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Abstract
In this contribution, we evaluate with psychophysical experiments several methods for encoding HDR content. Unlike other studies both luma and color difference encoding are tested in a rigorous 4AFC threshold experiments to determine the minimum bit-depth required. Results show that the Perceptual Quantizer (PQ) encoding provides the best perceptual uniformity in the considered luminance range, however the gain in bit-depth is rather modest. More significant difference can be observed between color difference encoding schemes, from which YDuDv encoding seems to be the most efficient.

1 Introduction

This document reports experiments related to the encoding of High Dynamic Range (HDR) color samples using color difference representation. Several methods are evaluated, in particular for use in image and video compression. Unlike other studies [1], we test both luma and chroma encoding in a rigorous 4AFC threshold experiments to determine the minimum bit-depth required.

2 Experimental Procedures

We conducted a series of psychophysical experiments in which we measured the minimum bit-depth at which the contouring artefacts remain invisible. The observers were presented four patches with smooth gradients in which only one was quantized. They were then asked to select one that appears different from the others (4AFC). The patches were shown on a 10-bit HD LCD panel, whose bit-depth was further enhanced to 12-bits by spatio-temporal dithering. The patch (700x400 pixels) average luminance varies from 0.05 to 150 cd/m². We assume that the measurements above 150 cd/m² can be extrapolated as the CSF does not vary much above that level. To achieve luminance levels lower than 5 cd/m², the observers wore a pair goggles with attached neutral density filters (Kodak Wratten 96, 1.0D and 2.0D). The QUEST procedure [2] was used to determine the detection threshold in terms of fractional numbers of bit used for encoding.

3 Experiment 1: Luminance encoding

One of the key component of every color encoding is a non-linear mapping applied to linear intensities (or trichromatic color values), here noted Perceptual Transfer Functions (PTF). One of the first perceptually uniform coding of HDR luminance was derived from the threshold versus intensity (t.v.i.) models [10]. Several such PTFs, some of them discussed in the ad hoc MPEG group on High Dynamic Range and Wide Color Gamut Content Distribution [3], are listed in Table 1. Figure 1 plots the luminance encoding of values ranging from 0.005 to 10,000 cd/m² on 12 bits along with the associated maximum quantization error. The optimum encoding should require the smallest number of bits per pixel and at the same time it should minimize the visibility of contouring artefacts due to quantization into integer values.

PTF	Equation
PU-HDRVDP	lookup table
Perceptual Quantizer (PQ)	$\mathbf{V} = \frac{c_2\mathbf{L}^{m_1}+c_1}{1+c_3\mathbf{L}^{m_1}}^{m_2}$
Gamma-Log	$\mathbf{V} = \begin{cases} \mathbf{L}^{\gamma} & \text{if } \mathbf{L} \leq f \\ a \cdot log(\mathbf{L}+b)+c & \text{if } \mathbf{L} > f \end{cases}$
Rho-Gamma	$\mathbf{V} = log(1 + \frac{\frac{(\rho-1)\mathbf{L}}{L_{max}}^{\frac{1}{\gamma}}}{log(\rho)})$
Log-Linear	$\mathbf{V} = log_{10}(\mathbf{L})$
Arri Alexa	$\mathbf{V} = \begin{cases} max(0, e \cdot \mathbf{L} + f) & \text{if } \mathbf{L} \leq f \\ c \cdot log_{10}(a \cdot \mathbf{L} + b) + d & \text{if } \mathbf{L} > f \end{cases}$
S-Log	$\mathbf{V} = (a \cdot log_{10}(b \cdot \mathbf{L} + c) + d) + e$
PU based on Barten's CSF	lookup table

Table 1: PTFs considered with the corresponding equations. L is the HDR luminance in cd/m² while V is the luma (perceptually encoded luminance). The results of the PTF are normalized to the range [0;1].

