Exploring Workflows for Real-Time HDR-SDR Conversion

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Abstract. *Due to the growing demand for high quality imaging in the movie industry as well as in broadcasting environments, research on high dynamic range (HDR) technologies is enhanced more and more. The incentive for the great interest in HDR content is particularly based on properties such as natural reproducibility of a scene containing the approximate dynamic range of real-world brightness distribution, a broader color spectrum and a more intense spatial depth in the image. Especially in the broadcast-related scope there is still potential to further develop and improve HDR technology. As not every end user has an HDR-compatible device as of now, methods are needed to map high dynamic range content to standard dynamic range (SDR) including transfer function and color gamut. Considering usually demanded real-time HDR-SDR conversion workflows, conventional mappers often produce an unaesthetic and unnatural look due to color hue shifts, flat brightness distribution or unnatural looking skin tones, which causes loss of the creative intent of images especially but not only in context of intense lighting effects.*

On that account, the research team has set themselves the goal of analyzing existing mapping algorithms for a real-time broadcast use case in a show context. To properly test and apply the used algorithms on HDR video footage, a new dataset of HDR show content is produced. The insights of this comparison are depicted and explained.

Keywords. HDR, High Dynamic Range, PQ, SDR, Dynamic Range, Brightness, Live Broadcast Production, Television, Broadcast Engineering, Film, Motion Picture, HDR-SDR Conversion

I. Introduction

The demand for high quality content in the movie and broadcast industry is growing progressively and thus is the interest in developing high dynamic range (HDR) content [1].

Current trends in research and in motion picture imaging show that the popularity of HDR is constantly increasing and will be established more and more in the video and broadcast industry [2]. To provide both SDR- and HDR-based end user monitors with content, the industry is constrained to develop technologies to record the footage in HDR and convert it to high quality SDR using specific tone mapping processing. Tone mapping is a way of distributing the larger number of imageable brightness intensity levels (in HDR scope) of a scene to the more limited smaller number of display levels required to display the images on a standard dynamic range (SDR) monitor [3].

Tone mapping algorithms already exist in various designs, however, the results achieved by them have not been entirely satisfactory so far, especially in terms of broadcast environments. Challenges that occur repeatedly are for example clipping and loss of highlight, and shadow details when, for instance, highlights are compressed by knee operation [4]. These effects can potentially look unnatural or flat in the resulting image.

For example, the International Television Union (ITU) has formulated certain objectives that any quality tone mapper should possess, which include maintaining of shadow details, an appropriate expansion of mid-tones, expansion of highlights up to the peak display luminance, ensuring of only an appropriate adjustment of the chromatic content and preserving temporal stability [6]. There are two fundamentally different kinds of tone mapping procedures: static and dynamic tone mapping. With the former approach all tone mapping operators are set statically in advance. With the latter approach the image is adjusted frame by frame in real-time by modifying parameters, such as slope or knee [7].

In order to investigate in which areas different already existing tone mappers have their strengths and weaknesses and how “the optimal real-time tone mapper of the future” should function, several state-of-the-art and scientific tone mappers were implemented and examined, i. e., two exemplary mappings with a hardware device by AJA [8], the *NBCU LUT “PQ2SDR”* [9], the *ACES tone mapper* [10], the *ITU-R BT.2446-1* methods *A* and *C* [6], the *Reinhard-Devlin tone mapper* [11] and *Dolby Vision* [12]. ACES and

Dolby Vision were applied in DaVinci Resolve. The remaining tone mappers were implemented and applied in Python.

To apply the tone mappers to as diverse HDR show material as possible, already existing HDR images from the HdM HDR data set and the Hidden Gem Festival recording are used for the analysis, but also an additionally produced data set named "Video Disco"[1].

II. Methods

To be able to adequately compare these tone mappers with each other, they were applied to PQ material, since PQ (Perceptual Quantization) is a specified live broadcasting standard for HDR [3]. The major reasons for choosing PQ were that it is rated for up to 10,000 cd/m^2 peak display luminance and that the absolute correlation between code values and display luminances ensure exact reproduction reliability [3].

Acquisition

For the tone mapper comparison, a data set of HDR live broadcast material was required with well documented metadata in terms of scene linear light, subject distance, focal length, color space, transfer function.

The available footage of a similar HDR student production ("Hidden Gem Festival", 2017) was not sufficiently documented for this purpose and limited to 1000 cd/m^2 peak display luminance. Hence, the group decided to produce an additional show sequence with a starker black level, more highlights, and sufficient documentation.

The data set was mastered at 4,000 cd/m^2 display luminance, despite there not being any suitable reference monitor at the time to see the entire signal. This was decided purposefully to be able to use the material once brighter monitors become more widely available. The sequence was shot with an ARRI AMIRA and an ALEXA Mini LF camera.

From the resulting mentioned sources, 55 stills were exported to which the tone mappers were applied. As most real-time applications work with static mapping solutions, stills were found to be an adequate solution to compare the tone mappers in this paper. Hence, the two dynamic solutions have been limited to their spatially adaptive characteristics. Subsequently, these tone mappers were compared and analyzed.

Implementation & Analysis

To establish a comparable starting point for all tone mappers, they were programmed to process 10-bit PQ images in ITU-R BT.2020 color space[2] that are mastered to 4,000 cd/m^2. The outputs respectively are SDR images in ITU-R BT.709 domain[3]. Since some of the examined tone mappers do not include gamut mapping, an additional LUT for the color space transformation (ITU-R BT.2020 to ITU-R BT.709)

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[1] Available via https://www.hdm-stuttgart.de/vmlab/hdm-hdr-2023/

[2] ITU-R BT.2020 / Rec.2020 is a recommendation of the ITU, which defines specifications like resolutions, frame rates, color space or displayable colors for ultra-high-definition-video (UHD-TV). In comparison to Rec.709, which only covers 35,9% of the Rec.2020 color space, the color primaries of Rec.2020 are also used in its extension Rec.2100, which defines technical aspects for HDR-TV.

[3] Standard for digital high-definition-television and HD video in standard dynamic range (SDR). It's also a de facto standard for colors of digital standard-definition content with a vertical resolution of 576 (former PAL and SECAM-regions) or 480 (former NTSC-regions) lines.

was applied to these after the initial tone mapping process. This LUT provides a mapping optimized in IC_tC_p[4] to prevent the best color reproduction between both color spaces.

To analyze and evaluate the tone and gamut mapping process, a LUT test image [5] was integrated in each frame before HDR-SDR conversion as shown in Fig. 1. As the test pattern contains 33x33x33 combinations of RGB values between 0 and 1, it is possible to calculate a LUT that describes the differences between HDR source and SDR result. By analyzing these, the mapping characteristics become visible.

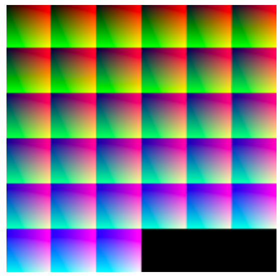

Figure 1: LUT test image

ITU-R BT.2446-1 Method A

The ITU-R Report BT.2446-1 [6] contains three methods for tone mapping and inverse tone mapping. In this paper, however, only method A and C will be examined as method B is not designed for conversion of HDR content with more than 291 cd/m^2 peak display luminance [6].

$$Y'_c = \begin{cases} 1.0770\, Y'_p & 0 \leq Y'_p \leq 0.7399 \\ -1.1510\, Y'^2_p + 2.7811\, Y'_p - 0.6302 & 0.7399 < Y'_p < 0 \\ 0.5000\, Y'_p + 0.5000 & 0.9909 \leq Y'_p \leq 1 \end{cases} \quad (1)$$

Method A is intended for various sources and its key feature is to produce a visual match with the HDR input. Step 1 of the tone mapping algorithm transforms the input signal to a perceptually linear space. Subsequently, in step 2 a knee function in the perceptual domain is applied considering the different luminance distributions within the image using case differentiation (Eq. 1). Step 3 converts the image back into the gamma domain [6].

