HDR SYSTEM README

22 Aug 2015

ASC Technology Committee, ASC UHD Committee

Introduction

With the emergence of consumer display products with a range of gamut, dynamic range and signal processing capabilities, it is apparent that mastering content to display the image we want the viewer to see brings challenges that cannot be addressed with legacy mastering and signal formats. Standards have been created over decades that specified how to deliver content to consumer displays that had capabilities defined by physical and electrical properties as well as cost. The last decade has brought new device technologies to consumers with capabilities beyond what is supported in the available signal format (Rec. 709). There now are numerous standards activities actively seeking to address gamut, frame rate, dynamic range, compression and so on. New specifications will address the signal format improvements necessary to take advantage of display capabilities, but perhaps an equally important challenge is how to master content for these new specifications. This paper discusses a practical approach for supporting a range of displays while reducing the burden that would otherwise come from having to create a master for each (e.g. OLED, LCD, projector)

Single Master HDR

It is believed by our group that it possible to have a single mastered appearance for High Dynamic Range (HDR), and thus a single master. It is recognized that there will be differences in low range and high range brightness/luminance and color gamuts in receiving displays and projectors. Despite these differences, it seems possible to create a single master containing the aesthetic intent, and convey a large portion of that mastered intent to every properly-calibrated display.

A key factor is the division of calibration and aesthetic adjustment. Calibration should rely on spectral radiometers, such that the entire end-to-end production chain (from camera to final viewer) can lock down colors (as chromaticities and associated spectra).

To accomplish this, it is essential that displays have a ‘mode’ where radiometric performance is known for a given signal stimulus. This has not been possible in consumer discrete pixel (flat panel) based displays and the CE industry recognizes this as a problem when dynamic range and gamut space is increased beyond typical Rec709 8bpp. There are separate activities and solutions being proposed for this issue.

It is realized that aesthetic appearance adjustment is required in many places in the production and distribution chain. It is recommended that each such stage of aesthetic adjustment should be a quantifiable delta from the radiometric calibration, such that its nature, purpose, and behavior, can be easily understood.

In this way, we believe that a Single Master HDR architecture is feasible, and that it should be top priority going forward.

'HDR System' Intended Range, Gamut, and Purpose

The HDR System is a test and exploration code suite intended to directly address aesthetic and technical issues. The initial aim is to gain aesthetic control over HDR masters, and provide tools to preserve the HDR image appearance over a population of displays having varying capabilities. The initial intended brightness range spans 200nits to 1000nits. Explorations below 200nits are of interest and known to be particularly important to other industries such as live broadcast, but felt to be challenging at this stage. Explorations above 1000nits are also of interest, but the tools to explore this range are not readily available. There is some concern that such high brightnesses creates potential for viewing discomfort depending on viewer adaptation to ambient lighting conditions. Both higher and lower brightness extensions can be explored in the future when/if mastery has been gained over the 200-1000nit range.

In a similar way, the initial HDR System gamut described here is self limited to P3 color primaries (the DCinema "minimum color gamut").

It is felt that by limiting range and gamut that the likelihood of validating the recommended solution is greatly improved.

Despite these current limitations (for practicality and expedience), the HDR System is not limited technically in gamut nor range by its present architecture.

Location of the HDR Master

In the HDR System, the 'HDR master' resides prior to the rgb-ratio-preserving rendering "nugget" (further defined below). The HDR master is logically scene-light-referred, even if graded and aesthetically adjusted. The HDR System ACES-RGB exr example files (see HDR System Content below) can be used directly at this location, without any adjustment, to yield a high quality appearance on supported display types. The choice of a scene-light-referred master is an open topic, and it is possible for the output of the rendering nugget to be used as the HDR master. The function of the rendering nugget is to apply the "system gamma boost" that is typical in imaging systems (including film). It is felt that such a system gamma boost is not as well understood for HDR as is the meaning and integrity of scene-referred light. Essentially any camera that can output ACES-rgb exr files is directly providing scene-referred light (usually with substantial dynamic range). This provides a direct connection to radiometric principles, which are the basis of this HDR system.

Display-type masters, such as Rec709 gamma 2.4, P3 with PQ_transfer function and similar, are display-type specific, and are thus not by nature display-type independent. The HDR System Master can be used with range pre-limited masters and does not by its architecture have dynamic range requirements in its architectural design. Tools for transforming display-type masters into the HDR System Master are provided (the inversion tool), but such masters are by nature limited to the source display-type's range and gamut. Further, the inversion tool is highly experimental, and such inversion may not have the potential to become a trusted HDR_System tool.

It is worth noting that the example scenes shown below have colors well outside of P3 gamut and thus may be useful for testing and evaluation of gamut-related issues. Such colors are preserved by the rendering nugget, but are lost with P3 or Rec709 display type outputs. The rendering nugget architecture is designed to be without range limitation in dynamic range or gamut. Thus, the stage is properly set for adding new device types beyond P3 gamut in the future (commented out matrices are provided to BT2020 gamut, for example).

Relationship to ACES

The Academy Color Encoding Space will be referred to herein as ACES RGB. It is supported as OpenExr half-float files (which pre-date ACES and IIF). The half-float was originally developed by NVidia and ILM, and has been available for over a decade in the OpenExr system (see openexr.com). ACES RGB uses CIE 1931 xy chromaticity-defined red green and blue primaries (with green and blue being "virtual" non-physical primaries).

Although the HDR System has its development history interlinked with ACES/IIF development, and owes many of its ideas to the work of ACES participants, the HDR System is not ACES, differing from ACES 1.0 in substantial ways. One of the principle differences between the HDR System and ACES is how they perform with respect to HDR rendering to devices. ACES 1.0 interoperability is available through display-type interoperability (e.g. P3_D60 gamma 2.6), as with any workflow process. However, no path currently exists (other than the untrusted experimental inversion process) to bring display-type signals into the HDR_System. Note that ACES 0.71 RRT/ODTs do have a similar appearance to some configurations of the HDR_System.

HDR System Primaries

The HDR System rendering nugget preserves R, G, and B relative ratios without requiring that RGB be ACES RGB primaries. Although the HDR System currently uses ACES RGB primaries for interoperation with ACES RGB exr files, the rendering nugget could just as easily use XYZ, BT2020 RGB linear, or other sets of primaries. Display-type transforms require specific knowledge of the color primaries for their color transform matrices. Optional Aesthetic Rendering Preambles have been "tuned" to work with ACES RGB. Such preambles would require the addition of to/from ACES RGB matrix transforms in order to function properly with alternate primaries (e.g. XYZ or BT2020 RGB). It is not recommended that P3 primaries be used in the rendering nugget, since crossing the P3 gamut boundary yields unwieldy negative numbers that are problematic with some display-type matrices. To summarize, the HDR System currently uses ACES RGB, but could be re-architected to use XYZ, BT2020 RGB linear, or other similar wide-gamut linear representations. With XYZ there should be no loss of any physically-realizable colors. With BT2020 RGB linear, the BT2020 gamut boundary remains, especially for cyan colors.