Figure 2 shows the result of an experiment, in which observers determined the minimum number of bits required for encoding luminance using four different PTFs (from Figure 1). The PTFs were scaled to encode the luminance ranging from 0.005 to 10,000 cd/m², and the measurements were made for luminance levels ranging from 0.05 to 150 cd/m². The results show that the encoding using the logarithmic function (Log-linear) requires disproportionate number of bits for dark (8.5 bits) and bright (10.5 bits) regions. The number of bits is more steady for the perceptually uniform encoding based on the HDR-VDP-2 CSF model (PU-HDRVDP) [4,5] and the Gamma-Log function [6], but the bit-depth is the most uniform across the luminance levels for Perceptual Quantizer (PQ) [1,7]. For all PTFs, the luminance from 0.005 to 10,000 cd/m² can be encoded without perceptual loss using 11 bits or more.

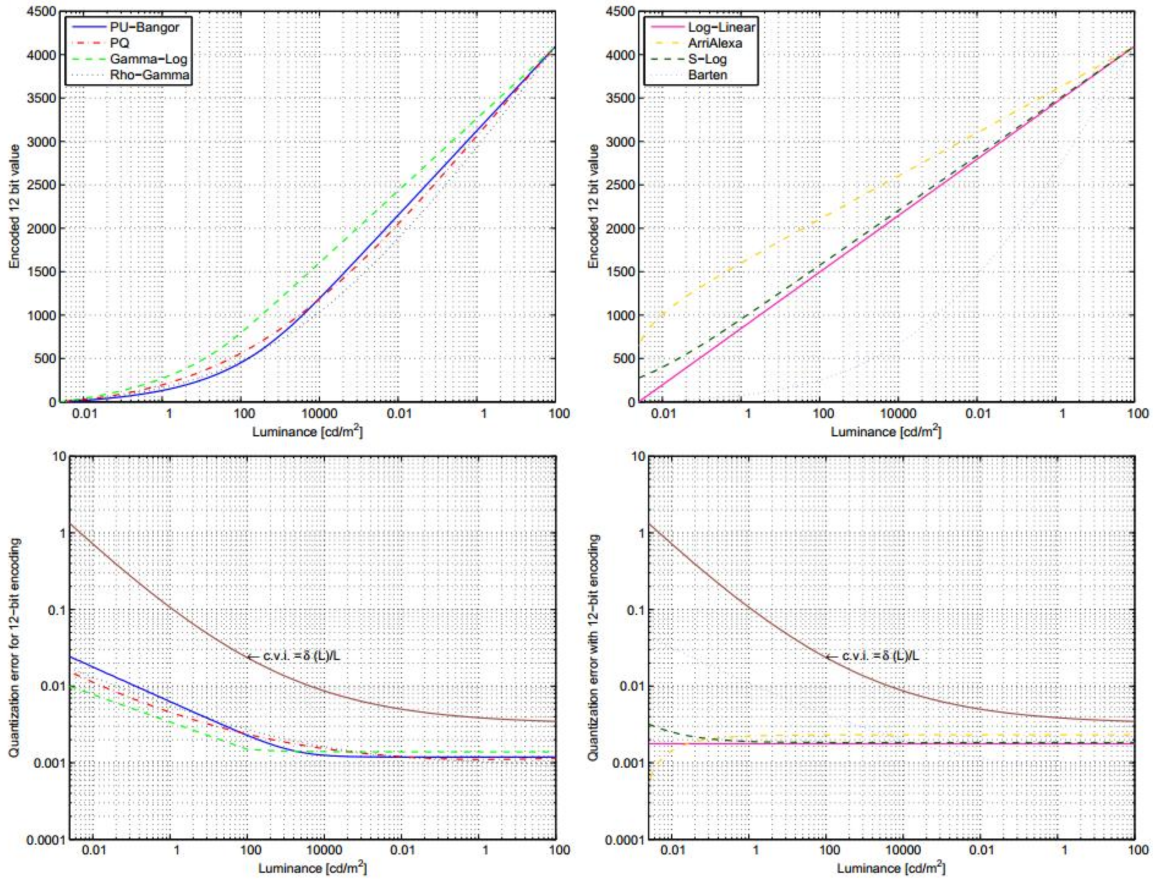

Figure 1: Top: luminance value encoded with different PTFs with 12 bits. Luminance range considered: [0.005; 10,000] cd/m². Bottom: quantization error for 12 bit-encoding. The bottom plots correspond to the legend of the top plots. The contrast versus intensity (c.v.i.) function has been added in the bottom plot.