The mapping is accomplished by using the HDR RGB signal as input signal, as well as the HDR luma signal. The output is an SDR signal specified in YC_bC_r space [6].

[4] IC_tC_p is a color representation for HDR and WCG moving images [22].

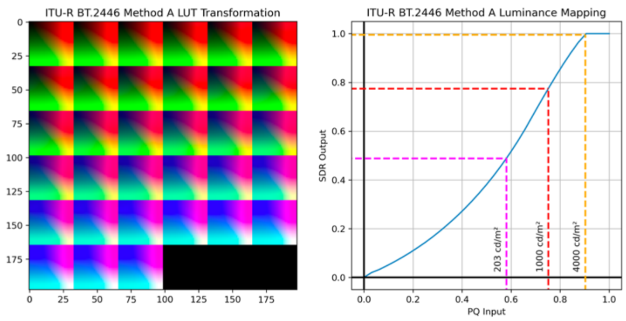

Figure 2: LUT image and transfer function of ITU-R BT.2446-1 method A

Regarding the luminance transfer function used in this static HDR-SDR conversion approach, all the available HDR image details are mapped into the SDR signal using an approximately linear approach. Analyzing the resulting test image (Fig. 2), nearly all the RGB combinations are transferred. Nevertheless, gamut mapping is applied, that is why the combinations are not identical in terms of color.

Since most of the signal information of an HDR image lies within the range between 0 and 203 cd/m^2, the most relevant image data is mapped to a comparatively low range within the SDR image which, e. g., causes quite dark images. For bright images that contain information around 1000 cd/m^2, this approach provides acceptable results due to the extensive highlight preservation.

ITU-R BT.2446-1 Method C

BT.2446 Method C is designed primarily for the live broadcast use case. Its main goal is to assure the optimal conversion of the image, using a parametric approach to map the image into the SDR [6]. The related tone mapping algorithm consists of a linear mapping function for the base image and a logarithmic function for the highlight sections of the image (Eq. 2).

$$Y_{SDR} = \begin{cases} k_1 * Y_{SDR} & Y_{HDR} < Y_{HDR,ip} \\ k_2 * \ln\left(\frac{Y_{HDR}}{Y_{HDR,ip}}\right) + k_4, & Y_{HDR} \geq Y_{HDR,ip} \end{cases} \qquad (2)$$

Parameters k_1 to k_4 describe the tone mapping properties and $Y_{HDR,ip}$ represents the knee point in the HDR signal which should be higher than the skin tone to maintain correct exposure [6].

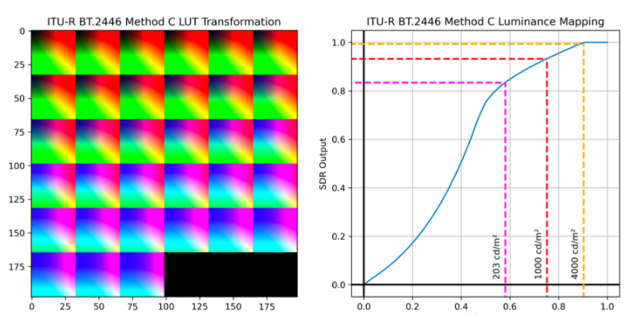

Figure 3: LUT image and transfer function of ITU-R BT.2446-1 Method C

Furthermore, it is possible to deduce a different set of parameter values for *k1* to *k4* according to the production intent [6]. In this research, HDR input mastered to 4,000 cd/m^2 was assumed. Analyzing the luminance mapping curve shown in Fig. 3, the base image of the HDR signal up to 203 cd/m^2 (HDR diffuse white) is mapped to more than 80 % of the SDR signal. While using an approximately linear HDR-SDR mapping between HDR black values and 58 % PQ level, a knee function with minimal exponential shape is applied to compress HDR levels up to 4,000 cd/m^2 display luminance into the upper SDR range

(Fig. 3). In terms of color, the applied gamut mapping causes saturated images transforming the entire BT.2020 color space into the more limited BT.709 container.

TV-Show Mapping Example

The FS-HDR from AJA is a device that allows real-time HDR/WCG[5] conversion with the Colorfront Engine Video Processing [8]. It is specifically designed to meet the needs of HDR broadcasting and deliver real time requirements such as low latency processing and color fidelity. This setting was used on a German UHD-HDR TV show.

In addition to the FS-HDR, an AJA Image Analyzer was applied to monitor the signal on its way to its destination.

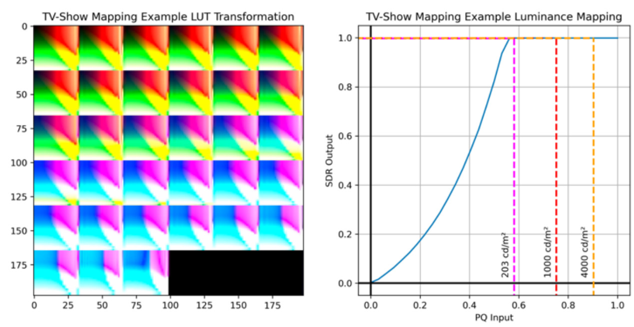

Figure 4: LUT image and transfer function of the TV-Show Mapping Example

FS-HDR Settings CF TV (adjusted Parameters only) Software-Version 4.1.1.6 Colorfront Transform Processing Version 170 Colorfront Engine Program Version 44646	
Transform	Colorfront Engine-TV
Conversion	PQ to SDR
Colorfront Engine	Adjust
Color Corrector	On
Master Lift	- 0.010
Master Gain	1.150
Saturation	0.800
Video Legalizer	YUV

Table 1: AJA FS-HDR - Adjusted Settings in the Colorfront TV Engine

One operating mode tested is Colorfront TV mode configured with settings depicted in Table 1. The customizable settings include both color and camera correction, as well as controls for knee point and knee pitch (for highlights and roll-off management), exposure, color temperature, and tint settings [7].

By transferring the HDR signal range of 0 to approximately 203 cd/m² into the full SDR range, this approach covers high quality transfer of the base image (Fig. 4). Highlights above HDR diffuse white are

[5] Wide Color Gamut

clipped to white in SDR as can be seen in the test pattern image. For dark to normal lighting this setting delivers an accurate representation, whereas as soon as bright lighting effects occur, clipping images are created. When using effects like star-filters, this setting, however, could achieve an equal visual appearance of the effect in comparison to HDR.

Subjectively Adjusted Hardware Tone Mapping

In Colorfront Live mode, parameters like HDR amount, ambient light compensation, HDR log look and SDR softness can be modified [8] and were set as shown in Table 2. The resulting luminance transfer function is shown in Figure 5. This setting is representative for a subjectively adjusted tone mapper. It was created by the authors based on their personal preferences for the data set used in this paper.