HDR System Whitepoint

It should be noted that ACES RGB has set R=G=B=D60 white. To many people, D60 is aesthetically preferable to D65. The HDR System is currently architected at the D60 whitepoint. However, use of D60 limits display-type top-end range of D65 system blue by 10% (much less than 10% in gamma 2.4 values, being about 4%). This should not be an issue in distributing to HDR displays having a D65 whitepoint. It is an issue when mastering to an HDR display in P3 or Rec709 having a D65 whitepoint, with the intent of using that master in the HDR System (via inversion) with the D60 whitepoint. In order to preserve the colors having bright blue in this scenario, care must be taken not to use the top 10% (linear light) of the blue range when mastering on D65 displays in this way since this would lead to clipping of blue if inverted for a D60 matrix. Mastering on D60 displays has no such limitation. Repurposing and interoperation are affected by this issue, but looking forward to a new HDR system, this should not be an issue (since viable HDR mastering displays will all support D60). The luminance reduction from a D60 whitepoint for HDR is less than 1% (10% of the blue component of luminance) on D65 whitepoint HDR displays.

Note that the HDR System could be re-architected to R=G=B=D65 using ACES primary chromaticities, or BT2020 R=G=B=D65, or to X=Y=Z=E (chromaticity .3333 .3333), or other useful whitepoints. However, at present, it is felt best to retain the HDR System whitepoint of R=G=B=D60 using ACES RGB primaries.

It is worth noting that there is nothing within the HDR System itself that is limited by any whitepoint, since the HDR System processing is entirely floating point. However, any display-type transform, as just described, is affected.

There is an inherent tension between R=G=B maximum white and aesthetic white. As an example, consider the R=G=B=white as a calibration of the "minimum P3 gamut" for DCinema. This greenish whitepoint was chosen over nearby D60 and D61, despite many objections to the greenish offset. Despite assurances that this greenish whitepoint would not be a problem, in practice it has been continuously problematic, and remains so. Thus, the aesthetic white and the calibration R=G=B whitepoint are intertwined in practice, even if not in theory.

It is currently unclear whether laser primaries, or other narrow-spectrum primaries, are a significant consideration for the HDR System. If so, it should be noted that existing definitions of whitepoint, and most tools for measuring whitepoint, are not specified properly for calibration. Further, even if properly calibrated, narrow-spectrum primaries do not lend themselves to color appearance accuracy. It may be best to defer HDR System exploration of narrow-spectrum primary display types (although the HDR System currently encompasses the gamut from a technical standpoint by using ACES RGB).

HDR Mastering Considerations

When mastering, the "colorfulness" of brighter portions of the scene, both saturated and desaturated, will be a function of absolute brightness (the "Hunt effect"). Many displays that are useful for HDR mastering, including the Dolby PRM in "dynamic" mode, and the Sony BVM-X300, will decrease overall brightness based upon the proportion of the screen area that is bright. The maximum brightness will be reduced for 100% screen area being white, vs. 1%, or 10% of the screen area being white. This reduction can be a factor of two or more. This may be aesthetically desirable, but the exact behavior must somehow be characterized. It may be necessary to check a mastering grade against a display-type that does not have the brightness reduction (such as a DLP projection on a very small area screen, thus being very bright). It also should be noted that dimmer displays may not have this large-bright-region darkening behavior. A 200nit display at the low end of the range may be sufficient to judge appearance for bright regions of the image.

It is also a good practice to check the color saturation appearance of bright screen regions on the dimmest display in the supported range. For example, a display set to 200nits might serve as such a reference display for bright-region "colorfulness" appearance. If the 200nit display has properly adjusted "colorfulness" for bright regions (both saturated and desaturated colorfulness), then brighter displays (e.g. 600nits) will appear too colorful (even if at the same measured chromaticity). This is the correct approach, although some discipline is required to work this way (which has no historical precedent). Some amount of bright region desaturation can be added to the bright display's bright regions for judging the appearance (e.g. using a low value of the `MDR_RADIOMETRIC_PROPORTION or HDR_RADIOMETRIC_PROPORTION`, as appropriate). The `MDR_RADIOMETRIC_PROPORTION or HDR_RADIOMETRIC_PROPORTION`, as appropriate, should be set to 1.0 when viewing, judging, and setting the 200nit bright region "colorfulness". When bright scene regions have proper appearance on the 200nit display, then the additional desaturation required for brighter displays will function properly.

To summarize, a calibrated display at the dim end of the HDR range (e.g. 200nits) should be available to serve as a reference for bright-scene-region "colorfulness" and appearance, using a `MDR_RADIOMETRIC_PROPORTION or HDR_RADIOMETRIC_PROPORTION,` as appropriate, set to 1.0 (thus yielding a radiometrically-calibrated HDR master). Brighter HDR displays can be desaturated from this bright region behavior (e.g. by reducing the radiometric proportion to a small value such as 0.1 or 0.2) for judging appearance. Some exploration of how best to do this will help work out the details.

Note that the principle of "colorfulness" requires that any single HDR master not attempt to achieve maximum color saturation of bright regions that may be possible on the brightest HDR display. The single HDR master concept requires that the bright region colorfulness be judged on the dimmest (e.g. 200nit) calibrated display, and desaturated as required to match equivalent "colorfulness" appearance on the brightest display (e.g. 1000nits), and proportionally at all brightnesses in between (e.g. 300-800nits).

Once confidence is gained in colorfulness appearance being identical between 200nits and 1000nits, it may be possible to grade exclusively to 1000nits, trusting that the lower values (e.g. 200nits) will have consistent colorfulness appearance (matching the colorfulness appearance at 1000nits). Note, however, that the gamut boundary should be checked for reasonableness with full radiometric preservation (at highest bright-end saturation). Such a reasonableness check can be done at full brightness. When mastering, the highest intended color saturation (for lowest brightness) should be in the master, and no architectural provision for boosting saturation should be utilized. This is required in order to preserve the reasonableness which has been established at the gamut boundary.

An HDR master using full "colorfulness" on the brightest HDR display will necessarily appear less colorful on dimmer displays, and thus is not consistent with the creation of a single HDR master. The current pactice when using the PQ transfer function is to desaturate for lower brightness displays when they receive higher PQ values. This is similarly inconsistent with achieving constant colorfulness appearance (which requires slight desaturation for the brightest displays, but no desaturation for displays of lower brightness).

As mentioned above, the variation of brightness with the bright amount of area on screen should also be taken into account (both in mastering and final presentation) when compensating for colorfulness.

HDR System Contents

Optional Available Test Scenes (4k ACES RGB exr half-float):

Note that these scenes have been pre-processed with noise reduction and sharpening using Image Essence LLC HDR preprocessing tools. JKP_Alps involved exposure and rgb gain balance and cross dissolves. ICAS scenes are not adjusted for exposure nor rgb balance.

• JKP_Alps, NikonD800E timelapse, and F55 (Courtesy of Joe Kane; DP: Florian Friedrich)

• ICAS Diner F65 (Courtesy of the ASC and Revelation Entertainment; DPs: Bob Primes ASC, Bruce Logan ASC). Terms and availability are still being worked out. Talk to Don Eklund or Curtis Clark ASC.

• ICAS Night F65 (Courtesy of the ASC and Revelation Entertainment; DPs: Fred Goodich ASC, Nancy Schreiber ASC). Terms and availability are still being worked out. Talk to Don Eklund or Curtis Clark ASC.

There is discussion about obtaining or creating additional scenes.

Code Modules:

• HDR_CPU.cpp: file-in/file-out code. Input files are exr half-float ACES RGB. Output files are exr or dpx, either with display-ready values. OpenExr must be installed to build. This code is casually supported (no guarantees) by Gary Demos. This code is an example only (i.e. use at your own risk, do not use for production, do not put this code into any products).

• HDR_CPU_INVERSE.cpp: file-in/file-out code. Input files are dpx display-ready values. Output files are exr half-float ACES RGB. This inversion code is experimental and unsupported (i.e. use at your own risk, do not use for production, do not put this code into any products).

