stream that is compatible with both SDR and HDR televisions. HLG does not depend on metadata being sent with the content, so the signal is display-independent and can be rendered unprocessed on an SDR display.

The HLG technology is royalty free and does not require licensing by either broadcasters or display equipment manufacturers.

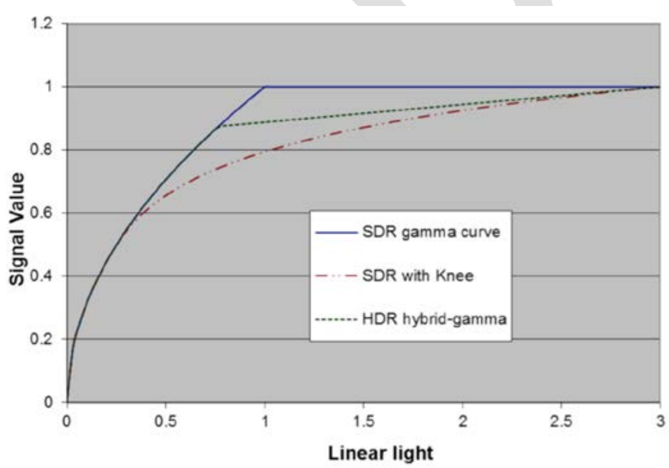

Figure 14: Hybrid log-gamma OETF vs. SDR OETFs. Image credit: BBC/NHK

The HLG proposal is fully specified from end to end. It has a complete mastering spec and a complete playback spec, so proper playback can be validated.

On December 14, 2015, Vatican Television Center broadcast the ceremony of the Holy Door using HLG and the BT.2020 color space.

HLG is compatible with existing 10-bit production workflows, according to BBC and NHK.

Linear light image data from a camera is mapped to the HLG OETF curve and to the wide color gamut color space defined by ITU BT.2020.

The HLG signals can be seamlessly carried via satellite, cable, IP and other distribution methods.

HLG Playback

- Minimum signal interface: HDMI 1.4
- Playback color representation: ITU-R BT.2020
- Playback transfer function (EOTF): inverse OETF plus rendering intent gamma
- Metadata: None
- Playback bit depth: 10 bits

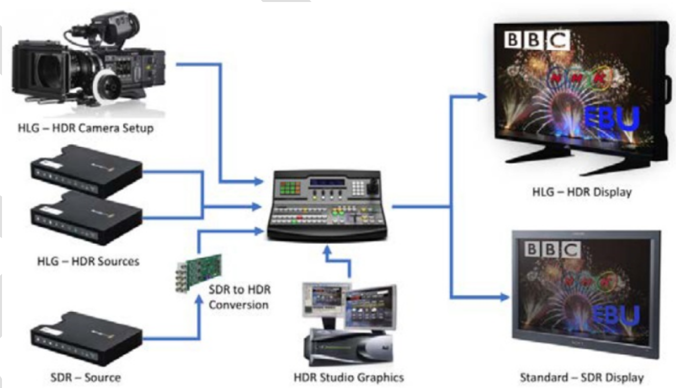

Figure 15: HLG encoded content can be played back on both HDR and SDR displays. Image credit: BBC

To receive an HLG broadcast, a TV needs to switch to high brightness mode and use the HLG EOTF, rather than a gamma power, BT.1886, or ST2084 EOTF.

The HLG system takes a relative luminance approach to its HDR transfer function, like BT.709, allowing each playback display to map a video signal's maximum code word to the peak luminance of that specific display, rather than to a specific luminance level.

Traditional SDR video systems have a capture OETF and a display EOTF that aren't exact inverses of each other, to provide a system gamma (OOTF) of approximately 1.1 to 1.2. This system gamma, referred to as the rendering intent, compensates for the effects of ambient light in the viewing environment. A byproduct of variable system gamma is that image saturation depends on the system gamma produced by each particular display. Higher system gamma creates a more saturated image.