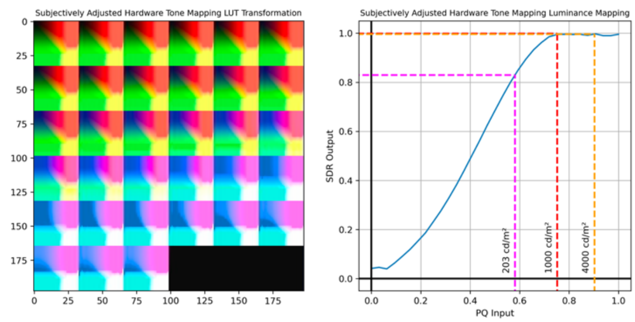

Figure 5: LUT image and transfer function of the Subjectively Adjusted Hardware Tone Mapping

FS-HDR Settings CF Live (adjusted Parameters only) Software-Version 4.1.1.6 Colorfront Transform Processing Version 170 Colorfront Engine Program Version 44646	
Transform	Colorfront Engine-Live
Dyn Range&Gamut IN	PQ BT.2020 1000 cd/m^2
Dyn Range&Gamut OUT	SDR BT.709 100 cd/m^2
Colorfront Engine	Adjust
HDR Amount	0.231
Amb Light Comp	- 0.092
HDR Log Look	0.465
SDR Softness	0.000
Master Lift	- 0.004
PQ Output Nit Level	1000
Video Legalizer	RGB

Table 2: AJA FS-HDR - Adjusted Settings in the Colorfront Live Engine

Comparing the levels of HDR diffuse white mapped into SDR, the resulting level is lower than in conventional mapping approaches which causes slightly darker skin tones (Fig. 5). The used black and white clipping potentially results in a more accurate contrast representation as well as in better highlight resolution because of broader availability of SDR code values for HDR data between 203 and 1,000 cd/m^2 display luminance.

5 NBCU PQ to SDR LUT

NBCUniversal has developed several tone mapping LUTs to enable single-stream production that feeds both HDR and SDR transmission simultaneously [20]. LUT No. 5 was especially developed for conversion between PQ and SDR content.

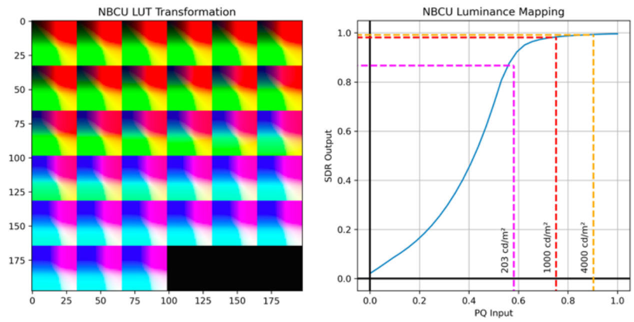

Figure 6: LUT image and transfer function of the 5 NBCU PQ2SDR LUT

Depicting a commonly used power shape in the lower part of the transfer curve, the NBCU LUT maps the base image parts into 90 % of the SDR signal range. Whilst using extreme highlight compression, it still maps HDR highlights up to 100 % PQ level into the SDR range (Fig. 6). The gamut mapping is similar to the Subjectively Adjusted Hardware Tone Mapping approach, but it causes an overall higher saturation. The steep curve between 40 % PQ (approximately 32 cd/m^2) and diffuse white at 203 cd/m^2 is notable compared to other approaches. This results in brighter skin tones.

SMPTE Standard ACES

The Academy Color Encoding Specification (ACES) specifies a digital color image encoding system that is standardized in SMPTE ST 2065-1 [10]. By providing open standards for maintaining consistent image fidelity in a production workflow, it aims to facilitate the complexity of different image capture devices and color management [21]. Simply put, within the ACES pipeline, images are transformed into the ACES color space using an IDT (Input Device Transform) and then transformed into the desired output space using an ODT (Output Device Transform). For this project, a PQ-to-ACES IDT followed by an ACES-to-Rec.709 ODT have been used [21].

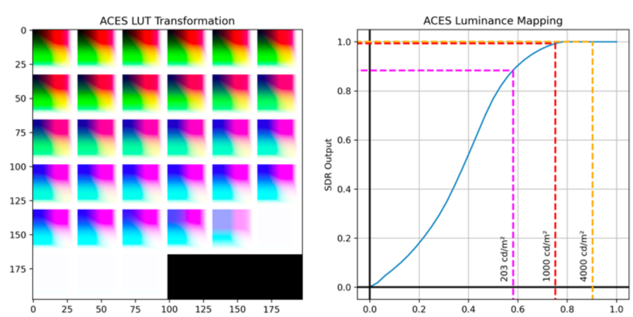

Figure 7: LUT image and transfer function of the ACES Tone Mapper

The ACES approach is similar to the previous methods, as it causes clipping of HDR highlights over 1,000 cd/m^2 and transfers the range up to HDR diffuse white into nearly 90 % SDR signal range. In terms of color space transformation, the approach causes drastically more gamut clipping than any other approaches (Fig. 7).

Reinhard-Devlin

This dynamic tone mapper is based on the assumption that HDR-SDR conversion is similar to the brightness adaptation of the human visual system. Contrast, overall intensity, color correction, and light adaptation can be parametrically adjusted [11].

To implement the algorithm, the Rec.709 luminance formula is applied (Eq. 3), then the average logarithmic luminance is calculated. With the use of the logarithmic minimum and maximum the key is determined whereupon the constant *m* (contrast) is computed (Eq. 4).

$$L = 0.2125 I_R + 0.7154 I_G + 0.0721 I_B \qquad (3)$$

$$m = 0.3 + 0.7k^{1.4} \qquad (4)$$

The contrast parameter is dependent on whether the image generally is high or low-key and the range of operation for the contrast is constrained to [0.3;1). For this application *m* initially was set to 1.

During set-up, the overall intensity of the image can be changed with a parameter. For most images, a range of [-8,8] causes useful values for said parameter [11].

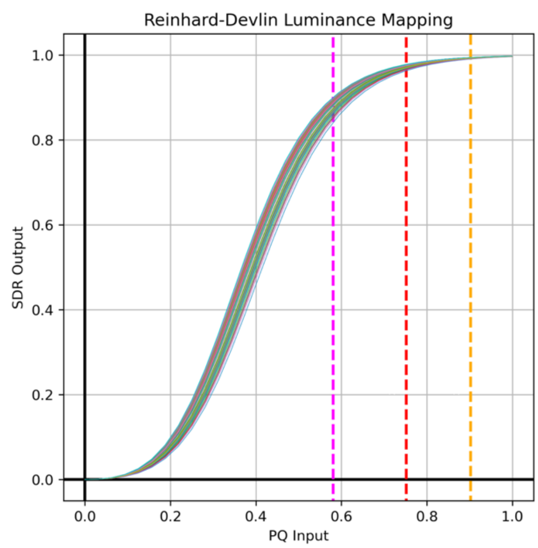

Figure 8: Transfer functions of the Reinhard-Devlin Tone Mapper

As one of the two dynamic methods evaluated in this paper, the Reinhard-Devlin approach builds its transfer function dependent on the input luminance signal. Fig. 8 depicts the transfer functions for the 55 stills analyzed in this paper (see appendix). The shape of the “s”-style curve changes depending on the image's average luminance level (Fig. 8).