• HDR_LMT.cpp: file-in/file-out code. Input and output files are exr half-float ACES RGB. The LMT selection in hdr_macros.h is applied. The resulting exr files will have the selected LMT appearance present when further seen through the rendering nugget (no additional LMT).

• hdr_macros.h: Contains macros to process the rendering nugget and MDR Rec709 or HDR P3_D60. This file can be optionally included by OpenCL at runtime to process in the GPU (see next), or included in the .cpp files above during compile. The rendering nugget and MDR/HDR display-type transform code is casually supported (no guarantees) by Gary Demos. All aesthetic rendering preambles and interaction code is unsupported. This code is an example only (i.e. use at your own risk, do not use for production, do not put this code into any products).

• HDR_GPU_CL_GL_LINUX: Read exr half-float ACES RGB into memory, and display to the X11 screen using CL/GL interop. Binary-only optionally available on linux systems (requires also .cl file) in the GPU. Must be hand-installed by Gary Demos as a binary, source code not provided. The hand-install may not be successful on some linux and gpu configurations, no guarantee. Note, on NVidia GPU's, the cl file must continuously change to force re-interpret (stale cache workaround) of the hdr_macros.h file if making changes. This code is unsupported (i.e. use at your own risk, do not use for production, do not put this code into any products).

Header Information Disclaimer

No information is used in dpx nor exr headers beyond that sufficient to indicate resolution, pixel locations, and endian-ness. Such additional information is ignored when reading, and no attempt is made to place meaningful information into headers during writing. File types are implicit due to use context, but not due to any additional nor header information. See code for details with respect to dpx, or see OpenExr documentation with respect to exr header defaults (which are ignored, no reliance should be placed on any meaning within any OpenExr file header).

Use and Exploration of HDR System

Rendering Nugget

The purpose of the rendering nugget is to apply a "system gamma" while retaining the relative ratios of r, g, and b. By preserving the relative ratios, chromaticity is maintained (independently of how chromaticity is defined). The way that this is done is by utilizing a norm function of r, g, and b to create a single number that can be utilized to achieve the system gamma. The system gamma is not an exponent, but rather a curve function. It is commonly called a "tone curve", although the word "tone" isn't very descriptive. In motion picture film, there is a mid-brightness (gray) gamma boost, centered around the Laboratory Aim Density (LAD). LAD is defined as 18% grey in the scene, which maps to 10% transmittance (1.0 density) on the print film. This is the key design point for the tone curve, wherein .18 maps to .10. The mid-grey .10 will likely need to lift for higher brightness presentations. Thus, this mapping is not strict.

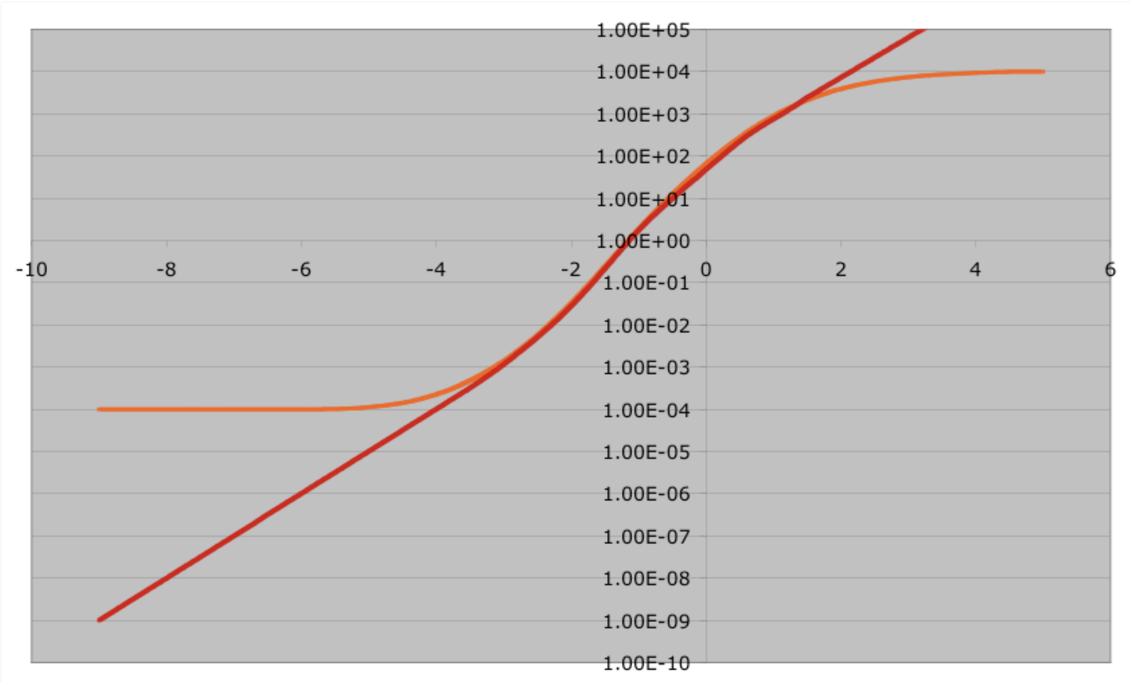
On film there is an "S-Curve" on both print and negative. Negative captures a broader dynamic range than is reproduced on the print, but the print magnifies the scene contrast via the system gamma. The scene-dark behavior of film is such that colors desaturate. This is undesirable as a forced system adjustment for HDR, but may be desirable as an aesthetic grading attribute. Due to this, the bottom part of the tone curve in the rendering nugget has S-Curve behavior to some degree, but does not desaturate. The slope flattens currently to .02, which goes through 0.0 on through to negative values with the same .02 slope. Negative values are a bit experimental, and are not smoothly continuous near zero (there are slope discontinuities in computation of the norm). RGB values are clipped up to zero after the rendering nugget process.

The top of the S-Curve on film is a desaturation as the print film approaches clear. If R, G, and B separately "ride" the S-Curve top brightness, then red will flatten out first, then green, and then blue. Thus, bright saturated reds will gradually go orange, then yellow, then white. Although this is common behavior, it is clearly not always desirable, and there is no direct analogy with HDR.

Thus, the top of the tone curve in the rendering nugget is slope 1.0, such that out_value = in_value for bright norm values. Thus, there is no S-Curve top whatsoever in the rendering nugget.

Using the norm lookup/interpolate through the tone curve, a value is obtained that is used in ratio to the norm to scale R, G, and B. Thus, this single scale factor will inherently preserve R, G, and B ratios (and thus chromaticities).

Here is a logarithmic (horizontal) vs linear(vertical) plot of the current HDR System tone curve (in red) vs. ACES 0.2's rrt tone curve (in orange).


1.00E+05
1.00E+04
1.00E+03
1.00E+02
1.00E+01
1.00E+00
1.00E-01
1.00E-02
1.00E-03
1.00E-04
1.00E-05
1.00E-06
1.00E-07
1.00E-08
1.00E-09
1.00E-10
-10
-8
-6
-4
-2
0
2
4
6

Aesthetic Rendering Preambles

The Aesthetic Rendering Preambles change appearance, and so by design do not preserve R, G, B relative ratios (and thus do not preserve chromaticity). These various optional preambles attempt to modify the look of the image to create a pleasing appearance. However, there are a number of configurations of these preambles to fit different scene types. There are also varying levels of complexity, as reflected in the names of the preambles. The mastered appearance in the HDR System is the output of any one (or none) of these preambles, but is logically prior to the rendering nugget.