In the HLG system, the system gamma is automatically adjusted in each playback display, based on its dynamic range and the ambient lighting surrounding the display. A playback display with very high dynamic range and low ambient surround might produce a system gamma as high as 1.6. A display with just better than SDR capability might produce a system gamma of only 1.3.

To avoid saturation differences with the differences in system gamma, an HLG-compliant display first inverts the capture OETF and calculates the relative Y value for each pixel. A rendering intent gamma is then developed for each pixel, based on the pixel's derived Y value, plus the display's black level, peak luminance, and surround light level. The rendering intent gamma is applied to each of the pixel's RGB components in unison.

This inclusion of each pixel's relative Y value in the rendering intent preserves the colorimetry of each pixel value despite different rendering intents (system gamma). This amounts to HLG displays doing a limited form of color volume mapping, despite metadata not being used by the system.

Unlike HDR systems that use the SMPTE ST2084 PQ curve, the HLG system is defined by its OETF. It was designed to have the OOTF (rendering intent) applied in the display (figure 16).

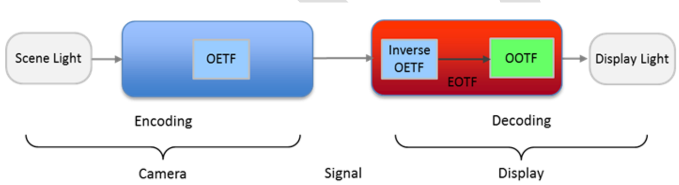

Figure 16: In an HLG system, the OOTF (rendering intent) is applied in the display. Image credit: ITU

HLG mastered content renders on both HDR and SDR TVs. When HLG HDR content is decoded and displayed on an SDR display, the image may look a bit different from a non-HLG HDR image, but it will be perceptibly HDR-looking according to BBC/NHK.

However, this backwards compatibility of HLG with SDR displays applies only to SDR displays implementing the BT.2020 color space.

System 4: Technicolor/Philips HDR Technology

Technicolor and Philips are combining their technologies to propose an HDR delivery system that is intended primarily to boost adoption of HDR by over-the-top (OTT) video-streaming services and pay-TV providers. Company representatives said that a finished system should be ready for demonstration at the NAB 2016 show.

The information available to date suggests that the Technicolor/Philips HDR Technology will be a single-stream, EOTF independent, open standard delivery mechanism, rather than a fully specified HDR format. A Technicolor pre-processor will take a 10-bit HDR video signal from a camera, convert the HDR to 8-bit SDR, and create a single SDR video stream that includes frame-by-frame HDR conversion metadata.

When played back by an SDR device, the device will simply ignore the extra metadata and play back the SDR video. When played back through a Technicolor/Philips HDR decoder to an HDR display, the metadata will allow the full HDR image to be reconstructed by the HDR display.

Technicolor has said that leading System-on-Chip (SoC) manufacturers are integrating Technicolor's HDR decoder technology into their offerings for Set Top Box (STB) and TVs.

Synthesized HDR

Some HDR TVs and LUT processors have been attempting to synthesize HDR content from legacy SDR HDTV content. With the demand for HDR content not yet being satisfied in the market, being able to create pseudo HDR content from existing SDR content is an attractive objective. However, you can't turn a peach pit back into a peach without knowing what fruit was taken away to get to the pit.

There are two basic methods of transporting HDR content to an HDR display.

You can: (send the entire peach)

1. Capture HDR content from a video camera.
2. Send a full range HDR signal to the display.
3. Display the original HDR content.

Or, you can: (reconstruct the peach)

1. Capture HDR content from a video camera.
2. Grade the HDR content down to SDR levels while recording the grading changes that are made in each frame.
3. Send the SDR signal to the display along with the grading data (metadata).
4. Use the metadata to reverse the grading changes that were made in each frame to reconstruct the original HDR signal.
5. Display the reconstructed HDR content.