Dolby Vision

Dolby Vision is a proprietary technology developed by Dolby for HDR video and HDR-SDR conversion. It uses dynamic metadata that optimizes the image quality by adjusting each frame of the HDR video to the consumer’s display capabilities [12][6].

[6] In this case, a simulated SDR display.

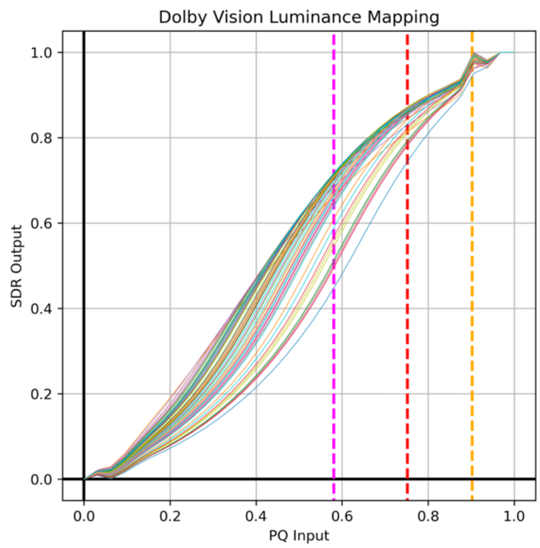

Figure 9: Transfer functions of Dolby Vision

Dolby Vision is the second dynamic approach examined in this work. It maps depending on maximum, minimum and average luminance levels of the input signal. In comparison to conventional mapping functions, HDR diffuse white is mapped to a remarkably lower SDR signal level and the function itself is approximately linear (Fig. 9), similar to the ITU-R BT.2446 method A approach. However, Dolby Vision incorporates a knee function in terms of highlight mapping.

III. Results

A total of 55 stills, extracted from the material described in the *Acquisition* chapter, were processed through the tone mappers and the results were then analyzed and compared with one another. A smaller selection will be examined in more detail below.

The analysis is based on subjective metrics by comparing the stills visually, with special attention on lowlight and highlight compression as well as skin tone mapping and the transfer of the creative intent of the image's composition. General technical conditions, such as signal range and run time, were considered beforehand.

Comparison

All tone mapping operators chosen for this paper have their own merits and weaknesses, each suitable for different uses in the world of tone mapping.

The static real-time algorithms can be implemented as 3D LUTs, causing close to no delay. The dynamic approaches can possibly cause minimal delay but are based on simple calculations that are limited to a single frame. In terms of used signal range all variants match the SDR range correctly.

It was clearly noticeable after visual comparison that on-air graphics should not be applied to a dirty feed. Depending on the algorithm, dynamic range compression causes hue shifts and a shifting white point. Graphics should really be applied after conversion, as most companies are strict on their CIs and the conversion possibly changes the colors immensely, depending on the chosen workflow. A few approaches, prominently the NBCU LUT-based approach, do not dull the white excessively and could potentially still be considered legitimate results for stakeholders involved (see e. g., Fig. 10[7]).

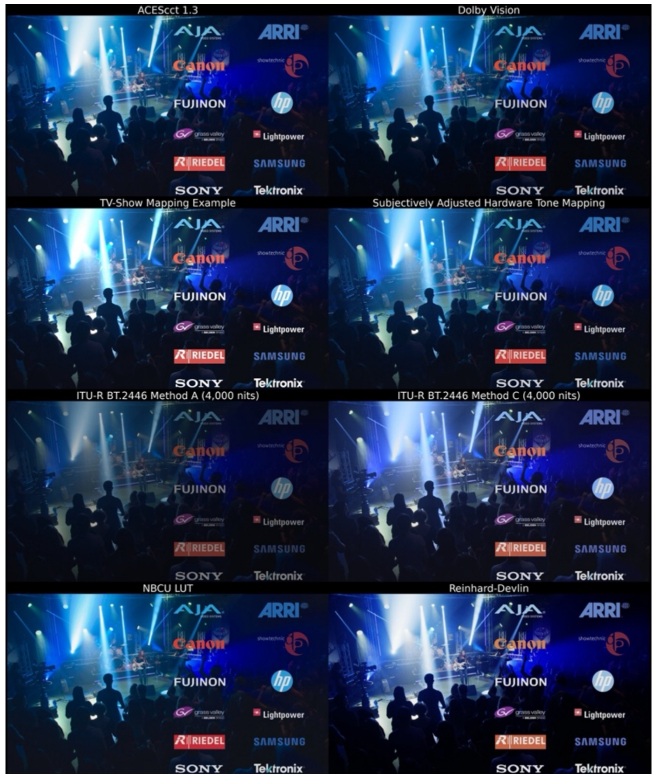

Figure 10: On-air graphics, tone mapped.

An additional fact is the compatibility of the chosen mappers with footage mastered above 1,000 cd/m^2. Unlike the studio produced footage, which is using the additional dynamic range mostly for highlights and peak luminances, as explained later in this chapter, the image shown in Fig. 11 is a lot brighter, using more of the 4,000 cd/m^2 range available. The results here show that in these instances, the static approaches seem to be at a loss as for what to do with the bright parts of the images, i. e., a new LUT would be needed for content with a higher average luminance level.

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[7] The tone mappers are from left to right: ACES, Dolby Vision, TV-Show Mapping Example, Subjectively Adjusted Hardware Tone Mapping, ITU-R Recommendation BT.2446-0 Method A, ITU-R Recommendation BT.2446-0 Method C, NBCU and Reinhard Devlin’s tone mapping approach.

Figure 11: A very bright car.

In this case the better results were generated with mappers that make calculations based on every single frame's information or map the dynamic range more linearly (e. g. Dolby Vision, ITU-R BT.2446 Method A), as seen in Fig. 11.

However, the strong disadvantage of these mappers is that these approaches cause the images to generally appear significantly darker. Regarding live show situations with special lighting effects and fully saturated colors, as shown in Fig. 12, these tone mapping algorithms' results create a wildly different feel for the scene lighting used by causing shifts of the creative intent.

Figure 12: Change of lighting direction caused by different mapping

Figure 13: Consistent lighting from the back

While the main lighting direction of a white spotlight is transferred by the ITU-R BT.2446's method C approach as well as the Reinhard-Devlin mapping, approaches like Dolby Vision and ITU-R BT.2446's method A in this case change the main lighting direction to the red lights from the back (Fig. 12).

Furthermore, the results seen in Fig. 13 can be separated into two groups, depending on how the tone mappers behave, as well. Considering Dolby Vision or ITU-R BT.2446's method A, the result is a remarkably darker image. The light beam on the bottom left loses its bright luminance, yet darker details as in the face of the singer maintain a respectively dynamic look (Fig.13). The remaining tone mappers keep the brightness of the light beam on a similar level but details like highlights and speculars of the tinsel or the skin tone are visually compressed and thus get lost. This sequence presents a challenge for all tone mapping approaches and the necessity of specifically engineering a custom tone mapping approach for an individual use case.

Regarding show lighting situations, another important comparison is the compression method of highlights itself, especially in scenes with another inconsistent back lighting like shown in Fig. 13.

