



A Perceptual EOTF for Extended Dynamic Range Imagery

Scott Miller - Dolby Laboratories, Inc.



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Today's Guest Speaker

Scott Miller

Senior member of the
research staff
Dolby Laboratories



What is an EOTF and why is it so important?

- EOTF stands for Electro-Optical Transfer Function
 - It describes how to turn digital code words into visible light
- The image on the reference display is what truly **defines** the signal
- An artist makes creative decisions on what the content will look like while viewing a reference display
 - Could be sitting at a grading desk in a post production suite
 - Could be sitting in front of camera control units at a live production
- Interoperability depends upon consistent image reproduction
 - All reference displays need to operate the same way




Where is the EOTF in current standards?

- SMPTE 292M, SMPTE 372M, HDMI?
 - No EOTF, these are simply interface specifications
 - They don't say everything about what the RGB or $YCbCr$ values mean
- ITU-R Rec. BT.601, 709, 2020?
 - Again no EOTF, these are encoding specifications which define the OETF (Opto-Electrical Transfer Function) used for image capture
- But image display \neq inverse of image capture
 - Because of rendering intent
 - Bright scene capture environment, much dimmer display environment



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So where is our current EOTF defined?

- Right here: 
- Current “Gamma” nonlinearity is based on CRT physics
 - Very much the same since the 1930s
 - Finally standardized by ITU-R Rec. BT.1886 (in 2011!!!)
 - With CRTs almost extinct the effort was made to officially document their response curve



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Recap: EOTFs vs. OETFs

- OETF functions (as used in Rec.709 and the like) were derived from the display EOTF, not the other way around
 - EOTF was determined by CRT physics
 - OETF = Inverse EOTF + Rendering Intent
- EOTF definition is necessary to view finished content properly
 - EOTF must match the reference display used by the artist to create original program
- OETF definition is just a rough target
 - Camera curves are adjusted for preference during shooting
 - Textbook Rec709 function is almost never used in practice



Why is a new EOTF needed?

- Ideally, the EOTF should be defined by the human visual response
- Current Gamma worked well enough for the CRT era
 - It is a sort of perceptual EOTF
 - But only at relatively low luminance levels and small dynamic ranges
- Some suggest stretching or tweaking gamma would allow us to squeeze a little bit more brightness and dynamic range out of our current system
- We believe next generation systems will be much brighter and have much higher dynamic range because that is what viewers will demand!



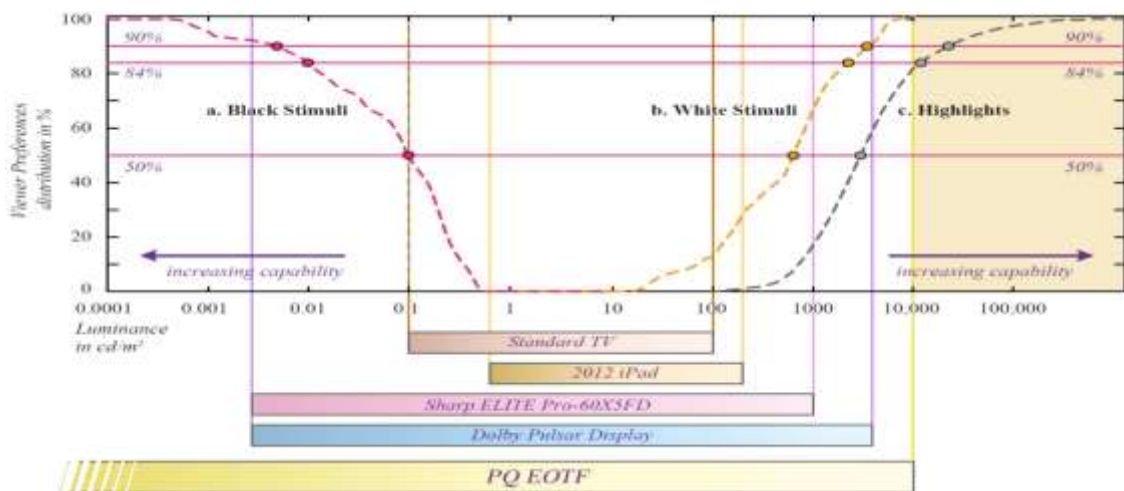
What do viewers prefer?