When systems attempt to create pseudo HDR content from existing SDR HDTV content, without HDR conversion metadata, there isn't any information on what the camera signal might have been before the content was graded down to SDR levels, or on what the creative intent would have been if an HDR grade had been created. Without metadata, a display or LUT box can only compress most of the SDR signal, leaving the brightest signal levels as prominent highlights.

This uninformed process can't differentiate bright pixels that should integrate with their surrounding pixels from bright pixels that should be isolated highlights. And, when an 8-bit SDR HDTV signal is stretched to HDR levels, image contouring (banding) will be created at some levels.

On a bright HDR display, the converted SDR signal may look like the familiar uncalibrated SDR torch mode, with brighter highlights and neon colors, but the picture certainly won't be HDR. The peach pit got bigger and more pitted, but it didn't get turned back into a peach.

Expanding the top 5% of the signal to create highlights is similar to the familiar Dynamic mode on existing TVs. It looks different than the original intent, but it's not usually visually appealing for long term viewing.

Also, a number of studios respect creative intent to the point that they don't plan on remastering existing content to HDR unless there is a member of the content's original creative team available to guide or approve the newly graded HDR content.

Automatic conversion of SDR to HDR by a TV or other device is somewhat similar to automatic conversions that have been done from 2D flat content to synthesized 3D stereoscopic content. Without a colorist or other creative guiding the conversion, the results are usually less than desirable.

Viewing Conditions

For SDR, lighting on the back wall surrounding the display has typically been specified to be no more than 10% of the luminance of the content APL. For HDR, the industry is considering 5 nits (cd/m2) to be a desirable surround luminance level (very dark).

The 0.0005 cd/m2 black level specified by CTA for OLED black level won't work well in a bright room or one with white walls, so the lower brightness of OLED may not be a benefit unless you have a very dark surround.

HDR Display Calibration

Color calibrating the new HDR TVs is more critical than ever to assure the highest possible image accuracy to the original creative intent. Calibrating the reference monitors used for evaluating and color grading HDR content is also more crucial now for the production and post-production industry.

With the ST2084 EOTF being the first absolute luminance EOTF and with HDR UHDTVs mapping the color volume of HDR-mastered content to each display's color volume, HDR calibration is a brand new paradigm compared to traditional calibration.

The PQ curve covers a much wider luminance range than HDTV and maps each signal value directly to the same absolute luminance level on every HDR display, unlike the traditional gamma curve, where a specific signal value produces a different luminance level on each different display, depending upon each display's peak luminance.

Calibrators will need to use proper tools, proper procedures, and calibrate to the new HDR and WCG standards. Calibration software needs to support the wider BT.2020 UHD color space and the new SMPTE ST2084 EOTF (PQ curve) for HDR.

Calibrators will also need a light meter that accurately reads the higher HDR luminance levels, such as the C6 HDR, and an HDR test pattern source that can generate the required test patterns and metadata to enable the appropriate HDR mode on the display under test.

CalMAN HDR Calibration

CalMAN display calibration software contains the tools for testing and calibrating the new HDR/WCG displays.

Dolby Vision

CalMAN provides a Dolby Vision test and calibration workflow that was developed in collaboration with Dolby engineers to ensure optimal results with Dolby Vision displays.

A review of the workflow reveals that Dolby Vision calibration is similar to and yet different than for existing SDTV and HDTV displays. The goal of legacy calibration has been to match a display's performance to industry standards (e.g. BT.709, BT.1886, etc.). However, Dolby Vision displays perform a real-time color volume mapping of HDR content to a display's programmed capabilities, its Golden Reference.

Due to the process in which content is mapped to a display's Golden Reference values, testing and calibration of a Dolby Vision display is focused on the display performing as closely as possible to its Golden Reference values. Compliance of a display to its Golden Reference values will insure accurate picture results after content is mapped to the display's programmed capabilities.