Figure 14: Extreme lighting from the back

Figure 15: Blinding light causing different impressions

Depending on their luminance transfer functions, some tone mappers were lacking the code values to display the necessary brightness steps when trying to compress the highlights up to 4,000 cd/m^2 in 10 % of the SDR signal range like the NBCU LUT (Fig. 14). In this case, the prominent light ray having a heavy hotspot in the middle of its beam path is causing banding artifacts as the resulting dynamic range is too small to display such stark contrasts. Approaches that apply highlight clipping like the TV-Show Mapping Example perform better in this context as well as discussed ITU-R BT.2446's method A and Dolby Vision but without further correction, these are not transferring the creative intent accurately in this context as well (Fig. 14).

Therefore, in a live show context, static approaches seem to be more consistent, especially when using blinding light effects. The tone mappers struggling are the ones that are calculating stats on every single frame – they are heavily influenced by short moments of changing image contrasts as opposed to global, static approaches, as seen in Fig. 15.

For broadcasting environments, a static approach seems to be beneficial in various ways and in particular in context of show lighting, as their runtime complexity is negligible, and while not every result is perfectly accurate, the results are reliably consistent every single time which is highly valued, especially in agile broadcasting environments.

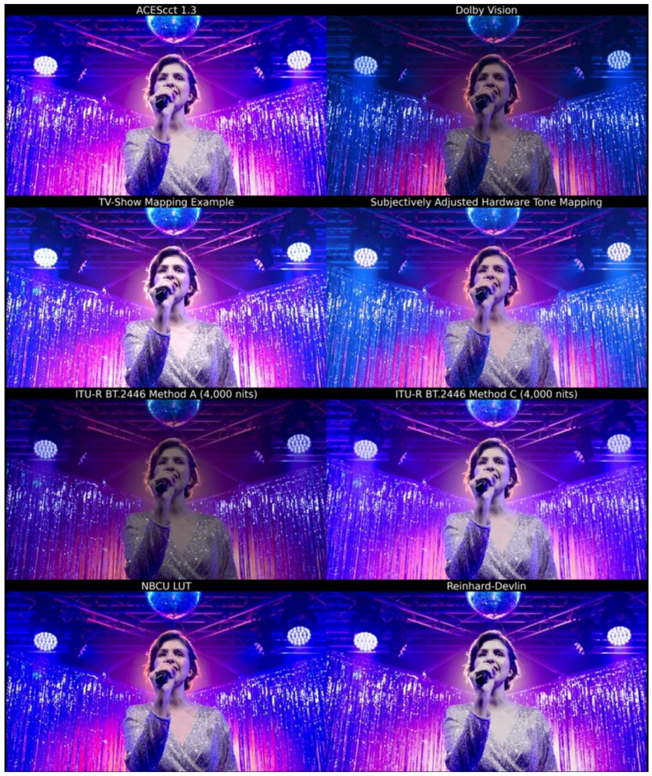

Figure 16: Lighting with complementary colors

Some of the static tone mappers cause certain color contrasts to essentially cancel each other out, which can be a problem for colorful footage, especially considering the color space transformation needed (Fig. 16). While the mid tones are mapped appropriately in most cases, especially the Reinhard-Devlin approach causes paler skin as well as the ITU-R BT.2446's method C algorithm, while ITU-R BT.2446's method A and Dolby Vision seem stable in terms of color but reduce the face's luminance immensely (Fig. 16).

Contrary to the initial assumption, there were some scenes that worked well enough across all tone mappers. Fig. 17 might be showing a varying amount of contrast between the light on the hands and the texture of the suit, but overall, the creative intent of the still is about the same across the board (Fig.17).

Referring to Fig. 18, method A causes the blue hues to shift. Additionally, the steep "s"-curve of the Reinhard-Devlin approach as well as the black level clip used in the TV-Show Mapping Example are compressing the lowlights more than the remaining approaches (e. g., Fig. 17 and 18). Causing loss of information but enhancing the overall contrast, these settings might be visually more appealing depending on the creative intent (Fig. 18).

Figure 17: A handsome man playing the piano

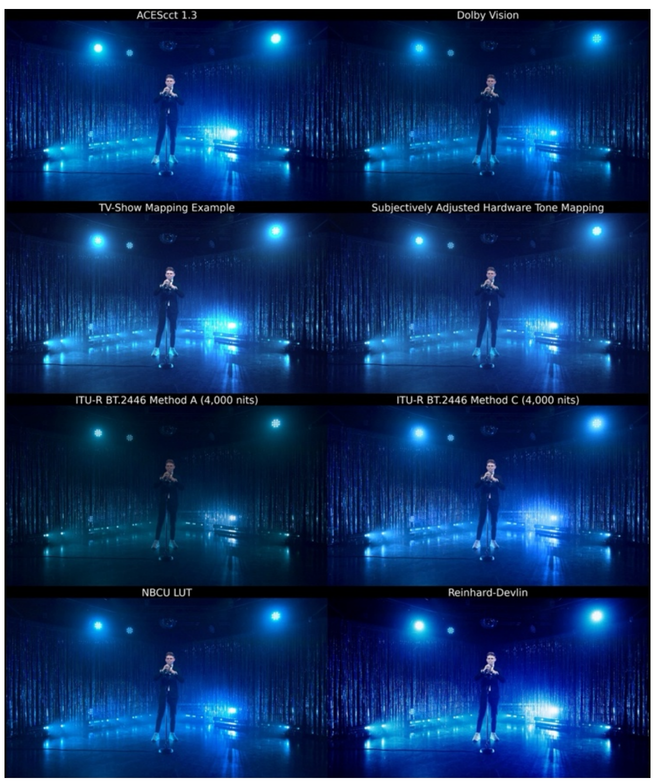

Figure 18: Scene with lots of contrast

Conclusion

Based on the subjective tests done to compare the approaches listed in this paper, all tone mapping approaches (as well as the associated gamut mapping) perform well in different use cases. ITU-R BT.2446's method C and dynamic approaches like Dolby Vision are offering the best highlight preservation for the most part. Nevertheless, the result is a darker image in comparison to the remaining approaches. Especially in a live show context, where the signal levels above HDR diffuse white are mostly used for highlights and speculars, these approaches do not meet the creative intent without requiring additional grading work. In addition, the dynamic approach isn't as reliable as static ones when it comes to preserving the artistic intent, particularly in show situations where bright lighting effects play a major role. However, for natural lighting and very high average luminance levels, these dynamic methods offer an adaptive luminance and color mapping, resulting in a better visual output for images that do not follow typical exposure practices.

After having considered the advantages and disadvantages, based on the 55 stills analyzed, the overall most reliable results were produced by the Subjectively Adjusted Hardware Tone Mapping. The resulting tone mapped SDR images present themselves with a look that closely matches the creative intent of the HDR originals in terms of luminance and color representation. Additional winners are the NBCU LUT and the Reinhard-Devlin approach.

Nevertheless, the results of the analysis suggest that there is neither a single static approach covering all use cases nor a dynamic conversion fitting all situations. Finally, creative supervision is necessary not only for the initial image composition and lighting design, but also for all mapping processes.

IV. Future Work

This detailed analysis of tone mappers provides insights for research and for the broadcast industry. In particular, the development of a novel tone mapping approach for broadcast TV show application, considering the observations gained above, would be a potential next step. Based on the findings of this paper, this chapter aims to outline ideas for a tone mapping approach that individually responds to the content produced respectively.

Future tone mapping solutions for broadcast production should be driven by parameterizable and standardized approaches. All tone mappers are based on the same "s-shape" design, which is typical for the process of mapping from HDR to SDR. Suggestions for mapping parameters could be derivations of highlight compression, lowlight compression and contrast.

