# Design of a Framework for HDR Sequence Rendering Evaluation

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## Abstract

*A framework for evaluation of HDR video sequence rendering is proposed. We present the signal processing flow of an experimental configuration in which we placed a calibrated CRT monitor next to the HDR display to allow side-by-side evaluations. The HDR display was built using off-shelf components: a LCD panel and a DLP (Digital Light Projector). HDR images consisting of XYZ tristimulus images are converted to six channel images using HDR display characterization. The same HDR images in XYZ format can be tone mapped and rendered to the CRT display. Colorimetric measurement of random verification targets was taken from both calibrated displays and standard images were visually examined as well. Furthermore, we also evaluated how colorimetrically accurate is the image reproduction on HDR display compared to an original HDR scene. Based on the accuracy of the measurements and the visual match for the images we can conclude that we have a reasonably colorimetric accurate system to evaluate tone mapping algorithms. The specification of a computer system with processing and displaying capability for HDR video sequences is also presented showing specifications of what is required to perform this evaluation. We expect this framework to be useful as a reference to everyone trying to evaluate the accuracy of tone mapping for both HDR still image and image sequences.*

## Introduction

High-dynamic range (HDR) images are now becoming widely available. Computer generated imagery, from games and other applications, is the most common source, but a growing number of alternatives exist for natural image capture. Of special interest to the authors, is high frame rate HDR image capture, as exemplified by Pixim's DPS.[1] The development of HDR displays has lagged the availability of HDR content, and most HDR images must be tonally compressed to be viewed with typical CRT and LCD displays. To support this dynamic range compression, many researchers have proposed methods for rendering high-contrast HDR images to non-HDR displays.[2-11] Such rendering methods are basically strategies to perform tone mapping. For further details, several of these tone mapping algorithms are reviewed by Devlin.[12] Some of these researches also explore time-dependent visual adaptation rendering.[13, 14]

The abundance of proposed tone mapping algorithms lead to researches in HDR image rendering to perform psychophysical evaluation experiment comparing a HDR image or scene with a tone-mapped image.[15,16] However, as stated in the CIE TC8-08: Spatial Appearance Modelling and HDR Rendering, it is necessary to make comparisons of rendering algorithms against an original to evaluate its accuracy of appearance.[17] Since it is not practical to have an original nature HDR scene always available under a controlled observation condition,[18] it is necessary to build display devices that improves dynamic range capabilities by many orders of magnitude compared to current displays in order to show the original scene. Such HDR displays, although still rare, can be built. Seetzen *et al*.[19-20] have presented several systems capable of displaying images with dynamic range typical to what is seen in the real world. One of the proposed display systems is based on a combination of off-the-shelf components consisting of a Digital Light Projector (DLP) and an LCD panel. This HDR display is based on a dual modulation principle, where the LCD panel is used as an optical filter that modulates a high intensity but lower resolution image coming from the DLP projector. We have implemented a system similar to Seetzen's *et al.*, with the notable exception that while their design required the filter wheel of the DLP projector to be removed in order to reduce light loss, in our own design we kept the filter color wheel in place. This eliminated unnecessary problems of electronic synchronization and increased the color gamut of the HDR display system. Increasing the color gamut was not the main motivation for building this display such as in the multi-primary display systems available to render spectral images.[21,22] Rather, the goal was to build a display system that provides sufficient gamut to reduce color matching errors and thereby allow side-by-side comparisons to support our work on HDR video sequence rendering algorithms. Ledda et al. published studies evaluating HDR displays against reality in terms of contrast ratios, appearance and peripheral vision.[23] In our previous study, we were able to colorimetrically characterize a HDR display.[24] In the study presented here, we extend the colorimetric characterization to the system including image capture, in order to evaluate how colorimetrically accurate is the image reproduction on HDR display compared to an original HDR scene. We also included a study of a colorimetric comparison between HDR display and a conventional low-dynamic range display (LDR) for non-HDR scenes. This verification is fundamental since appearance modeling of HDR scenes is going to benefit from an accurate calibration. Furthermore, manipulation of HDR image sequences can be computationally intensive and it requires a framework design that supports all the necessary computation. Thus, this article also presents a framework for HDR image sequence evaluation showing calibration procedures, processing flow and system description.