- We conducted an extended dynamic range viewer preference study
- Required very wide range display
 - 0.004 to 20,000 cd/m² capability
 - P3 color gamut
- 3 picture height viewing distance
- Dark (cinema type) room environment



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Preference Study Results



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How dark is black?

- Reference Video: 0.005 – 0.01 cd/m²
- Reference Cinema: 0.01 – 0.03 cd/m²
- Best consumer devices today: ~ 0.001 cd/m²
- “True Black” is an elusive target
 - With long enough adaptation time, you can see handfuls of photons
- 0.0001 cd/m² is very dark
 - Takes a minute or two to see this level after turning off lights
 - Still very dim looking even after full adaptation
- ~0.00001 – 0.000001 is the visual system limit (cone threshold ~0.003)



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How bright is white?

- Reference Video: 80 – 120 cd/m²
- Reference Cinema: 48 cd/m²
- Best consumer devices today: ~ 1500 cd/m²
- Some commercial devices today: 4000 – 5000 cd/m²
- 10,000 cd/m² is easy to get a look at & measure
 - Typical brightness of a fluorescent tube
 - Bright, but not painful to look at even in an indoor environment



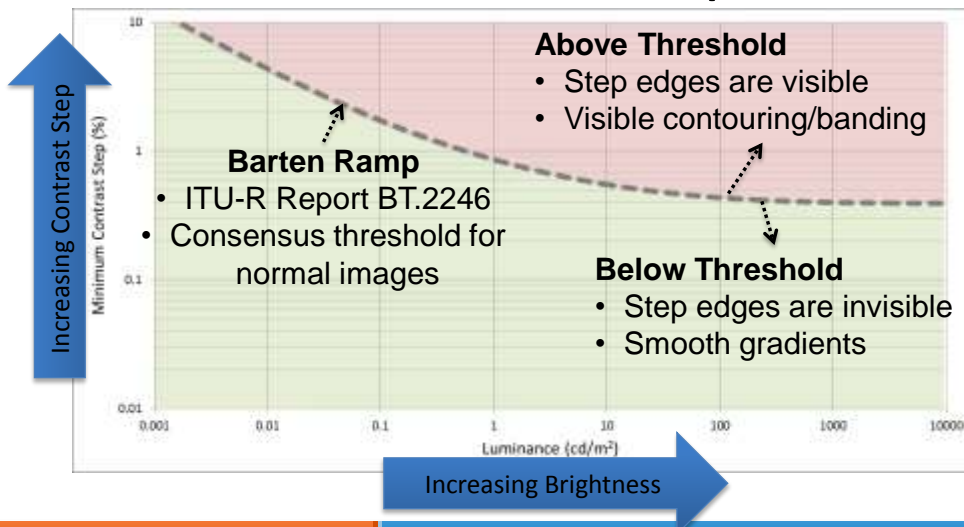
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Building a new EOTF

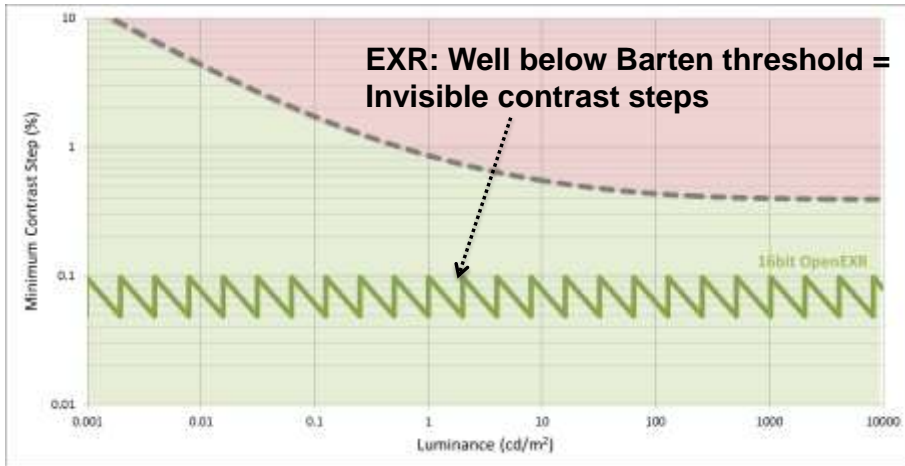
- Take 0 to 10,000 cd/m² dynamic range
- Assume practical system will need to be 10-12 bits
 - Due to current infrastructure and silicon constraints
- Use human visual system to determine performance we need
- Start fitting some curves



