Real-Content Based Method for HDR Tone Curve Characterization

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Abstract

The classic window pattern with a black background is the basis of any display characterization, but nowadays, displays, particularly smartphone displays, integrate complex image processing and adaptations, meaning that they cannot be entirely characterized with these simple patterns. In this paper we discuss a new EOTF (Electro-Optical Transfer Function) measurement method performed directly on real-life scene HDR videos and show how this method relates to the display system user-experience.

Author Keywords

HDR; Display; Metrology; Tone Curve; Imaging Colorimeter

1. Introduction

In recent years, display technologies that allow larger dynamic ranges and wider color gamuts have reached the market of consumer electronics. This means that many more colors and much wider tone range from deep black to very bright can be accurately displayed. This is noteworthy in the smartphone industry where OLED displays have become widespread.

These new capabilities create new challenges for consumer electronics manufacturers, since they can and have to implement support for new HDR (High-Dynamic Range) formats. Moreover, the possible viewing environment of smartphone displays cover a wide diversity of ambient lighting conditions, ranging from complete darkness (0 lux) to direct sunlight (~100,000 lux). As a result, smartphones usually implement display pipelines including complex image processing that changes with the displayed content and the viewing conditions. The purpose of these complex display pipelines is to guarantee an appropriate contrast and comfortable average and peak brightness in all viewing use cases.

The complexities of these adaptations make evaluating a smartphone display more challenging: usually, a display characterization is performed using simple geometrical patterns, usually a colored rectangular window on a uniform black background. This is very different from content that would be displayed in a real usage scenario, and completely bypasses the software adaptation meant to improve user experience. Measurements made on these simple patterns could provide misleading results. Therefore, there is a need for new type of patterns and measurement methods

2. Limitations of common Measurement Targets

Let us first introduce the importance of characterizing EOTF (Electro-Optical Transfer Function) in displays, especially for smartphones, and the limitations of current methods and common measurement targets. The EOTF is a function that maps the encoded signal intensity of an image or video to luminance on a display

(a) EOTF and the HDR10 standard: One of the most adopted HDR video standard is HDR10. The EOTF for HDR10, video levels, is the PQ (Perceptual Quantizer), as defined in [3]. The PQ defines the absolute luminance to be displayed as a function of the encoded video levels, unlike most EOTFs (ie. gamma curve or HLG (Hybrid Log-Gamma) transfer function) which use relative brightness instead of absolute luminance. The PQ is suited for movie theaters and home television since the ambient lighting in these viewing conditions is usually controlled and doesn't vary too much. Meanwhile, smartphone displays must adapt to a wider diversity of lighting conditions and limit their peak brightness in the dark, therefore also reducing the dynamic range. This means that smartphone manufacturers usually need to adapt their device's EOTF to various patterns to guarantee optimal contrast for all.

(b) Preliminary work on smartphone EOTF adaptation: To confirm that smartphones do indeed adapt their EOTFs to displayed content, we perform a simple test. We measure the EOTF of an iPhone 14 Pro Max with a Konica Minolta CS2000 spectroradiometer on two separate sets of HDR10 video patterns. Pattern series 1 is a collection of classic gray window on black background, which is the standard way to characterize a display's EOTF [2] whereas pattern series 2 adds gray levels ranging through all signal levels outside of the measurement area. To ensure that there is no influence of veiling glare from the grey levels outside of the measurement area, we mask them using black tape. We can observe differences in the shape of the measured EOTFs: For pattern series 2, the curve is steeper in the brighter levels, and clipping occurs at a higher signal level as well. This shows that the measured device does indeed adapt its EOTF to the displayed pattern.