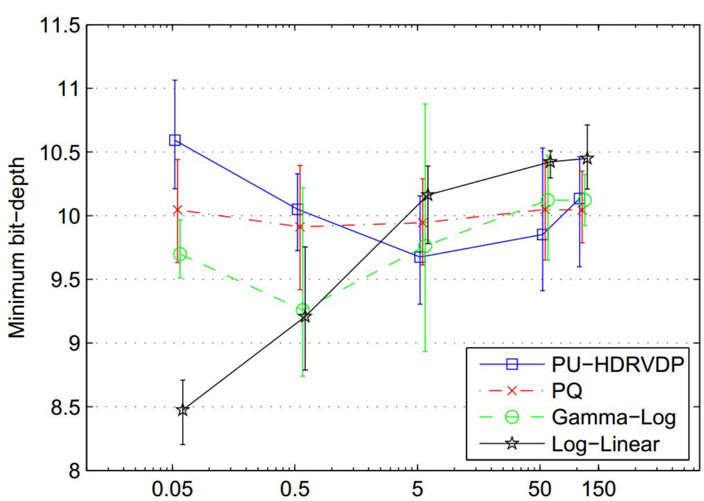

Figure 2: Minimum bit-depth required to encode HDR luminance values using several PTFs. For improved legibility the location of the error bars have been shifted along the x-axis. The error bars denote 95% confidence intervals describing the variance between observers. Note that, even though fractional bit quantization was measured in the experiment, in all practical applications the number of bits need to be rounded up.

4 Correlation between color channels

There are two main representations of color pixels: additive color spaces, such as RGB, and the color spaces that separate luminance and chrominance components, such as YCbCr. In this contribution, we focus on the latter, which is favored for video compression as it removes the luminance information from the chrominance channels. YCbCr is most commonly used for SDR image and video compression [8]. However YCbCr encoding is tied to an SDR color space [8,9] and cannot encompass the range of colors and luminance present in HDR content. That is why, alternative color difference encoding are under investigation. We propose to evaluate three different color difference encodings according to three criteria: the decorrelation between the luma and chroma channels, the minimum bit-depth at which the contouring artefacts remain invisible and the perceptual uniformity. The three selected representations are YCbCr with the BT.2020 color space [9], YDzDx [10] and a modified LogLu'v' [11] representation that we call YDuDv.

Achieving high decorrelation ensures that no redundant information will be encoded. Table 2 reports the Pearson product-moment correlation coefficient [12] between the luma and chroma channels for 5 HDR images [13]. Results show that the YDuDv achieves a higher decorrelation for three out of the five images. Furthermore, for two images (FireEater2 and Tibul2), the YDzDx and YCbCr encoding have high correlation factor (close to one). To evaluate these color difference encodings with respect to the minimum bit-depth and the perceptual uniformity, we performed a second psychophysical experiment as explained hereafter.

Chroma	**Dz**	**Cb**	**Du**	**Dx**	**Cr**	**Dv**
Balloon	0.033	0.098	0.014	0.272	0.052	0.190
FireEater2	0.950	0.740	0.391	0.909	0.790	0.375
Market3	0.226	0.176	0.379	0.189	0.289	0.224
Seine	0.413	0.407	0.245	0.445	0.390	0.262
Tibul2	0.933	0.860	0.086	0.912	0.540	0.027

Table 2: Pearson product-moment correlation coefficient [12] between the luma and the two chroma channels for each of the three color difference encodings. Those encodings were performed on 12 bits.

5 Experiment 2: Color encoding

In the second experiment we determined the minimum number of bits required to encode color using the PQ PTF and one of the color difference encoding schemes. The test patches contained three different gradients: one along the luminance and two along the CIE u' and v' chrominances [14] (Figure 3). The detection threshold for contouring artefacts was determined separately for quantization of luma and two chroma channels. The results of that experiment are plotted in Figure 4. As expected, the results for luma quantization shown on the left are similar to those shown in Figure 3. However, YCbCr encoding appears to require about 0.5 bit less of precision. In case of chroma channel quantization (Figure 4-right), the difference in bit-depth precision between different chroma encoding schemes is much larger. Using YDuDv encoding [11], based on the CIE u' v' chromatic coordinates, requires the fewest bits to encode, especially at low luminance levels. Given that two chroma channels need to be encoded, this can bring significant gains in compression efficiency. Note, however that the YDuDv is also the least perceptually uniform scheme.