Intro to Contrast Step Curves

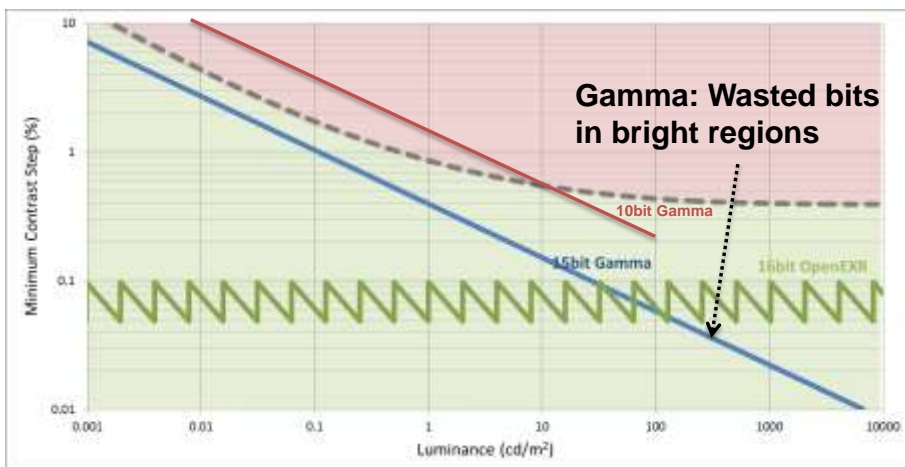


OpenEXR



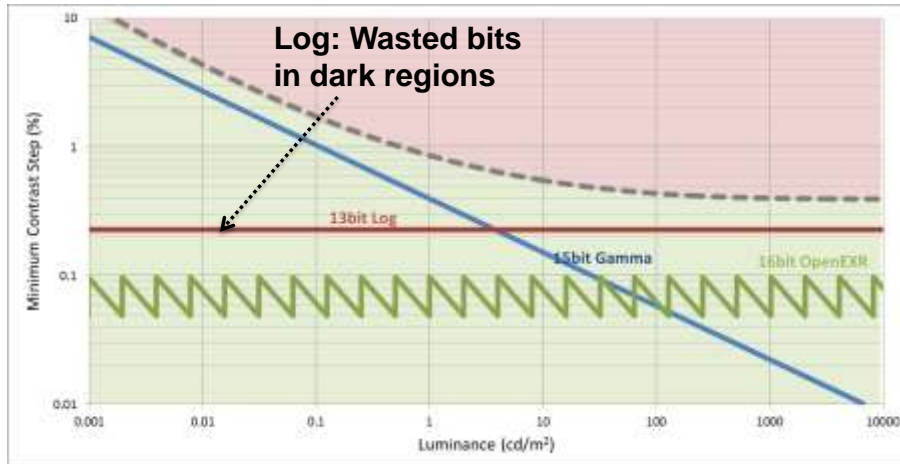
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Gamma (Rec1886)



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Log



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Barten Contrast Sensitivity Function (CSF)

$$CSF = \frac{1}{m_i} = \frac{M_{opt}(u)/k}{\sqrt{2 \left(\frac{1}{X_0^2} + \frac{1}{X_{max}^2} + \frac{u^2}{N_{max}^2} \right) \left(\frac{1}{\eta p E} + \frac{\Phi_0}{1 - e^{-(u/u_0)^2}} \right)}}$$