The aesthetic rendering preambles are provided for testing, and are not supported, and not intended to be a fixed set of options in the HDR System. Note that color grading can be in series with these preambles, or use none of them. Note further that the preamble may precede as well as follow a grading adjustment (although the precede configuration is heretofore mostly untested). It is the net result, in the logical position prior to the rendering nugget, that represents the intended HDR appearance. This is the master which embodies the HDR intended appearance. The master further contains the intended presentation chromaticities at 200nits. The nugget is required, as is and appropriate display-type transform, for mastering to judge appearance. Limitations in the mastering display (or projector) must be considered, but there are several high quality mastering-grade displays available in the 600nit to 1000nit range.

The configurations are controlled by the following:

```
/* select one of the following: */
#define BYPASS_LMT /* This selects solely the rendering nugget.  For
radiometric processing, select this and set the HDR/MDR
RADIOMETRIC_PROPORTION to 1.0. */
//#define SIMPLE_LMT
//#define GAMMA_AND_MAT
//#define MODERATE_LMT
//#define FULL_LMT
//#define DOUBLE_LMT

/* the typical setting for scenes with prominent faces is to turn off
bright highlights, and turn on faces highlight desaturation */
/* the typical setting for scenes without prominent faces is to turn on
bright highlights, and turn off faces highlight desaturation */
#define BRIGHT_HIGHLIGHTS_IN_TONE_CURVE /* if defined: use bright
highlights, if not defined: use lower highlights */
//#define FACES_HIGHLIGHTS /* if defined: desaturate highlights for
faces, if not defined: more color saturation in bright colors (does not
apply to BYPASS_LMT nor GAMMA_AND_MAT) */
```

```
/* a radiometric proportion of 1.0 is fully RGB-relative-ratio
preserving, and thus is chromaticity preserving */
/* a radiometric proportion of 0.0 fully desaturates bright colors */
#define MDR_RADIOMETRIC_PROPORTION 1.0 /* Set to 1.0 for radiometric
MDR.  Darker displays can have more color saturation in bright colors
*/
#define HDR_RADIOMETRIC_PROPORTION 1.0 /* Set to 1.0 for radiometric
HDR.  Brighter displays appear more "colorful" (the Hunt effect), and
thus bright colors can be somewhat less saturated */
#define ROOM_BRIGHTENING 0.2 /* a room_brightening of 0.0 is for dark
surround viewing, 1.0 is for viewing in a bright room (applied only to
radiometric portion) */

//#define PQ_TRANSFER_FUNCTION /* use PQ transfer function HDR instead
of gamma exponent */

#ifdef PQ_TRANSFER_FUNCTION
 #define PQ_In_SCALE 1100.0 /* This should be set to the actual display
maximum, at (or a little below) display max clip.  Note the asymptote
will map to this value in the high limit */
#endif /* PQ_TRANSFER_FUNCTION */
```

The most useful configurations have been found to be:

1) The BYPASS_LMT shown above (rendering nugget, full rgb relative ratio preservation)
2) FULL_LMT aesthetic rendering preamble to boost color saturation (complex)
3) FULL_LMT plus turn off `BRIGHT_HIGHLIGHTS_IN_TONE_CURVE but enable FACES_HIGHLIGHTS.` This configuration is useful when faces are prominent in the scene.

A useful nomenclature for including in tool names set in these three configurations are “ngt” for nugget, nothing for full, and nobr_fc for full+no_bright_highlights+faces.


nugget, room=.2,hdr, radiometric=1.0
full, br, no_fc, room=.2, radiometric=1.0
full, nobr, fc, room=.2, radiometric=1.0
nugget, hdr, radiometric=0.0
full, br, nofc, radiometric=0.0
full, nobr, fc, radiometric=0.0

Display-Type Transforms

The HDR System supports two example display-type transforms. These are selected on the command line (display type 1 for MDR Rec709 300nits and display type 2 for HDR P3_D60 700nits). The processing is based upon an asymptote, and is algorithmically identical for MDR and HDR. An asymptote such as x/(1+x) can be seen to leave x unchanged for low values, to be at .5 when x=1, and gradually approach 1.0 as x goes to infinity. The parameters vary from MDR to HDR, providing a template suitable to match these parameters to the specific range. However, unaltered MDR and HDR can be varied with simple scaling within a range of about +- one stop (+- a factor of two) and still remain reasonable. Both MDR and HDR settings are relatively tolerant of such brightness scaling, yielding only modest appearance variation (despite such scaling).

The RGB-relative-ratio preserving process uses a norm and the asymptote. The blend factors `MDR_RADIOMETRIC_PROPORTION and HDR_RADIOMETRIC_PROPORTION` control how much the RGB values desaturate at the bright end, vs. the amount that the RGB relative ratios are preserved. At a setting of 0.0, the bright end of the asymptote desaturates fully (like film). When `MDR_RADIOMETRIC_PROPORTION and HDR_RADIOMETRIC_PROPORTION` are set to 1.0, the RGB relative ratios are fully preserved at all brightnesses. The blend factor allows some amount of each.

For system calibration, and for mastering, the `MDR_RADIOMETRIC_PROPORTION and HDR_RADIOMETRIC_PROPORTION` should be set to 1.0. See the note about HDR mastering above.

When using HDR_CPU_INVERSE, the `MDR_RADIOMETRIC_PROPORTION and HDR_RADIOMETRIC_PROPORTION` should also be set to 1.0.

Any blend value from 0.0 to 1.0 is useful, with values near 0.5 being the most useful to preserve bright color saturation (both saturated and desaturated color saturation). Typical behavior on bright displays is to desaturate fully (0.0 for the blend proportion).

Note that once bright color (both saturated and desaturated colors) is desaturated, it usually cannot be recovered. If it is the intent that bright color always be desaturated, then this should be done as an aesthetic adjustment and baked into the master (currently the master is prior to the rendering nugget). However, brighter displays (e.g. 1000nits) will appear more colorful (the "Hunt effect") than dimmer displays (e.g. 200nits) even with the same measured chromaticities. Thus, the `MDR_RADIOMETRIC_PROPORTION and HDR_RADIOMETRIC_PROPORTION` are inherently tied to the specific presentation display, and its settings (due to the resulting absolute brightness only being known locally at that display).

The current recommendation is to set the radiometric_proportion to 1.0 for grading at 200nits, and let the grading itself be the source of any bright region desaturation. For 1000nits, hopefully a fixed radiometric_proportion will be determined (e.g. 0.6 or whatever it ends up being) that matches appearance with 200nits with 1.0. If so, then grading can be done at 1000nits with that radiometric proportion (e.g. 0.6, or whatever it ends up being) with confidence that the colorfulness appearance at 200nits with 1.0 is visually equivalent. Note, however, that the gamut boundary should be examined for reasonableness at the full 1.0 saturation. Procedures for setting bright colorfulness should trust only full 1.0 saturation, but can allow reduction of bright color saturation on bright displays subsequently. Desaturation of bright colors will not disturb reasonableness of appearance, but increasing color saturation might result in unreasonable appearance at the gamut boundary.