## Processing Flow

We have placed a calibrated CRT monitor next to the HDR display to allow side-by-side evaluations. The processing flow for these experiments is shown in Figure 1. It shows how the captured image of the original scene was displayed on both HDR and CRT displays. We started with the capture of a HDR scene whose tristimulus $XYZ_m$ values were also measured. The capture produced a raw linear data that was processed to give a reconstructed $XYZ_r$ tristimulus image. This image was our reference and starting point for both HDR display rendering and tone-mapping rendering for the CRT (LDR) display. For still images, these values are calculated from high-dynamic range RGB data, passed through a standard 3x3 color transformation matrix. For image sequences, we have the capability of using the Pixim DPS sensor architecture to capture 60 fps, high-dynamic range, raw CFA data at 720 columns by 540 rows in resolution, which we process to produce XYZ values.

The HDR display system was capable of showing 14 bit dynamic range data. We scaled the XYZ reference values to fit within the 1400 cd/m2 range of the HDR display. Using our HDR inverse model, we produced a sextuplet of values ($R_PG_PB_P$ values for the DLP and $R_LG_LB_L$ values for the LCD) that drive the HDR display.

The CRT display can reproduce up to 183 cd/m2 of luminance. For scenes that are within the capabilities of the CRT display, there is no need for rendering using tone mapping operators. One important consideration was the angular and spatial non-uniformity of both displays. The angular non-uniformity was particularly severe for the HDR display. In order to broaden the image viewing angles, a diffuse surface was set against the front of the LCD panel holding it with a glass panel. We also used the original LCD display lenticular-type sheet in addition to the diffusion sheet to improve the light throughput. The remaining residual spatial non-uniformity was compensated for by applying a spatial roll-off compensation to the XYZ tristimulus values, accounting for the spatial non-uniformities of both HDR and CRT displays. The spatially corrected image is then passed through the CRT inverse model to produce an image that matches well with the HDR display.

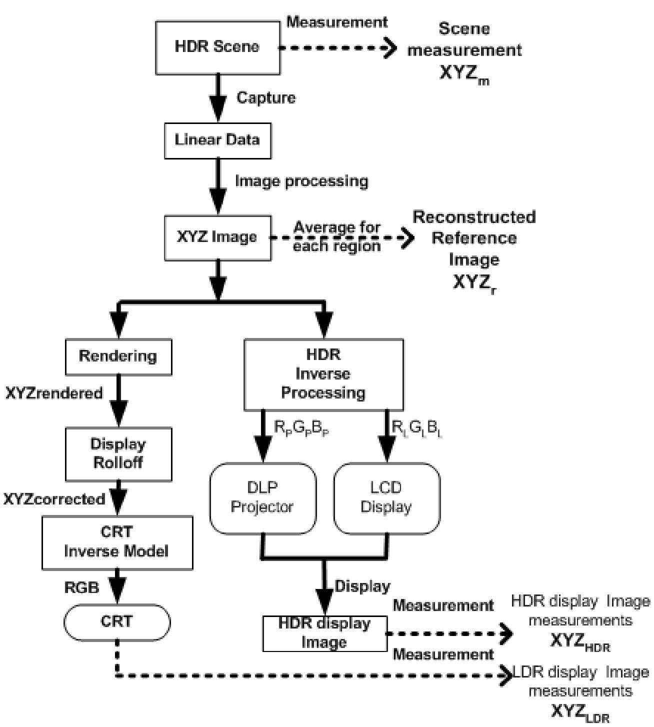



*Figure 1. Processing flowchart.*

For HDR scenes, there is a need to map the XYZ reference values to fall within the capabilities of the CRT display. Our main focus has always been on the tone mapping operation, however, early on in our work, we discovered that for reliable evaluations, it was important to ensure color fidelity to minimize the distractions caused by color mismatches in the scene. The CRT and HDR inverse models are going to be explained in more detail in the section of calibration process for CRT and HDR displays.