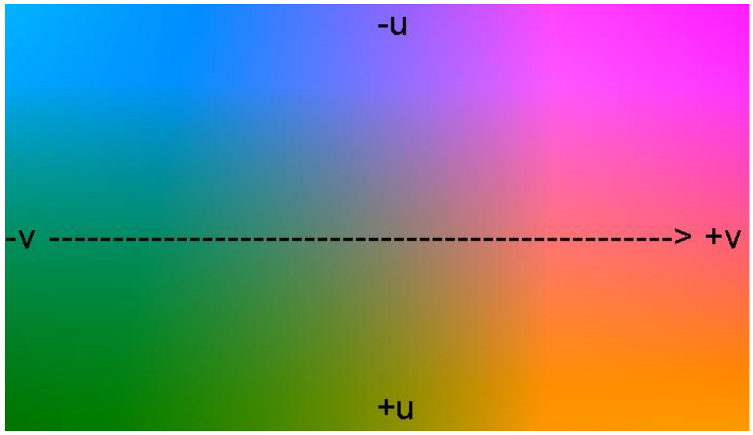

Figure 3: Test patch with three different gradients: one along the luminance and two along the CIE u' and v' chrominances. Chrominance gradient ranges from -0.1 to 0.1 around the D65 white point.

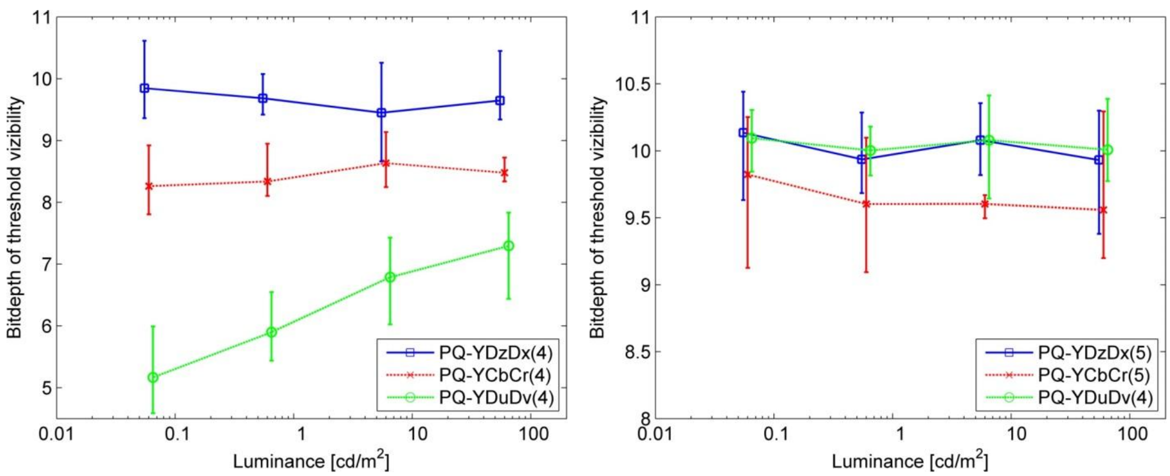

Figure 4: Minimum bit-required to encode color pixel using the three chroma encoding schemes: YDzDx, YCbCr and YDuDv. Left: results for luma channel quantization. Right: results for the quantization of two chroma channels. For improved legibility the location of the error bars have been shifted along the x-axis.

6 Conclusions

We presented an experimental evaluation of schemes used to encode HDR samples values. In particular, it was observed that the PQ encoding provides the best perceptual uniformity in the considered luminance range, however the gain in bit-depth is rather moderate. In some applications, logarithmic encoding can prove equally effective, especially since it does not required HDR values to be calibrated in absolute units. A more significant difference can be observed between color difference encoding schemes, from which YDuDv encoding [11] seems to be the most efficient. More details on this contribution can be found in **R. Boitard, R. K. Mantiuk. To be published in: Proc. of Human Vision and Electronic Imaging XX, IS&T/SPIE's Symposium on Electronic Imaging, 2015.**

7 References

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