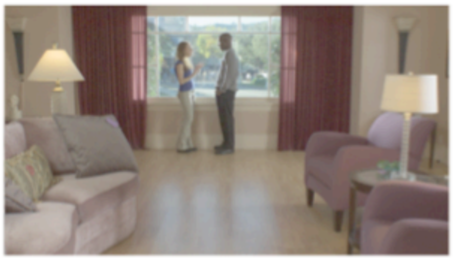
The other key parameter enabled by `RADIOMETRIC_ODTS` is the `ROOM_BRIGHTENING` parameter. This parameter is intended to adjust the image appearance for ambient room surround brightness. At 0.0, `ROOM_BRIGHTENING` is set for dark surround viewing. At 1.0, `ROOM_BRIGHTENING` is set for high room ambient light. Since `ROOM_BRIGHTENING` is only applied to the rgb-ratio preserving path, the rgb ratios are unaltered through this adjustment. Note that dark parts of a scene (including dark faces) appear darker in higher ambient surround vs dark surround. Maintaining appearance requires brightening those darker regions.

Since `ROOM_BRIGHTENING` is only applied to the rgb-ratio preserving section, its affect is scaled by the `MDR_RADIOMETRIC_PROPORTION and HDR_RADIOMETRIC_PROPORTION` . If these are 0.0, there will be no affect, and if they are 1.0, there will be a large affect. The intent is that some setting with `MDR_RADIOMETRIC_PROPORTION and HDR_RADIOMETRIC_PROPORTION` in the .1 to .5 range may be found that properly adjusts to viewing room ambient light. There may be some interaction between the radiometric_proportion and the room_brightening, related to the radiometric proportion being used for colorfulness appearance compensation (between 200nits and 1000nits). Experiments will likely show how this should vary.

As with colorfulness as a function of absolute brightness, the ambient surround is only knowable at each viewing display, and thus must be processed accordingly within each such display. An alternative is to send messages back upstream from a given display to convey this information to an upstream processor. However, the information needed for ambient and absolute brightness compensation only exists at the display itself.

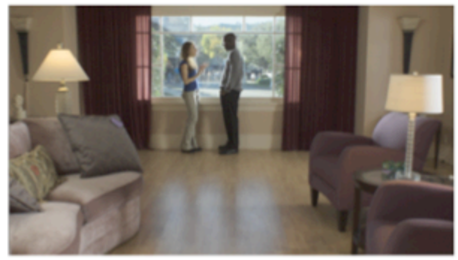
note: colors not accurately reproduced on slides (shown for approximate comparison)

Aesthetic Rendering Embodies Overall Gamma Boost



Scene-referred
Without Aesthetic Rendering
With P3 Gamma/Gamut
And Limited Display Range S-Curve

Similar to ACES P3_D60_ODT Only (no RRT)



Scene-referred
Through Faces Aesthetic Rendering
Then Via P3 Gamma/Gamut
and Limited Display Range S-Curve

Similar to ACES RRT+P3_D60_ODT

Faces Rendering
Minus Two Stops (Scene)

Faces Rendering
Nominal Exposure (Scene)

Faces Rendering
Plus Two Stops (Scene)

note: colors not accurately reproduced on slides (shown for approximate comparison)

Nugget (basic) Rendering
Nominal Exposure (Scene)

Nominal (non-face) Rendering
Nominal Exposure (Scene)

Alternate Display-Type Configurations

Comments in the code show potentially useful variations to the initial HDR and MDR display-type configurations. Example commented-out matrices are present for D60 to D65 conversion at P3 and Rec709. There are also conversion matrices to BT2020 at either D60 nor D65.

The gamma values are set at 2.4, but may be changed to any useful value (e.g. P3_D60 at gamma 2.6).

The flag `PQ_TRANSFER_FUNCTION` alternately selects the pq_ transfer function instead of gamma 2.4. Note that `PQ_TRANSFER_FUNCTION` is a bit of a mystery, with unusual operations such as an exponent of `78.84375`. The use of `PQ_TRANSFER_FUNCTION` is not recommended without expert advice.

The value `PQ_In_SCALE` should be set to correspond to the actual maximum of any given HDR display. Display behavior when receiving PQ transfer function data is sometimes to hard-clip at the display's maximum brightness (which should, but may not always in practice, correspond to the numerical equivalent in nits as represented by the PQ transfer function). The asymptotes in the display-type HDR transform will tend in the limit to the value of `PQ_In_SCALE`. Artifacts from a hard clip will be visible if `PQ_In_SCALE` is set higher than the display's clip point.

Some displays support some form of desaturating soft clip below `PQ_In_SCALE`. At present, it is not known what translation such soft-clip processing will yield between values in the PQ transfer function, and radiometric brightness and chromaticity emitted from the display screen. Note also that desaturation for values below PQ_In_SCALE operates in a manner opposite to colorfulness compensation (which desaturates brighter values, and desaturates less, or none, at lower brightnesses).

Note: Display-type transforms are currently implemented to use full range. If SMPTE range were to be utilized, it should be noted that negative numbers are potentially directly supportable, as are numbers above logical 1.0 (e.g. above 940 in 10bits). However, in such case care should be taken to ensure that such numbers have a clear meaning (via a corresponding precise specification of the numerical meaning of all values used).

Note: When using a gamma (vs pq_transfer function), the 2.22 gamma with linear black toe is sometimes used instead of gamma 2.4, although this distinction is confusing in BT1881. Reference monitors have long used 2.4, as measured by Adv Imaging with the BVM HD CRT.

Check List For HDR_CPU

• Check that the hdr_macros.h file is set up as intended. In particular check flags such as PQ_TRANSFER_FUNCTION, MDR_DISPLAY_GAMMA, HDR_DISPLAY_GAMMA, MDR_RADIOMETRIC_PROPORTION and/or HDR_RADIOMETRIC_PROPORTION, and ROOM_BRIGHTENING.

Also check that BYPASS_LMT is set, or one of the five optional preambles (which always implicitly include BYPASS_LMT) is set as intended.

If not using BYPASS_LMT or GAMMA_AND_MAT, BRIGHT_HIGHLIGHTS_IN_TONE_CURVE controls the top brightness gain (unity, vs less than unity) . The parameter FACES_HIGHLIGHTS also can enable highlight desaturation on bright face regions (e.g. forehead, nose, chin). Usually no bright highlights are used with faces highlights (nobr_fc).

• Compile HDR_CPU.cpp by using copy and paste of the build line at the beginning of the code. A gnu C++ compiler must be on the system, and OpenExr must be installed for this to build. There is no makefile.

• Make sure the input files are exr half-float in ACES RGB primaries (extension .exr)

• Select either dpx or exr half-float output (extensions .dpx or .exr)

• Use %07d in the name (for 7 digits with leading zeros) for the range of frames. If you are unfamiliar with this, ask a C programmer how this frame number structure is typically specified.

• Select the range of frames to process (start to end frame numbers)

• Select either 1 for MDR or 2 for HDR as the display-type

• Debug the path and file names if it doesn't start right up. There is little or no startup time needed. The processing is 16-way multithreaded, which may be problematic on processors having a small number of cores. Memory use is not excessive, but memory should have sufficient size for 4k workflows if working on 4k files (the test ACES files are all 4k).

• The output .exr or .dpx files have pixels ready to put up on the display_type specified.

Check List For HDR_LMT

• Check that the hdr_macros.h file is set up as intended. In particular select one of the five optional preambles is set as intended. BYPASS_LMT may not be selected (since it implies no LMT).

If not using `GAMMA_AND_MAT`, `BRIGHT_HIGHLIGHTS_IN_TONE_CURVE` controls the top brightness gain (unity, vs less than unity) . The parameter `FACES_HIGHLIGHTS` also can enable highlight desaturation on bright face regions (e.g. forehead, nose, chin). Usually no bright highlights are used with faces highlights (nobr_fc).