$$M_{opt}(u) = e^{-2\pi^2 \sigma^2 u^2}$$

$$\sigma = \sqrt{\sigma_0^2 + (C_{ab} d)^2}$$

$$d = 5 - 3 \tanh(0.4 \log(L X_0^2 / 40^2))$$

$$E = \frac{\pi d^2}{4} L \left(1 - (d/9.7)^2 + (d/12.4)^4 \right)$$

$$k = 3.0$$

$$\sigma_0 = 0.5 \text{ arc min}$$

$$C_{ab} = 0.08 \text{ arc min/mm}$$

$$T = 0.1 \text{ sec}$$

$$X_{max} = 12^\circ$$

$$N_{max} = 15 \text{ cycles}$$

$$\eta = 0.03$$

$$\Phi_0 = 3 \times 10^{-8} \text{ sec deg}^2$$

$$u_0 = 7 \text{ cycles/deg}$$

$$p = 1.25 \times 10^6 \text{ photons/sec/deg}^2 / T d$$

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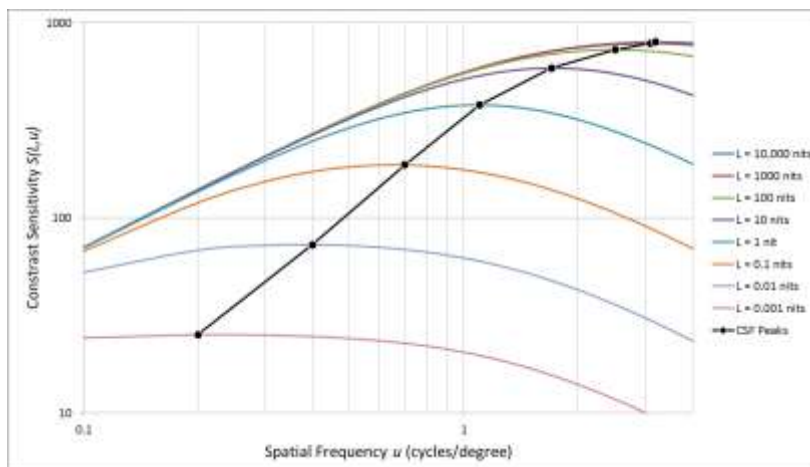
Creating JND steps with Barten

- Barten parameters chosen conservatively
- 40 degree angular size
- Vary spatial frequency at every luminance level to track peaks of the CSF
- Select peak luminance level
- Iteratively calculate the rest of the steps



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Tracking Peaks of Contrast Sensitivity



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Sensitivity, Modulation, and Luminance

- Once we know the the sensitivity $S(u)$, we also know the modulation threshold (m_t):

$$m_t = \frac{1}{S(u)}$$

- From the definition of modulation, we also know the relationship between it and two levels of luminance under test:

$$m = \frac{L_{max} - L_{min}}{L_{max} + L_{min}} \quad \text{so:} \quad L_{max} = L_{min} \frac{1+m}{1-m} \quad \text{or} \quad L_{min} = L_{max} \frac{1-m}{1+m}$$



Making the JND Based Curve

$$L_{j+1} = L_j \frac{1+m_t}{1-m_t} \quad \text{or} \quad L_{j-1} = L_j \frac{1-m_t}{1+m_t}$$

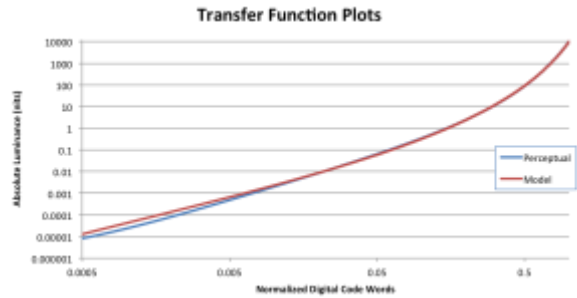
$$L_{j+1} = L_j \frac{1+f*m_t}{1-f*m_t} \quad \text{or} \quad L_{j-1} = L_j \frac{1-f*m_t}{1+f*m_t} \quad \text{where} \quad f < 1$$

- Start with 10,000 cd/m² peak level
- Pick JND fraction f such that a near-zero bottom level is reached at the other end of the range
- $f = 0.9$ JNDs per code word for a 12 bit, 10,000 cd/m² system



Functional Approximation

- Would be great to have a functional form of the Iterative LUT
- Helpful for standardization
- Simpler to document
- Invertibility is very useful
- Found good alignment with modified Naka-Rushton model