In detail, the parameters should include knee point and knee slope to allow the characteristics of highlights to be modified (cf. Fig. 19).

Furthermore, a second power function that defines overall dynamics of the mid and black tones that is tangent to a "toe point" is needed. Analogously to the knee parameters, the toe point should also be configurable to achieve a smooth transition in the colors and blacks (Fig. 19). While the knee parameters define the diffuse white mapping, highlight compression and clipping, the toe parameters control the contrast and black compression of the image.

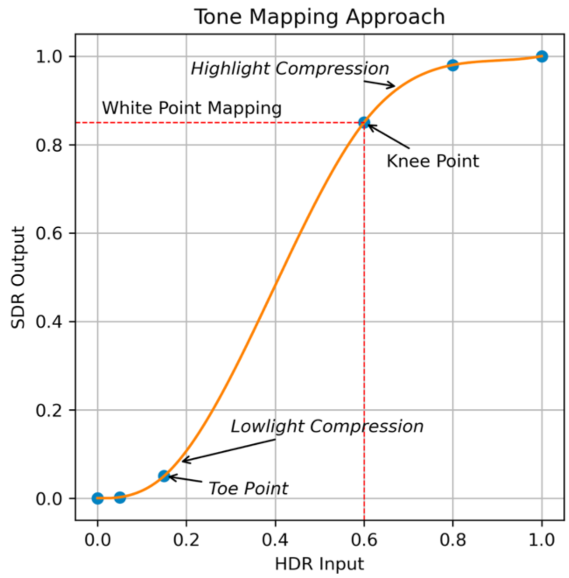

Figure 19: An ideal tone mapping curve.

Moreover, this set of parameters should be available for the whole production chain of creating HDR and SDR live content simultaneously. This makes it possible for all production participants that are responsible for the creative intent to exchange the tone mapping idea, from lighting designers to vision shaders and colorists in post-production. This exchange could be based on a simple set of numbers in the metadata of a file or in SDI ancillary data. Besides, since not all the tone mappers examined included color space transformation, the parameterizable mapping algorithm should also be capable of processing gamut mapping, as both areas are strongly related to each other in terms of the final result.

In conclusion, the topic of HDR-SDR conversion is a significant area of research. With a mapping solution that standardizes the process of mapping across departments, many processes in a production could be simplified. This would further aid the goal of a production meeting its artistic intent in all deliverables, as HDR-SDR workflows continue to become the norm for productions.