Currently, the only test pattern source capable of encoding the Dolby metadata is CalMAN's built in pattern window. The test pattern metadata conveys to the display the attributes of the virtual mastering display and content.

For each supported Dolby Vision display, the CalMAN workflow loads a set of Golden Reference test targets that define the display's expected measurement values. The defined test targets allow CalMAN to test whether a Dolby Vision display's content mapping and luminance mapping roll-off is functioning properly.

HDR10

CalMAN provides the ST2084 EOTF specified for HDR10-compatible displays. CalMAN also controls external pattern generators that now include ST2086 metadata with their video output signals.

CalMAN also allows us to select different mastering display capabilities to be conveyed in the metadata. This enables an HDR10 display to be tested with various mastering display conditions, to test the mapping performance of the display, based on the metadata.

Currently, the test pattern sources supported by CalMAN that are capable of encoding HDR10 test patterns are the Quantum Data 780 or 804a, the Astro 876 or 877, and the Murideo SIX-G generators.

HDR10 is not yet fully specified from end to end. It has a complete mastering spec, but the playback spec is not complete, as there is no standard for HDR10 color volume mapping on playback. This allows the white point and EOTF to be verified and calibrated, but the color gamut can't be calibrated, as there are no standardized targets.

HDR Mastering Displays

Testing or calibrating an HDR mastering display is a bit different than an HDR playback display. Because metadata is neither normally present nor required at the input to a mastering display and the displays are manually switched to the desired EOTF, white point and gamut modes, a special pattern generator is not required.

An HDR mastering display should be set to its ST2084 mode. There should be no luminance roll off on a mastering display. Each display simply hard clips at its peak luminance capability.

A mastering display will be calibrated to the D65 white point, or, in the case of an OLED display, to the OLED offset from the D65 point.

For the gamut target, there are two optional use cases being used. The display may be operated in its P3 gamut mode. In this case, the studio will convert the content to BT.2020 later in their workflow. CalMAN should be set to test and/or calibrate to the P3 gamut target.

Or, the display may be operated in its BT.2020 gamut mode. In this case, CalMAN should be set to test to the BT.2020 gamut target, expecting the display to clip at its native gamut limits.

A good practice would be to just use a 10% window size in all cases, as it is required for accurate OLED measurements.

Conclusion

We have attempted to bring some order to the information that is currently available on high dynamic range and wide color gamut as it is likely to exist in the UHDTV system. This situation is still changing, however. SpectraCal will continue to update this preliminary paper as additional information on proposed systems becomes available and as industry standards are more fully defined.

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Joel Barsotti is Head of Advanced Color Research at SpectraCal. He has been the primary architect of every version of CalMAN since version 4.0. Joel has designed several iterations of 3D LUT profiling code, each of which has significantly advanced the state of the art. His innovations include: CalMAN AutoCube technology, CalMAN Dynamic Profiling process, Dynamic Linearity Correction, Intelligent Resolution Profiling, Lightning LUT, 3D LUT Retargeting, the adaptation of volumetric interpolation to color science, grayscale priority interpolation, and grayscale tint reduction, making CalMAN one of the most sophisticated color management packages available.

About SpectraCal

SpectraCal specializes in the tools and training necessary to achieve images representative of the content creator's intent for environments from low to high ambient light while achieving the colorimetry, contrast, and dynamic range necessary for the image to have the proper impact on the viewer.

SpectraCal CalMAN software was developed to support the display calibrator in the step by step process of screen optimization. The foundation of screen optimization through display calibration is to understand the elements in a display that require adjustment and how each element inter-relates to the others. From its inception, CalMAN has earned rave reviews and has become the preeminent display calibration software package on the market, compatible with virtually all color meters available today. As display technology evolves, CalMAN will continue to provide the first choice for display calibration solutions.

More Information

For more information on CalMAN professional quality solutions for your displays:

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