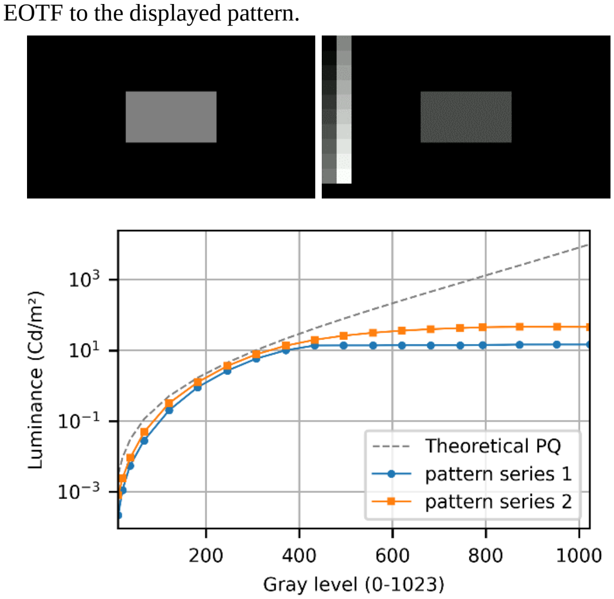


Figure 1. Sample patterns for series 1 (left) and 2 (right), and associated measured EOTFs on an iPhone 14 Pro Max

3. Establishing a new method

(a) Pattern selection: Since we have demonstrated that displayed content can influence the EOTF of a smartphone, we need to come up with patterns that match a typical use case for watching HDR videos. We use a selection of patterns of

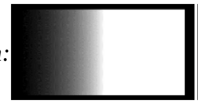
Pattern name:	***Gradient***	***Gray***	***Night***	***Park***	***Daylight***	***Sunset***
Pattern:						
Max signal level:	1023	847	894	808	615	771
Average signal level:	411	116	136	317	309	292
Proportion over 600:	33.2%	<0.1%	0.4%	6.7%	<0.1%	3.4%
Proportion under 200:	35.5%	74.6%	76.4%	28.3%	19.1%	36.9%

Figure 2. Patterns used for our measurements

captured real-life content, along with simpler gray gradient patterns. These patterns contain a variety of content. The "Gray" pattern depicts 8 transparent jars of different shades of gray paint on a black background, and the "Night" pattern includes a woman walking at night in a street while holding sparkler fireworks. These 2 having mostly dark tones with few to no bright tones. Other patterns like "Park" that depicts 3 people talking in a well-lit park outdoors, or "Sunset" that depicts a setting sun have mostly bright tones with some dark areas. "Daylight", that shows the outside of a monument filmed during the day, mainly has tones around the middle of the range, with few areas in the extreme darks or brights. The last pattern, "Gradient", is a simple gradient of grey levels covering the whole range of signal (0-1023). Its histogram is completely flat, and it is supposed to serve as a simple reference point to test the validity of our method.

To measure these patterns with an imaging colorimeter, we have modified the original patterns to display a single frame loop; this is required, since the capture time for the imaging colorimeter must be well over the duration of a single frame of a video stream to measure the dark areas. We make sure to preserve the original encoding and video levels in the process.

All our video patterns have a DCI 4K resolution (4096x2160), 10-bit color and all necessary metadata to comply to the HDR10 format.

(b) Cumulative histogram method

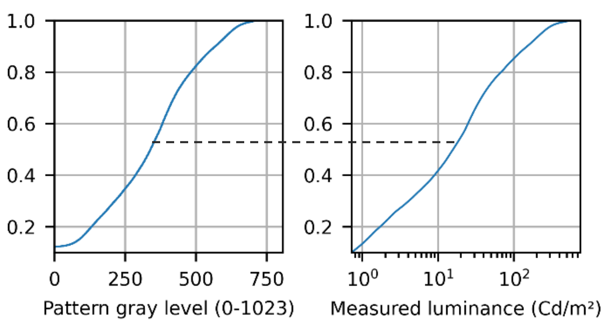


Figure 3. Cumulative histograms of a pattern and of the associated luminance measurement