V. Acknowledgements

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VI. References

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VII. Appendix

Figure A.1: HDR SDR mapping comparison - No. 1

Figure A.2: HDR SDR mapping comparison - No. 2

Figure A.3: HDR SDR mapping comparison - No. 3

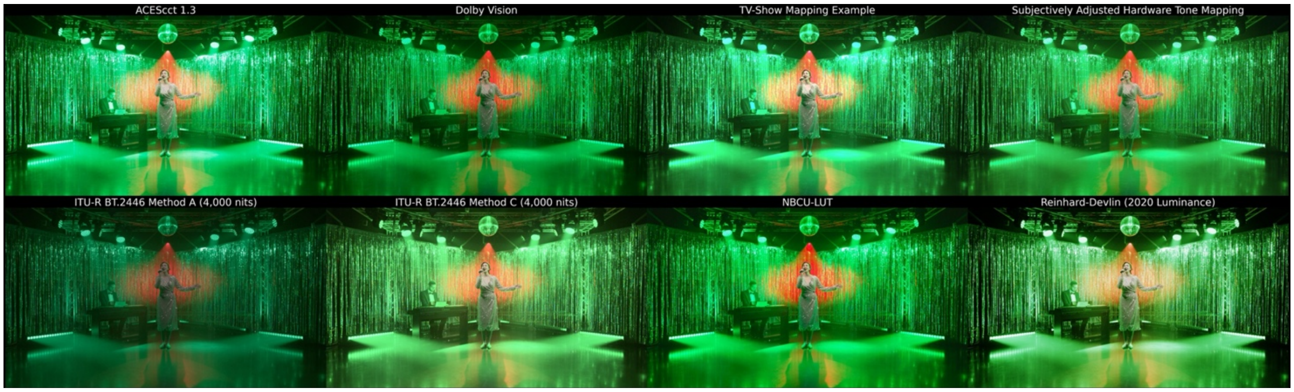

Figure A.4: HDR SDR mapping comparison - No. 4

Figure A.5: HDR SDR mapping comparison - No. 5

Figure A.6: HDR SDR mapping comparison - No. 6

Figure A.7: HDR SDR mapping comparison - No. 7

Figure A.8: HDR SDR mapping comparison - No. 8

Figure A.9: HDR SDR mapping comparison - No. 9

Figure A.10: HDR SDR mapping comparison - No. 10

Figure A.11: HDR SDR mapping comparison - No. 11

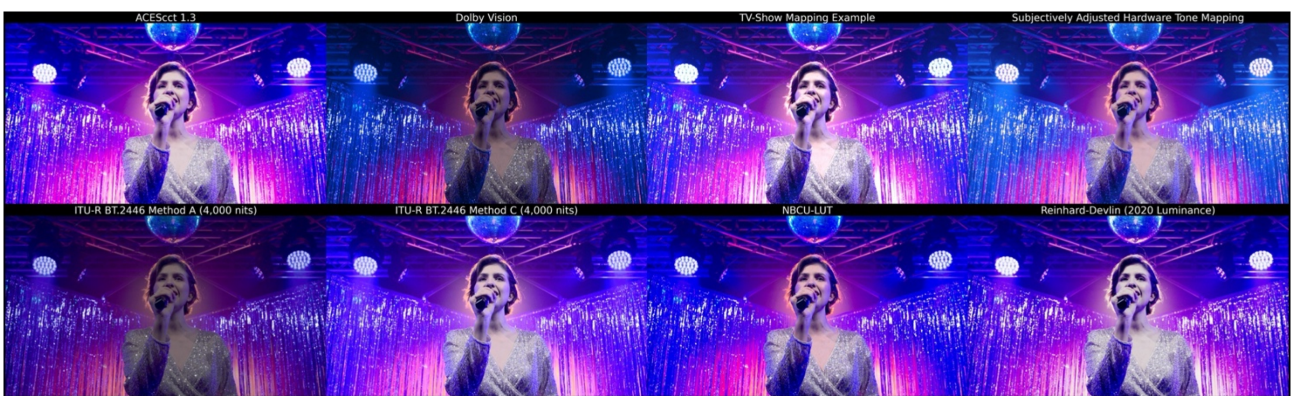

Figure A.12: HDR SDR mapping comparison - No. 12

Figure A.13: HDR SDR mapping comparison - No. 13

Figure A.14: HDR SDR mapping comparison - No. 14

Figure A.15: HDR SDR mapping comparison - No. 15

Figure A.16: HDR SDR mapping comparison - No. 16

Figure A.17: HDR SDR mapping comparison - No. 17

Figure A.18: HDR SDR mapping comparison - No. 18

Figure A.19: HDR SDR mapping comparison - No. 19

Figure A.20: HDR SDR mapping comparison - No. 20

Figure A.21: HDR SDR mapping comparison - No. 21

Figure A.22: HDR SDR mapping comparison - No. 22

Figure A.23: HDR SDR mapping comparison - No. 23

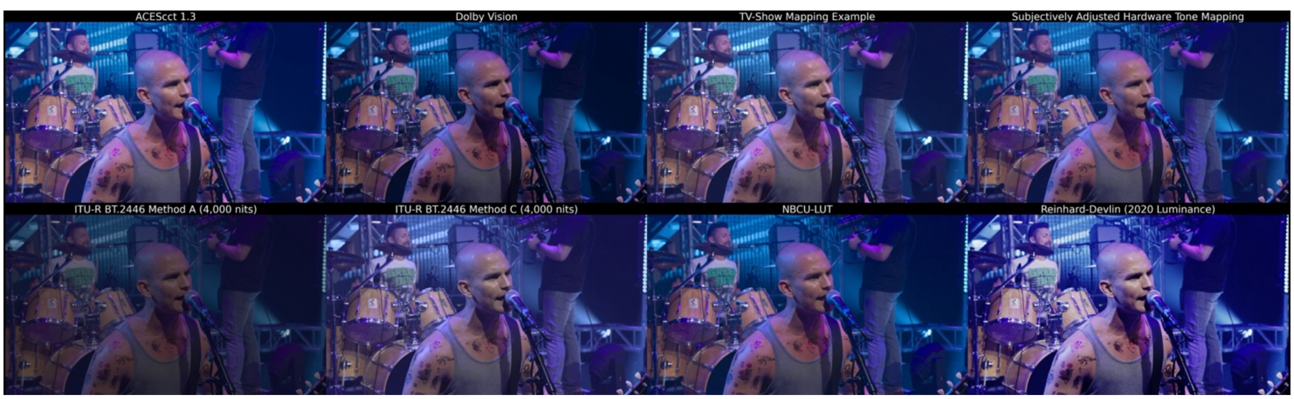

Figure A.24: HDR SDR mapping comparison - No. 24

Figure A.25: HDR SDR mapping comparison - No. 25

Figure A.26: HDR SDR mapping comparison - No. 26

Figure A.27: HDR SDR mapping comparison - No. 27

Figure A.28: HDR SDR mapping comparison - No. 28

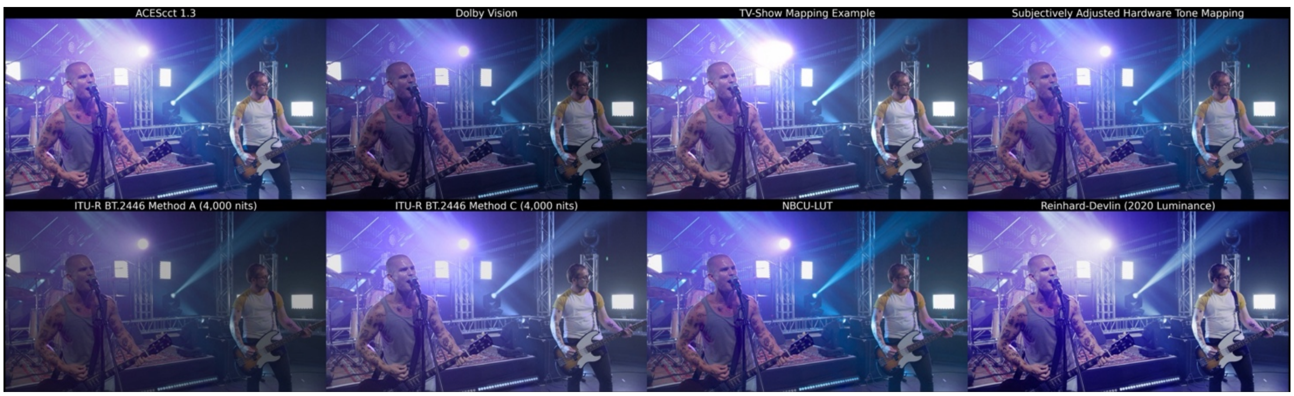

Figure A.29: HDR SDR mapping comparison - No. 29

Figure A.30: HDR SDR mapping comparison - No. 30

Figure A.31: HDR SDR mapping comparison - No. 31

Figure A.32: HDR SDR mapping comparison - No. 32

Figure A.33: HDR SDR mapping comparison - No. 33

Figure A.34: HDR SDR mapping comparison - No. 34

Figure A.35: HDR SDR mapping comparison - No. 35

Figure A.36: HDR SDR mapping comparison - No. 36

Figure A.37: HDR SDR mapping comparison - No. 37

Figure A.38: HDR SDR mapping comparison - No. 38

Figure A.39: HDR SDR mapping comparison - No. 39

Figure A.40: HDR SDR mapping comparison - No. 40

Figure A.41: HDR SDR mapping comparison - No. 41

Figure A.42: HDR SDR mapping comparison - No. 42

Figure A.43: HDR SDR mapping comparison - No. 43