## System Description

An HP xw8200 workstation drives the displays in this system, shown in Figure 2. Attached to this workstation is an Nvidia Quadro FX3400 PCI express graphics card, a BlackMagic Decklink Extreme 10-bit SDI board, and an Nvidia FX5200 PCI graphics board. The FX3400 is a dual-display card that drives the DLP projector and the LCD panel of the HDR display. It provides the bandwidth necessary to display 60 fps HDR sequences. The DeckLink Extreme card drives the CRT display. It has the ability to play uncompressed 10-bit SDI video streams through its QuickTime drivers. Because of the physical setup, the HDR display requires an upside down image on the LCD panel, and a reversed image on the DLP projector. As such, it is impractical to use the FX3400 for normal interaction with the system, hence the addition of the FX5200 card. It has two LCD flat panel displays attached to it. On the workstation, the desktop is extended through all five output displays. The FX3400 has the ability to couple its two displays into a single rendering surface. This capability allows the display of HDR sequences in real time by defining an OpenGL display buffer that spans across the two displays, and blitting an LCD surface and DLP surface into the buffer every 1/60$^{th}$ of a second, with double buffering. Of particular note is that this method ensures that the two DLP and LCD images are synchronized. The workstation is equipped with sufficient memory to buffer 300 frames of HDR data. This is what currently limits the length of HDR image sequences that can be displayed. Note that for still images, it is sufficient to simply use MATLAB code to process, display and place the windows in the appropriate locations within the desktop. The majority of the work was first done on still images to validate our setup and to work out our original ideas. However, since our eventual goal is to apply any algorithms we develop towards real-time video processing of HDR scenes, we developed the system with the ability to validate on HDR sequences.

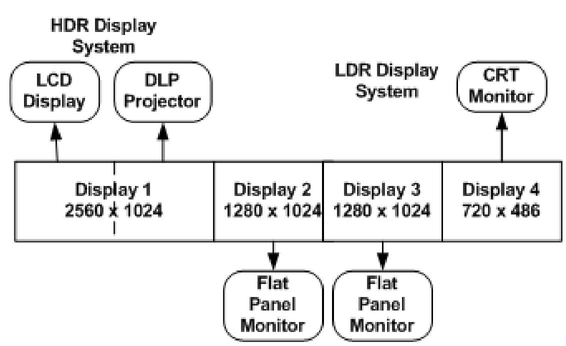



*Figure 2. Desktop Setup*

Because of the computationally intensive nature of sequences, we found it necessary to write our code to encapsulate the processing for each frame. This allows us to submit our jobs into a Linux server farm, distributing the processing across 20 servers, resulting in $1/20^{th}$ reduction in processing time. A frame of NTSC resolution data took approximately 20 minutes to process. At 300 frames (5 seconds real time), this would take 100 hours, far too long. By using parallel processing, this can be reduced to 5 hours, which is much more conducive to our research work, as we can submit jobs for processing overnight, and return the following day to do our evaluation.

## Calibration Process for CRT and HDR Displays

### LDR Display Characterization

A 19-inch Sony CRT Model PVM-1954Q Trinitron color video monitor was used to display rendered HDR images using tone mapping algorithms. The following standard procedure was used to pre-set the CRT display before calibration:

1. Warm-up for at least 10 minutes since the adjustments are not going to be accurate on a cold monitor.
2. Display SMPTE style color bars on monitor. We used a Textronix TSG200 NTSC generator.
3. Follow standard procedure to adjust brightness, contrast, chroma (color level) and color phase (tint or hue) knobs.25
4. In order to provide repeatability, the chromaticities and luminance of white (corresponding to red, green and blue values set to 255) is measured.