With Y_0 a brightness signal level of a video frame we can define the cumulative histogram $H_A(Y_0)$ of a video frame as the proportion of the frame pixels that have a signal value smaller than or equal to Y_0. With L_0 the luminance measured with the imaging colorimeter we can similarly define the cumulative histogram of the measurement $H_B(L_0)$ as the proportion of pixels in the measured luminance map that have a luminance smaller than or equal to L_0. Both functions are by definition continuous and monotonically increasing, and their values are between 0 and 1. But since we are working on a discrete number of points for both the pattern and the measurement, we only measure a discrete number of points on these cumulative histograms. By performing linear interpolation between these data points, we can obtain functions that are both continuous and strictly monotonically increasing. We also know, by definition of the EOTF, that the measured luminance L relates to the EOTF as follows: $L = EOTF(Y)$. We also assume that the EOTF is the same on the whole display, and there are no local EOTF enhancements. Since the measured luminance is a transformation of the pattern grey level by the EOTF, and by assuming that the EOTF is also strictly monotonically increasing, then the statistical data of the pattern is preserved, and proportion of each grey level is translated to the luminance space. Therefore, we can deduce that if $H_A(Y_A)=H_B(L_B)$, then $L_B=EOTF(Y_A)$. It follows that we can recover the EOTF of the display from the cumulative histograms as follows:

$$EOTF(Y) = H_B^{-1} \circ H_A(Y)$$

The mathematical principle behind our method is similar to [4], which used cumulative histograms to recover the brightness transfer function from captured images. This method is robust to scaling, rotation and even blurring or slight changes in the scene since the cumulative histogtam is mostly preserved in these scenarios.

4. Testing on a reference display

To test the validity of our method, we have experienced it on a screen on which we control and master the whole display pipeline. For this we use a Sony BVM-HX310. This is a professional master monitor used for HDR color grading and video mastering. It has a large dynamic range, with a peak luminance of 1200 nits and the ability to display very deep blacks. Moreover, we have full control of the display pipeline and we setup the display so that the EOTF used for displaying HDR10 content will be the ST 2084 PQ, clipping at nits, regardless of video content.

We measure the patterns using a Radiant ProMetric I29 colorimeter, with a Canon 35mm lens with a 1.4x teleconverter. The imaging colorimeter uses a color and luminance calibration specific to the monitor to ensure the best possible fidelity for the measurement. To maximize the available measured dynamic range, we perform multi-exposure measurements. All measurements are performed in complete darkness.

Even though we have established previously that the method is robust to slight changes in orientation and scaling, we perform image registration to line up the measurement as well as possible with the original pattern. We simply measure a white rectangular pattern and perform corner detection to detect the active area of the display, then we make sure the imaging colorimeter and the measured display stay still between measurements.

The reference EOTF which we use to verify our method was measured with the Konica Minolta CS-2000 spectroradiometer on a series of gray windows on black background

The first results on our patterns show that the EOTF measured with our cumulative histogram method closely matches the reference EOTF for the brighter levels, but the dark tones (<300 signal level) appear a much higher measured luminance with our method, as shown on Figure 4.

The differences in brightness for the lower signal levels can most likely be explained by veiling glare [5]. Veiling glare is an artifact where bright objects in or outside the field of view of the capture device lens will create reflections inside the lens. These reflections make the scene appear brighter in the capture, which is especially noticeable on darker parts of the image. This is especially noticeable on the "Gradient" pattern. Even though the pattern was supposed to represent a simple test case, it is especially prone to veiling glare since a large portion of the image is above the clipping point, meaning that about 20% of the display surface is at peak brightness. Moreover, the dark parts are on the opposite side of the zones at peak brightness, relative to the center of the field of view, where flare artifacts are often the more visible.