• Compile HDR_LMT.cpp by using copy and paste of the build line at the beginning of the code. A gnu C++ compiler must be on the system, and OpenExr must be installed for this to build. There is no makefile.

• Make sure the input files are exr half-float in ACES RGB primaries (extension .exr)

• Output files must be exr half-float (extension .exr)

• Use %07d in the name (for 7 digits with leading zeros) for the range of frames. If you are unfamiliar with this, ask a C programmer how this frame number structure is typically specified.

• Select the range of frames to process (start to end frame numbers)

• Debug the path and file names if it doesn't start right up. There is little or no startup time needed. The processing is 16-way multithreaded, which may be problematic on processors having a small number of cores. Memory use is not excessive, but memory should have sufficient size for 4k workflows if working on 4k files (the test ACES files are all 4k).

• The output .exr files have pixels (with LMT applied) for use as input to the rendering nugget (or even possibly input to grading, but then through the rendering nugget).

Use and Exploration of the HDR_CPU_INVERSE

NOTE: The CPU Inverse is experimental and completely unsupported. It is meant to serve only as a possible example, and to enable testing by providing some potentially useful interoperability at the current stage. The use of any dpx input to HDR_CPU_INVERSE will be limited in gamut, dynamic range, and bit depth due to current practice limitations. These limitations will be present in the ACES RGB exr file that results (and may not have acceptable appearance).

The HDR_CPU_INVERSE program is a fairly exotic and experimental piece of code. It operates by scattering random ACES RGB values forward through the rendering nugget and display-type transform. The resulting values then form an inverse map with holes in it. An ad-hoc algorithm is used to sweep paths of hole-filling using neighbors (especially darker neighbors). Although the result of this is a fully populated 3-Dimensional inverse lookup table (dpx to exr), there is no guarantee that the values at the bright, dark, and gamut extremes of this table are reasonable. In general there will be hard-clipping of all of these. Whether the limitations are acceptable is dependent upon the use case (i.e. dependent upon the contents of the images being processed).

Using the JKP test charts that cover full saturation, it has been experimentally found (for HDR P3_D60 display-type) that reasonable behavior falls under 1014/1023. Because of this, currently all dpx input values are hard-clipped to 1014 maximum. It has also been experimentally found that the brightest pure colors require some desaturation. This is due to the ACES to P3_D60 diagonal matrix terms in the HDR display-type transform. The amount of bright red desaturation required is substantial. The desaturation is achieved by adding some green and blue for large pure red. The desaturation required for other saturated colors is small (but necessary). Note that this desaturation is proportional to the magnitude, such that there is no desaturation at low values of pure colors.

The lookup table is 256 cubed (8bits RGB being 24bits of table). The low order 2bits of the 10-bit dpx RGB values are interpolated. Note that such interpolation could be extended usefully to higher bit-depths, although table accuracy limitations and noise-like properties may not warrant such extension.

Note that this algorithmic method does not care what configuration the rendering nugget, optional preambles, or display-type parameters are set. However, only one configuration of some of the parameters is the intended use. Parameters which may be varied and yet still remain within the intended uses include `PQ_TRANSFER_FUNCTION` , gamma value, and colors space matrix (e.g. D60 or D65, Rec709, P3, BT2020).

The parameters which are not intended to vary are mandatory use of `BYPASS_LMT` (thus RGB relative ratio preservation), `MDR_RADIOMETRIC_PROPORTION` or `HDR_RADIOMETRIC_PROPORTION` (as appropriate) set to 1.0 (again RGB relative ratio preservation). The `ROOM_BRIGHTENING` parameter may be set to any useful value, corresponding to the viewing surround used to create the image being inverted (e.g. 1.0 if mastered in bright surround, 0.0 if mastered in dark surround, or perhaps 0.2 or 0.3 for 8nit surround).

With these settings, the RGB relative ratios, and thus chromaticities are preserved through the inversion process. Thus, the chromaticities of the resulting ACES RGB are identical to the chromaticities of the dpx file that was thus inverted (assuming the parameters matched its colors space and gamma parameters).

The intention is that bright color desaturation, and room brightening, should be applied in subsequent display presentation via a subsequent forward rendering nugget and device-type transform. The device-type transform might use a possible different setting of `ROOM_BRIGHTENING` if viewed in a bright (or dim) room. It might use a different setting for MDR_RADIOMETRIC_PROPORTION or HDR_RADIOMETRIC_PROPORTION (as appropriate).

Another way to think about this is that all bright color saturation in the inverted source is preserved, whether or not it is intended to be desaturated. If the intent is to desaturate it further, then this is easily done. If not, then the bright color desaturation already present in the inversion source file will be exactly preserved.

Once the inverted ACES RGB source has been obtained via inversion, then other display-type transforms can be used. For example, a P3_D60 pq_transfer function HDR dpx source can be inverted into ACES RGB. That ACES RGB can use a different display-type transform to yield Rec709 D65 at 300nits (MDR) at gamma 2.4.

Note that dpx files having R=G=B=D65 will be converted via the device-type forward matrix to invert back into ACES R=G=B=D60. Thus, interoperation between D60 and D65 is a matter of which matrix is used in the display-type transform both for inversion and for subsequent presentation. Of course, the issues described above concerning the top 10% of blue (1% of luminance) remain.

Checklist for HDR_CPU_INVERSE

• Know what colorspace and gamma is used in the dpx file to be inverted into ACES RGB. Also know whether the file is HDR or MDR.

• Check that the hdr_macros.h file is set up to match. In particular check flags `PQ_TRANSFER_FUNCTION, MDR_DISPLAY_GAMMA, HDR_DISPLAY_GAMMA (if not PQ_TRANSFER_FUNCTION and HDR)`. Use the appropriate matrix if D65. Default matrices are D60 (including MDR rec709).

• Check that the hdr_macros.h file is set up as required for inversion. In particular check that `MDR_RADIOMETRIC_PROPORTION and/or HDR_RADIOMETRIC_PROPORTION (as appropriate) is set at 1.0`, and `ROOM_BRIGHTENING` is set to the surround level used during mastering (e.g. 0.0 mastered images created in dark surround).

• Also check that `BYPASS_LMT` is set.

• Compile HDR_CPU_INVERSE.cpp using by copy and paste of the build line at the beginning of the code. A gnu C++ compiler must be on the system, and OpenExr must be installed for this to build. There is no makefile.

• Invoke the command line using HDR or MDR to match the dynamic range of the input dpx file.

• Make sure the input files are dpx 10-bit rgb files in the appropriate primaries (Rec709, BT2020, and or P3 in D60 or D65 whitepoints current specified or available in commented matrices). Input file extension .dpx.

• Select exr half-float output files (extension .exr). These will be ACES RGB files with R=G=B=D60. These files could be considered as "scene referred", but clearly they are only indirectly so.

• Use %07d in the name (for 7 digits with leading zeros) for the range of frames. If you are unfamiliar with this, ask a C programmer how this frame number structure is typically specified.

• Select the range of frames to process (start to end frame numbers)

• This code is not multi-threaded since atomic operations that would be needed are not available in pthreads. Memory use is not excessive, but memory should have sufficient size for 4k workflows if working on 4k files (the test ACES files are all 4k). There is a long-duration computation before frames are processed, wherein the inverse is populated by the random number process. The process is set at 32 batches, but 128batches may be needed to best fill extremes of bright, dark, and saturated colors. Computation may be several minutes for 32 batches, and four times as long for 128 batches.