Figure A.44: HDR SDR mapping comparison - No. 44

Figure A.45: HDR SDR mapping comparison - No. 45

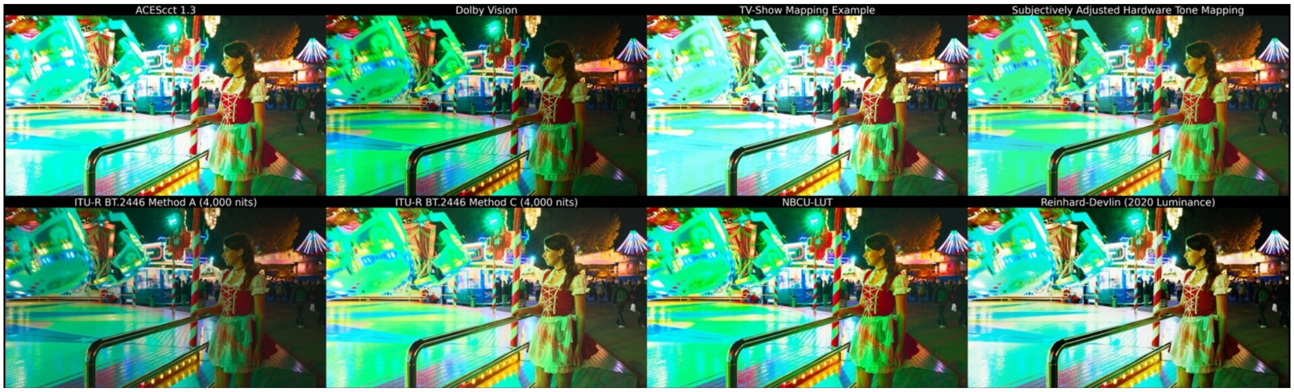

Figure A.46: HDR SDR mapping comparison - No. 46

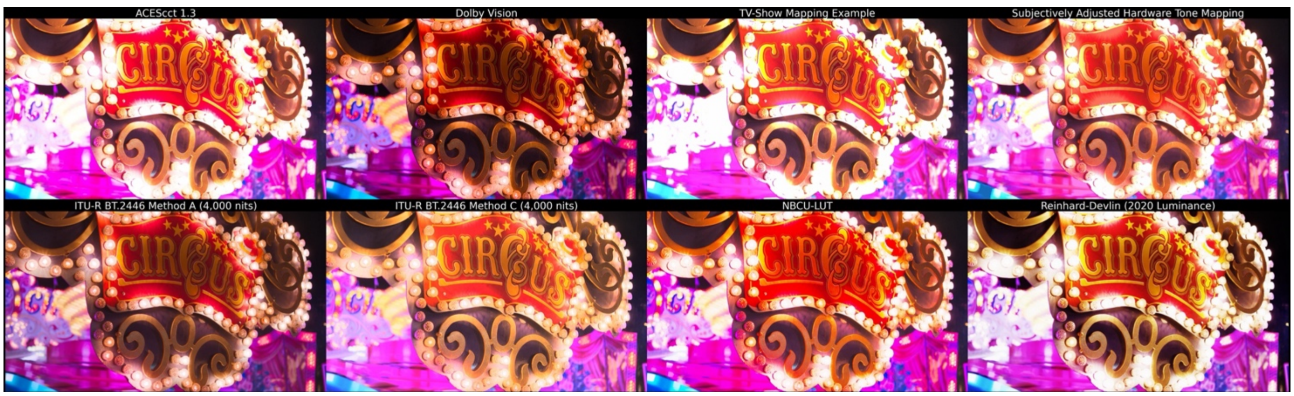

Figure A.47: HDR SDR mapping comparison - No. 47

Figure A.48: HDR SDR mapping comparison - No. 48

Figure A.49: HDR SDR mapping comparison - No. 49

Figure A.50: HDR SDR mapping comparison - No. 50

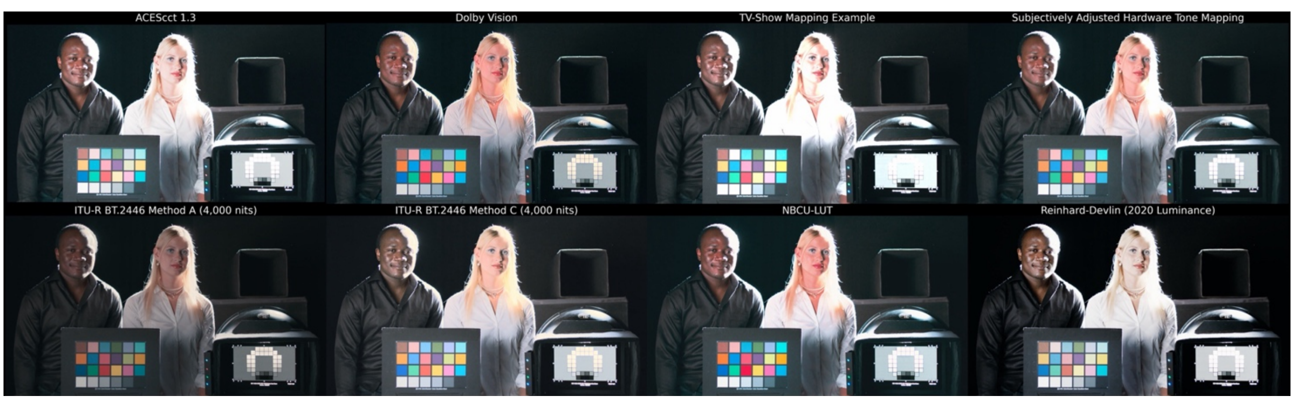

Figure A.51: HDR SDR mapping comparison - No. 51

Figure A.52: HDR SDR mapping comparison - No. 52

Figure A.53: HDR SDR mapping comparison - No. 53

Figure A.54: HDR SDR mapping comparison - No. 54

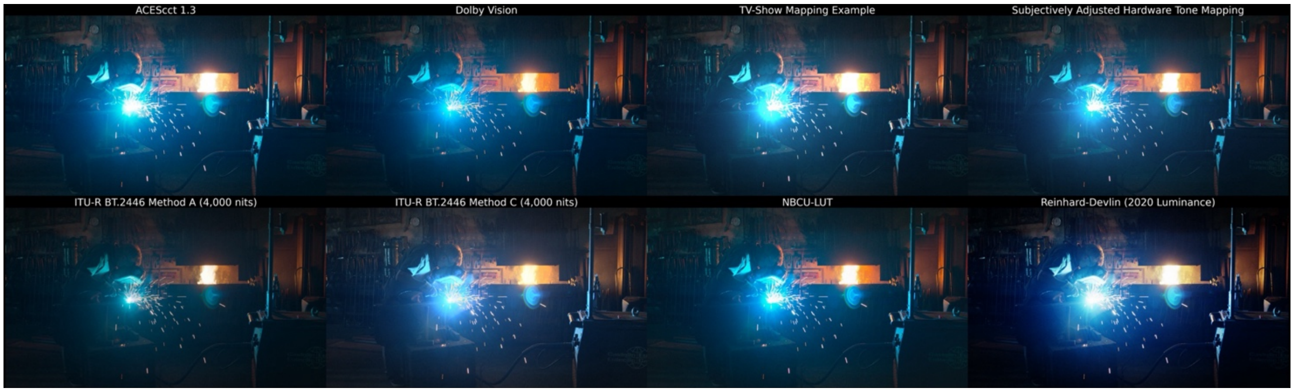

Figure A.55: HDR SDR mapping comparison - No. 55

AJA FS HDR Settings - “TV-Show Mapping Example” Colorfront TV *Software-Version 4.1.1.6* *Colorfront Transform Processing Version 170* *Colorfront Engine Program Version 44646*	
ProcAmp Enable	Off
Transform	Colorfront Engine-TV
Conversion	PQ to SDR
Colorfront Engine	Adjust
Knee Point	1.000
Knee Slope	0.000
Color Corrector	On
Master Lift	- 0.010
Red Lift	0.000
Green Lift	0.000
Blue Lift	0.000
Master Gamma	1.000
Red Gamma	1.000
Green Gamma	1.000
Blue Gamma	1.000
Master Gain	1.150
Red Gain	1.000
Green Gain	1.000
Blue Gain	1.000

Saturation	0.800
Camera Correction	Off
CFE-TV Reset	Select
Video Legalizer	YUV
Legalizer White Clip	100.0 %
Legalizer Black Clip	0.0 %
Legalizer Chroma Clip	100.0 %

Table A.1: AJA FS HDR - Settings used for the Colorfront TV Engine

AJA FS HDR Settings - "Subjectively Adjusted Hardware Tone Mapping" Colorfront Live *Software-Version 4.1.1.6* *Colorfront Transform Processing Version 170* *Colorfront Engine Program Version 44646*	
Transform	Colorfront Engine-Live
Dyn Range&Gamut IN	PQ BT.2020 1000 cd/m^2
Dyn Range&Gamut OUT	SDR BT.709 100 cd/m^2
Colorfront Engine	Adjust
HDR Amount	0.231
Amb Light Comp	- 0.092
HDR Log Look	0.465
SDR Softness	0.000
Master Lift	- 0.004
Red Lift	0.000
Green Lift	0.000

Blue Lift	0.000
Master Gamma	1.000
Red Gamma	1.000
Green Gamma	1.000
Blue Gamma	1.000
Master Gain	1.150
Red Gain	1.000
Green Gain	1.000
Blue Gain	1.000
Saturation	1.000
Exposure	0.000
Color Temp	0.000
Tint	0.000
PQ Output Nit Level	1000
P3 Colorspace Clamp	Off
BT.2408 Mode	0.000
CFE-Live Reset	Select
Video Legalizer	RGB
Legalizer White Clip	100.0 %
Legalizer Black Clip	0.0 %

Table A.2: AJA FS HDR - Settings used for the Colorfront Live Engine