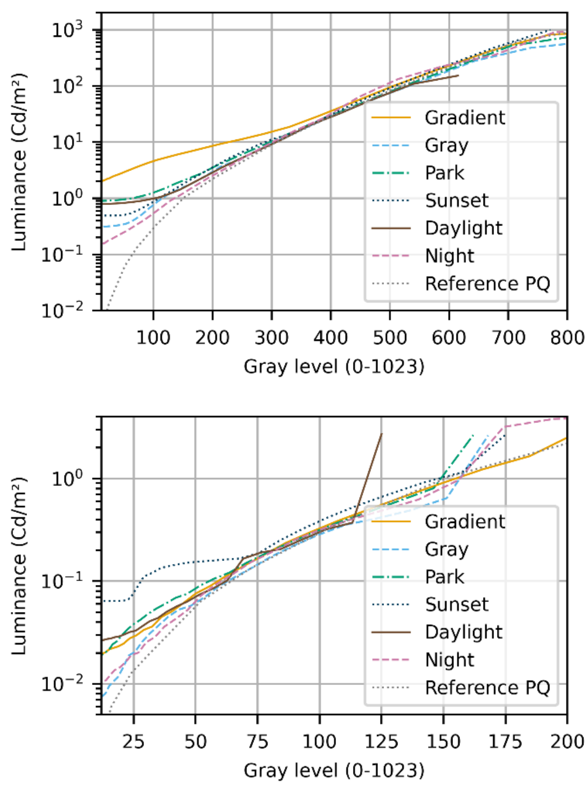


Figure 4. EOTFs measured with various patterns with our method. Top: regular patterns Bottom: patterns with only brightness levels in the range 0-200

To confirm that the limitation in measured dynamic range is not a limitation of the imaging colorimeter's sensitivity. We perform further testing, with new patterns based on the previously used ones. These patterns have their signal levels linearly scaled down so that the maximal grey value is 200 instead of 1023. We observe that the measured EOTF on these new patterns match the theorical EOTF more closely on the lower signal levels. This confirms that the issue is not linked to the sensitivity threshold of the imaging colorimeter but is dependent on the dynamic range of the measured content. These darker patterns can however not be used to characterize an arbitrary display since the displayed content is different enough to trigger an adaptation in the case of a smartphone display.

5. Results on smartphone displays

We now perform the same measurement campaign on a few smartphones. We choose an Apple iPhone 14 Pro Max, a Samsung S22 Ultra as well as a Xiaomi 12 T Pro. The goal is to have high-end smartphones from diverse manufacturers which deliver different peak luminance and EOTFs, and potentially adapt differently to the displayed content.

The measurement conditions are the same as for the reference monitor measurements, we use our Radiant ProMetric I29 colorimeter, with a specific calibration for each measured display. we perform multi-exposure measurements. Measurements are performed in complete darkness.

To assess the validity of our method and results, we use the EOTF measured on gray windows as previously. But as we demonstrated previously, this doesn't account for the device adapting its EOTF to displayed content. As such, we need another set of reference measurements.

We use a method like [1] to measure the device's EOTF on a given pattern: we generate a series of gray level spot targets overlaid on our pattern of captured real-life content. Measuring the EOTF with the spectroradiometer is much longer than measuring it using our method, since we measure 19 points, some requiring long exposure times up to 4 minutes. With this method, the measurement of an EOTF on one background takes 30-45 minutes on average. Therefore, for this study, we focus on only 2 patterns, the "Park" and the "Gray" patterns. We preserve all encoding parameters from our original patterns. We measure these targets using our Konica Minolta CS2000 spectroradiometer. To note that there is going to be some inevitable veiling glare on these spectroradiometer measurements since we haven't found any satisfying way to mask the whole background pattern for the measurement. However the impact of the veiling glare should be much smaller since the measurement spot covers most of the field of view of the CS2000 lens.

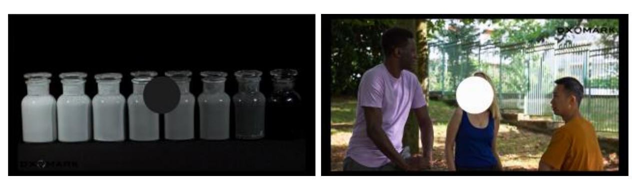


Figure 5. Sample patterns for reference spectroradiometer measurements

On neither the Xiaomi nor the Samsung phones could we observe conclusive evidence of EOTF adaptation to displayed content. However, on the iPhone 14 Pro Max we observe significant differences between the two measured patterns with the different background patterns, as seen on Figure 6. The EOTF on the "Gray" pattern clips at a lower signal level than the park pattern, and is steeper on darker tones Moreover, we can see that our method performs similarly to expose these different EOTF behaviors for different displayed patterns in the medium and bright tones (>300). This demonstrates that even though our method lacks accuracy in the darkest parts of a pattern due to veiling glare, it still allows us to accurately characterize the brightest part of the EOTF from the analysis of a single imaging colorimeter measurement.