• The output .exr files have pixels in ACES RGB. These can be used as input files identically to the uses that ICAS and JKP Alps scenes are used as input to HDR_CPU (or HDR_GPU_CL_GL), set as BYPASS_LMT. The display-type configuration of HDR or MDR may be used on such additional forward processing, with any parameter altered as appropriate. In other words, interoperability has been achieved across whitepoints, gammas, pq_transfer function, Rec709, P3, and MDR and HDR ranges.

Color Grading Using a 3DLUT

Using private tools, Gary Demos, working with Peter Postma, can now build 3DLUT configurations for the Baselight. Although this is still in initial testing, these 3DLUTs seem to be working. There have been twenty such 3D LUT configurations prepared thus far, with about half of them having been explored thus far. These come in the following groupings:

• 101-cube, 255-cube

• P3_D60_full_range gamma 2.6 (for Dolby-PRM), gamma 2.4 (for BVM-X300)

• simple_preamble_nobr_fc_norad, simple_preamble_br_nofc_rad

• full_preamble_nobr_fc_norad, full_preamble_br_nofc_rad

• nugget_rad

Note that 101-cubed 3D LUTs do not provide sufficient precision for HDR, but may be useful in experimentation, since they load fairly quickly. Actual grading should utilize the 255-cube configurations. Two of these can be loaded simultaneously.

There is a floating-point 1D shaper pre-lut which maps 0.0 to 64.0 into the 0.0 to 1.0 range, using a square root function (prepared by Peter Postma).

The 3D LUTs in 255-cube size are several hundred megabytes each.

Note that other configurations of preambles, the nugget, and display-type transforms are straightforward, and fairly quick to build. However, at present the tool for building 3D LUTs is private, and not currently part of the HDR_System toolkit. However, the hdr_macros.h file from the HDR_SYSTEM tools, and its settings, is used to create the 3DLUT files.

The 3D LUT files for the baselight from the HDR_System are available from Peter Postma of Baselight. production. The 3D LUTs are casually supported (no guarantees) by Gary Demos. The 3D LUTs are an example only (i.e. use at your own risk, do not use for production, do not put this code into any products).

Summary

It is hoped that these relatively simple code modules (the inverse excepted) form the basic tools that could be leveraged to achieve the single master goal for an HDR system. This is certainly early work on this topic, but the hope is that we can build on this initial set of tools and refine them to the level required.

Clearly many parts of the HDR image chain will need active participants. We thus seek additional contributors, to help with the testing, evaluation, and refinement of the HDR System.

GOOD LUCK!

Contact:
Gary Demos
Image Essence LLC
Chair of Adv Imaging, ASC Technology Committee
garyd@alumni.caltech.edu
(310) 383 2201 cellphone

Patent and Copyright Disclaimer

Appendix

Subject: HDR System Future Work

A number of areas require refinement and further exploration in the HDR_System toolkit (aka gd10). The goal of this work is to provide the technical infrastructural tools needed to support the concept of a single-HDR-master.

The HDR_System toolkit is built upon an RGB-ratio-preserving rendering "nugget" which uses a "tone-curve" (aka system gamma boost) curve based upon LAD (laboratory aim density in film). The curve is extended at high brightness with a unity slope, making the rendering nugget tone curve future-proof with respect to brightness range.

There are a number of available "aesthetic rendering preambles" in the "look modification transform" position immediately prior to the rendering nugget. These apply an aesthetic appearance adjustment having increased color saturation. The reason that there are a number of these (five) is that no one-size-fits-all that is appropriate for every scene. There is also a great deal of difference in the level of complexity of these preambles, with some being quite simple, and others being quite complex. It is also a time of exploration, especially for HDR.

Initial testing of the HDR_System has gone well, such that it is appropriate to look toward its refinement.

The following is a list outlining possible HDR_System work:

• The yellow-biased norm could use further scrutiny

• The norm's behavior near zero, and going negative, was never worked out

• Negative number behavior at all points in the processing pipeline needs further scrutiny. The meaning and use of negative numbers has never (yet) been fully understood. The rendering nugget passes negative numbers (at a low slope). However, the aesthetic rendering lmt ("look modification transform") preambles clip negative values up to zero. The simpler preambles, however, could be modified to process negative values (e.g. "gamma_and_mat_lmt"). The display-type transforms (MDR and HDR in various matrix primary, room ambient, radiometric proportion, and transfer function configurations) currently only partially retain negative intermediate terms, and the configurations hard-clip up to zero at key points. This negative display-type transfer processing behavior would benefit from analysis, and possibly additional handling of negative values during processing. A mapping to SMPTE reduced range might be considered, although the handling of values below 16/1023 and above 940/1023 has never been defined (except for xvYCC). Calibration often benefits from the below-zero values in the SMPTE color bars and other calibration charts, which below-zero swatches can be represented as negative values in floating point. Note that moving some of the computation into processing within the display changes the considerations with respect to preservation and use of negative numbers (for calibration and for other purposes).

• Matrices often have negative terms, including in some of the aesthetic rendering preamble lmt's, as well as in all display-type transforms. Applying a negative R, G, B value to a negative matrix term "folds over" into an artifact (often highly visible, especially in dark regions of the scene). Special matrix handling of negative matrix terms is needed for any processing involving negative R, G, or B values. Note that a hard clip up to zero is the simplest handling of such negative terms times negative values. However, soft clipping is probably preferable, if it can be worked out. Note also that a matrix having negative terms, even if R, G, and B are all positive, can result in transformed R, G, and/or B values which are negative. Thus, negative matrix terms must be scrutinized not only for negative inputs, but for negative row product sum outputs.

• The spline "tone curve" used by the rendering nugget could use some refinement. The slope match point slightly above zero matches to a straight line having slope .02 going through zero to negative values. The spline curve was matched in value and slope by adjusting "knot" values, but was never refined to full accuracy. Similarly, the top end is an extrapolation of top knot values, intended to have a unity slope with no offset such that output=input for high brightness values. The slope is close to 1.0, and the offset is close to zero, but the slope and offset have also not been refined to full accuracy.

• The "Full_lmt" preamble provides an appearance wherein grading yields an image similar to the camera original. However, the rendering nugget preserves chromaticity, but requires its input to have boosted color saturation (similar to grading through ACES 1.0, but different in appearance from ACES 1.0). It is not clear whether retaining the native camera appearance during grading (e.g. with the ICAS Lustre grade), vs. grading through the nugget, requiring increased color saturation vs the original (similar to the Baselight grade through ACES 1.0), is a better system architecture. The concept of applying the full_lmt prior to grading is also being considered. In such structure the grading is applied between the full_lmt and rendering nugget. The benefit of grading prior to the full_lmt, is that other lmt's are available, including no lmt, providing appearance alternatives.

```
                                             Master is Here
                                                  \/
Camera_ACES_RGB->Grading->Full_LMT->Radiometric Nugget->DisplayTransform
                        /\
      0.71 Grade "ACES-prime" was taken from Here
                        \/
Camera_ACES_RGB->Grading->0.71RRT->HDR_ODT
```

New untried configuration being considered:

```
                                             Master is Here
                                                  \/
Camera_ACES_RGB->Full_LMT->Grading->Radiometric Nugget->DisplayTransform
```

• The aesthetic rendering preambles could benefit from additional testing, and perhaps refinement. At present, the "full_lmt" is most similar to ACES 0.2x – 0.7x appearance. The use of preambles, vs. the use of the bare nugget, should be investigated further. Additional preambles, having different appearance characteristics, might be worth developing and testing.