Perceptual Quantizer (PQ) EOTF

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

$$m_1 = \frac{2610}{4096} \times \frac{1}{4} = 0.1593017578125$$

$$m_2 = \frac{2523}{4096} \times 128 = 78.84375$$

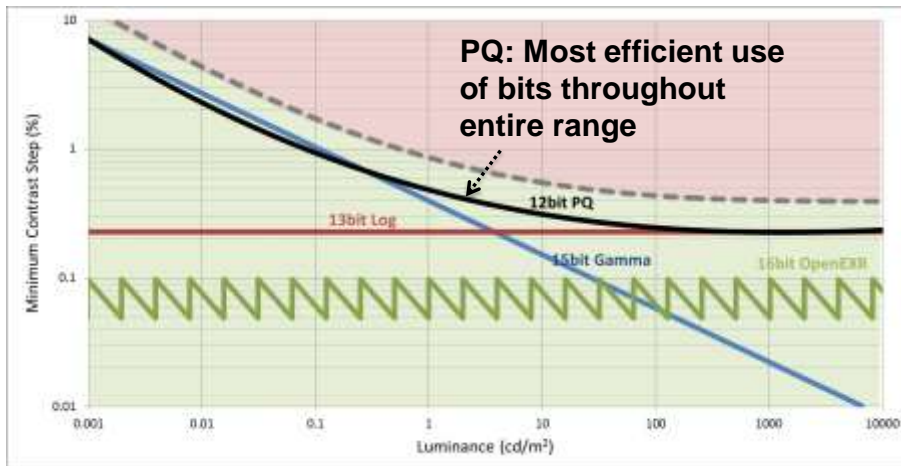
$$c_1 = \frac{3424}{4096} = 0.8359375$$

$$c_2 = \frac{2413}{4096} \times 32 = 18.8515625$$

$$c_3 = \frac{2392}{4096} \times 32 = 18.6875$$



Perceptual Quantizer (PQ)



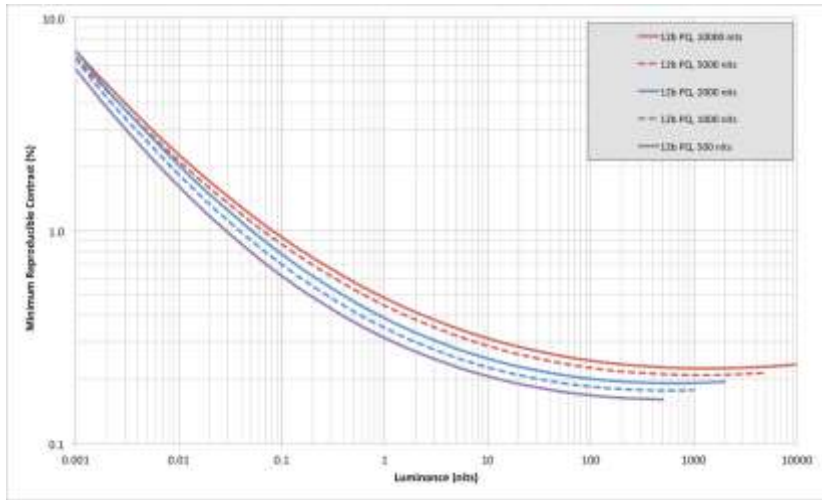
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Is a 10,000 cd/m² system overly ambitious?

- Wouldn't this "waste" a lot of code words that we won't be using for a while?
- The short answer is "No"
- The logarithmic shape of PQ at the top end allows substantial gains in peak brightness without costing huge numbers of code words
 - Think of it as headroom for further expansion
 - PQ headroom from 5000 to 10,000 cd/m² = 7% of code space
 - 100 cd/m² is near the midpoint of the code range
- Brighter displays are coming!
- If we were using traditional gamma curves, headroom waste would be a much bigger issue

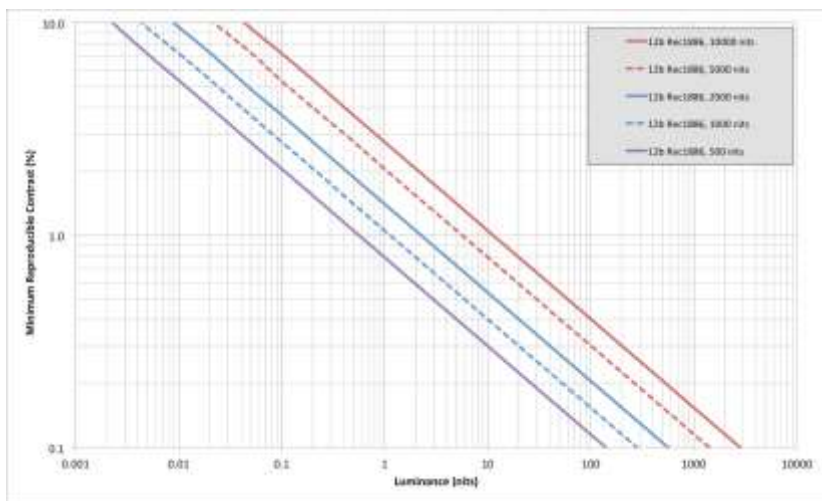
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EOTF Peak Variation for PQ