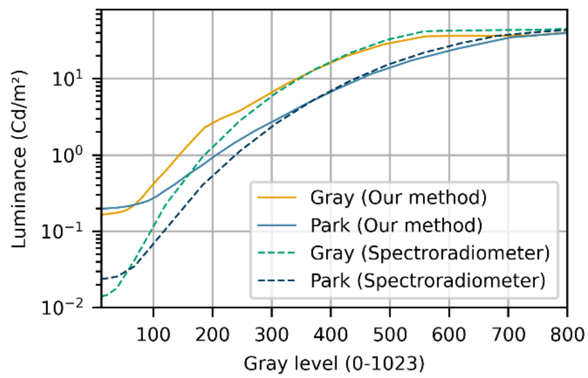


Figure 6. EOTFs of the iPhone 14 Pro Max measured with our method compared to EOTFs measured with gray targets on real content backgrounds

6. Limitations and possible future works

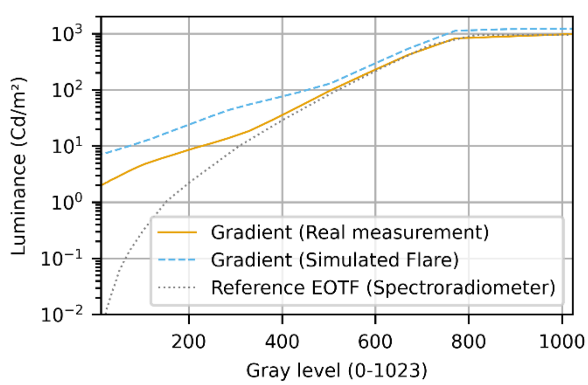


Figure 7. EOTFs measured on the reference display with our method and simulated measurement with flare modelling

To understand and quantify the limitations of our method, we performed some measurements to characterize the flare artifacts on our imaging colorimeter. We measure the glare spread function (GSF) for point light sources in the field by increments of 2.5°. [5, 6]

To quantify the measurement error on a specific pattern on our reference monitor, we can simulate the veiling glare using the pattern data, the measured GSF, and the real EOTF we measured with our spectroradiometer. We perform a simulation on the "Gradient" pattern, by making a few approximations. The comparison of the EOTF computed with this first simulation and the one computed with the actual measurement is shown on Figure 7. We can see that the behavior of the simulation is very similar to the actual measurement.

Contrary to the measurement method described in [1], our method doesn't account for the temporal component of video patterns, since we are limited to a single frame.

7. Conclusion

In a time where displays performance is continuously improving and most consumer electronics embed complex image processing and adaptations, it becomes necessary to develop new measurement methods that simulate actual use cases to better assess the real performance of a display systems in the hand of users.

We have confirmed that some smartphones adapt their EOTF to the content that is being displayed on screen. Previous literature such as [1] have proposed promising methods to go further than the classical window on black background for display measurements, but said method still requires slight alterations to the displayed content, and to measure an EOTF with enough precision takes more time than what would be optimal in a benchmarking context where there are lots of measurements to be performed.

Our method yields similar results than the method described in [1] to measure the EOTF and assess adaptations for tones in the upper part of the signal range (>300), while taking less time per EOTF measurement and requiring fewer alterations to the measured content.

However, we have identified veiling glare as a major limiting factor for the accuracy of our method for darker tones. Hopefully, there is a lot of potential for further investigation on how to improve our method by better characterizing and accounting for veiling glare.

8. References

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