• The mystery of the desaturated face appearance from the chromaticity-preserving rendering nugget has only been investigated cursorily. The use of a corresponding display-type chromaticity-preservation (via the radiometric_odts flag) seems to have helped reduce the magnitude of this problem. However, the problem is still present, at the level of a few percent. Given that CIE 1931's accuracy limits are also on the order of a few percent, one idea worth exploring is the intentional separation of the red and green primaries, as is common practice in camera (and film) native spectral sensing functions. Note also that "spectral color" (wherein R,Y,G,C,B,M, and W channels are spectrally processed instead of using CIE 1931 for all spectral ranges) has greatly reduced the desaturated appearance of the nugget. It doesn't seem right that chromaticity preservation using CIE 1931 appears desaturated on faces. Thus, this is worth substantial investigation. If such exploration were to be successful, the HDR_System would then appear correct at the input to the rendering nugget (as would be expected, but which is not currently the case unless an lmt such as the full_lmt is used between the camera-processing-software-output and the nugget input).

• The "radiometric_odts" construction, and the "radiometric_proportion" are new, and have been testing well. This has the benefit, combined with the radiometric rendering nugget, of being chromaticity-preserving for system and display calibration. However, there are fundamental issues with respect to bright color desaturation which suggest further investigation. Among these issues, is compensation for the Hunt effect where perceived colorfulness appearance is a function of absolute brightness at presentation. A current proposal is to grade for proper bright saturation level using a reference 200nit display. Higher brightness displays (up to 1000nits) would then be desaturated to match colorfulness appearance. It is hoped (yet to be verified) that the adjustment of the radiometric_proportion parameter between 200nits and 1000nits can be nailed down. If the radiometric_proportion parameter can be nailed down, then all grading can occur at 1000nits (or anywhere between 200nits and 1000nits), since the proper setting of this value for constant colorfulness will have been determined over this range. The variation of maximum brightness as a function of bright area (seen in the Dolby PRM, the Sony BVM-X300, and other reference displays) may need to be considered and become a parameter applied to setting the radiometric proportion during grading (or any presentation). The goal is simple, constant colorfulness appearance over 200nits to 1000nits on all displays, matching the appearance on the master, combined with radiometric_proportion being fixed always at 1.0 (fully radiometric) when viewing at 200nits.

• The MDR (medium dynamic range) and HDR (high dynamic range) display-type settings have proven broadly useful, and have been testing well. However, since MDR and HDR consist of different parameters to a common algorithm, some further investigation (and possibly refinement) of these parameters may be warranted.

• The "room_ambient" parameter in the radiometric portion of the display-type transform is new. It has been testing well thus far, but there has only been somewhat limited testing. It is also not clear whether this adjustment belongs with the also-radiometric rendering nugget as part of the end-to-end system gamma boost, and thus perhaps not part (or perhaps not exclusively part) of the display-type transform.

• The norm used in the radiometric portion of the HDR and MDR display-type transforms has not been investigated. Note that this is not a yellow-biased norm, and thus differs in its behavior with respect to the brightness treatment of color compared to the rendering nugget's norm. The radiometric display-type transform would thus benefit from investigation of its radiometric display-type norm (perhaps with some comparison to the yellow-biased rendering nugget's norm).

• The relationship of the asymptote in the display-type transform to the PQ_transfer_function (when it is used) has yet to be figured out. It seems that this should be moved into the display electronics as a variable, which is fundamentally a different signal than is currently being used to convey the PQ_transfer_function. The exploration of desaturation within displays, in circumstances where they receive a PQ signal above their absolute brightness, is currently an open item. This open item is further inconsistent with the movement of the display-type asymptote's setting into display electronics. If the use of the PQ_transfer_function integer to carry HDR persists, then it may be worth considering whether an in-display asymptote application is feasible through some form of inversion and signal re-processing.

Note that desaturation for lower brightness displays is inconsistent with Hunt effect compensation (which would desaturate brighter displays, not less-bright ones).

• Colors beyond P3, conveyed with BT2020 primaries, have yet to be explored. Note that the blue primary in P3 is the same as in Rec709. However, alternatively, we may be wise to remain within the P3 gamut, where we have sufficient experience to give us confidence in our color appearance (as we extend it to HDR). Even the use of P3 is likely to harbor mysteries (compared to Rec709), especially in HDR.

• The current MDR and HDR transforms hard clip any of R, G, and B that go negative (by hard clipping up to zero). A soft clip may be needed for this. Note that this is a natural consequence of using ACES_RGB wide-gamut primaries, and then reducing the gamut to BT2020 or P3 (or Rec709). Any matrix which reduces gamut will have negative matrix terms. Such terms must be handle specially when the row sum goes negative, or if there are negative values or R, G, or B as input to the matrix. Currently the HDR and MDR transforms clip up to zero prior to the matrix. Such a prior-to-the-matrix clip up to zero also could benefit from a soft clip. Note that ACES R, G, and/or B values which go negative are non-physical, thus being an artifact. Such negative ACES RGB values are commonplace in simple IDT processing using a simple IDT matrix. This is because camera spectral sensing functions are not linearly transformable into CIE 1931 (and CIE 1931 is used for the definition of ACES RGB primary chromaticities). To summarize, care must be taken with a) negative R, G, or B values entering the matrix and seeing negative matrix terms, and b) R, G, and B primaries going negative due to negative matrix terms, and their causing the row product sums to go negative, indicating out-of-display-gamut. Right now these are all being handled using hard clips of negative R, G, and/or B values up to zero. Note that hard clips have slope discontinuities, and also may squash color and brightness detail beyond the clip point (saturated colors loose detail). Note that this issue is generic to any matrix-implemented gamut reduction, and is thus not specific to the HDR_System HDR nor MDR display-type transforms.

• The current MDR and HDR transforms have their first matrix term up near two for P3 and above two for Rec709 (coming from ACES_RGB). The first row has negative terms for green and blue. If green and/or blue are not large enough, the red row product sum result will exceed one. This is a type of out-of-gamut that extends beyond maximum brightness, even though the values of R, G, and B are limited by the asymptote processing to 1.0 prior to the matrix (or slightly above 1.0, depending on .9 scale factor compensation, or not, for Y, C, and M in the norm computation). The current HDR and MDR processing hard clips to 1.0 after the matrix, and then restores the R, G, and B relative ratios for the radiometric norm-driven portion of the computation. Hard clipping to 1.0 will lose detail in bright portions of the image, especially for saturated colors (most especially for saturated reds). The hard clip also causes a slope discontinuity. Some sort of soft clip for this is worth working on. Note that this type of out-of-gamut does not occur for brightness below 0.5, since the largest first matrix term of two does not go out of range for red values below 0.5. Similarly, norm compensation need not go above 1.0 if Y, C, and M maxima of 1.1 are considered, thus reducing by multiplying by around 0.9. Currently the 0.9 norm factor is not applied (but is present as a comment). This was due to the desire of some of our participants for images as bright as possible (related as well to the brightness of LAD mid-grey). It should further be noted that typical display maxima for R, G, and B (and other primaries such as W in LG and Y in Sharp) may not be limited by the 1.0 maximum of R, G, and B. Thus, if the HDR or MDR algorithms eventually move into display electronics, some of these maximum range issues may not exist (by giving the display ACES_RGB to process). Note that this issue is generic to any matrix-implemented gamut reduction, and is thus not specific to the HDR_System HDR nor MDR display-type transforms.