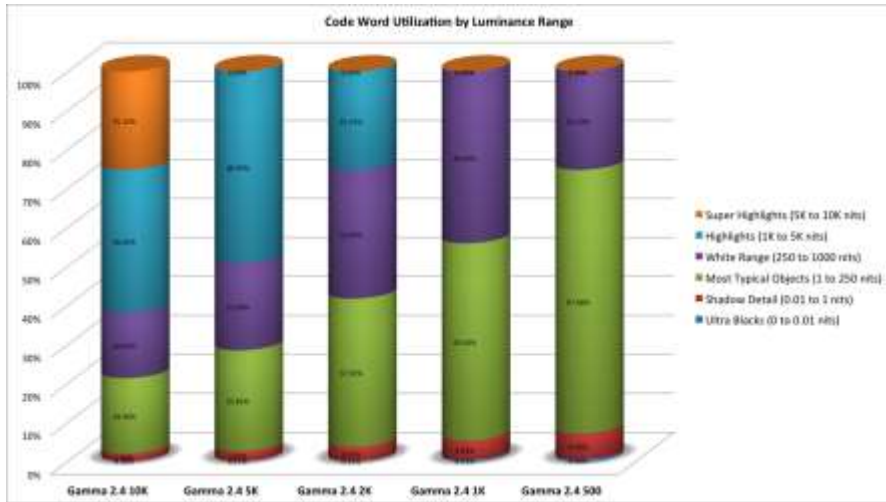
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EOTF Peak Variation for Gamma (Rec1886)



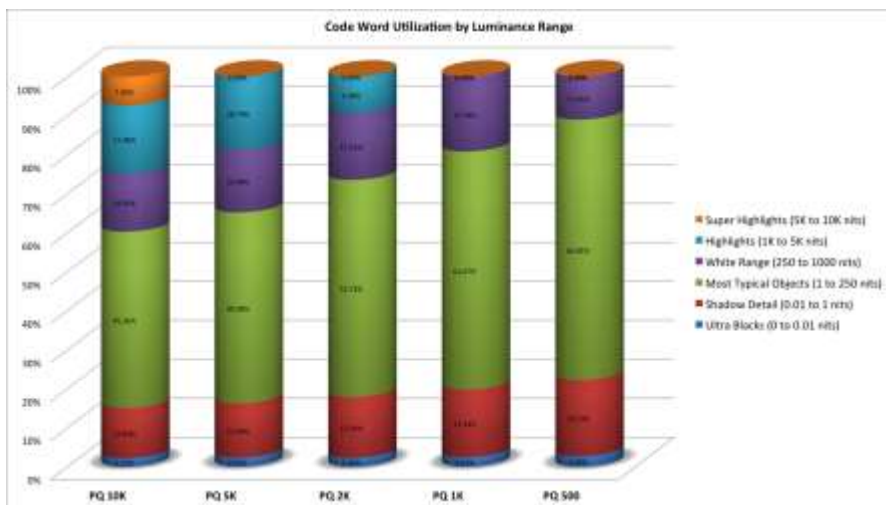
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Gamma (Rec1886) Code Words



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PQ Code Words



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Conclusions

- We need a standardized EOTF to define a new system for extended dynamic range
- Perceptual quantization is the most efficient way to encode extended dynamic range
 - Each code value corresponds to just under a perceptual step - less wasted codes
- A 10,000 cd/m² system makes a lot of sense
 - The extra dynamic range is appreciated, and preferred by viewers
 - It gives the system headroom for display improvements in the future
 - No more bits are required compared to ~1000 cd/m² systems



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Q & A



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