The Sony CRT display was calibrated using Photo Research PR-650 spectroradiometer to measure primaries and gray ramps. We measured XYZ tristimulus values setting the lens tip of the spectroradiometer 45 cm apart from the surface of the display pointing perpendicularly to its center. All measurements were taken in a dark environment. The lens was slightly defocused to avoid capturing structures on the diffused light coming from the CRT display. The CRT characterization models (both forward model from RGB to XYZ and inverse model from XYZ to RGB) were built using conventional CRT calibration procedure by calculation of linearization transfer curve and color transformation.[26]

### HDR Display Characterization

The colorimetric characterization of a HDR display can be divided in a forward model that estimates XYZ tristimulus values from devices red, green and blue signals and inverse model that estimates DLP projector and LCD panel sextuplets from XYZ. Several models have been proposed for the LCD display colorimetric characterization[27] and DLP colorimetric color management[28] and we recently published a characterization research of a high-dynamic range display system constituted by both DLP and LCD panel.[24] One of the greatest roadblocks for an accurate characterization is the fact the most common type of DLP projects uses a fourth clear filter besides red, green and blue. Therefore, a white linear signal has to be estimated from red, green and blue of the projector. This white channel is used to increase intensity when red, green, blue values surpass a certain threshold. A spectral-based High-Dynamic-Range (HDR) display model that estimates colorimetric XYZ tristimulus values from sextuplets of digital signals consisting of triplets of values for Liquid Crystal Display (LCD) monitor and triplets for the Digital Light Projector (DLP) has been proposed.[24] An inverse transformation was also derived based on an initial split followed by a search procedure using derived forward model.

#### HDR Display Forward Model

Due to limitations in space, the full development of the model is omitted. For further details, please read reference 24. In this model, the spectral radiance coming out from the LCD panel can be modeled by the attenuation function of the LCD panel and the spectral power radiance coming from the DLP reaching the back of the LCD panel. Using the principle of channel additivity for both LCD panel and HDR display combined with dimension reduction by means of eigenvector analysis it possible to derive the XYZ tristimulus value estimation for HDR display as follows:

$$XYZ_{HDR} = \sum_{i=1}^{4}\sum_{j=1}^{3} P_{i,j} C_{i,j}(D_{DLP,i}, D_{LCD,j}) \,, \qquad (1)$$

where $P_{i,j} = \mathrm{K} M_{\lambda} E_{\lambda,i,j}$ is a 3 by 3 matrix, where K is a scaling coefficient, $M_{\lambda}$ contains the color matching functions and $D_{DLP,i}$ and $D_{LCD,j}$ are respectively quantized digital signals from DLP channel *i* and LCD channel *j*. $C_{i,j}$ is a two-dimensional look-up-table that relates pairs of quantized digital signals to eigenvector coefficients that are used to estimate spectral radiance in conjunction with corresponding eigenvectors $E_{\lambda,i,j}$.

#### HDR Display Inverse Model

The inverse transformation is based in three parts. At first, we performed an initial split using a gamma curve with exponent 0.3 for the projector digital values normalized between 0 and 1, and used its inverse for the LCD values. Then, the LCD panel and DLP values were quantized from integer values between 0 to 255 and forward model is used to perform a search of the LCD panel signals assuming that the DLP signals are accurate. Finally, a refinement was run for the projector values for the sextuplets with LCD values that are close to 255 and which are yielding luminance Y values that are too low.

## Experiments

We built our HDR display system using a 17-inch ViewSonic VA720 LCD panel and a BenQ DLP. Both DLP and LCD panel were set on an optical table with a black fabric covering the light path. The distance from DLP lens tip and the back of the LCD panel was 85 cm. Spectral radiance measurements were performed in dark surroundings using Photo Research PR-650 spectroradiometer. At first, we measured the spectral radiance from DLP reaching the back of the LCD panel by setting the spectroradiometer lens tip 150 cm apart from the center of a card coated by barium sulphate that we used as our standard white. The white card was set parallel to the back of the LCD panel and the spectroradiometer was set behind the DLP. Ramps of red, green, blue and gray (i.e., when red, green and blue levels were same) were measured. The ramps for the white clear channel were calculated by subtracting the sum of red, green and blue channel spectral radiances from gray spectral radiances.

Next, we measured the spectral radiance from the front of the LCD panel setting the lens tip of the spectroradiometer 45 cm apart from the LCD panel pointing perpendicularly to its center. The lens was slightly defocused to avoid capturing structures on the diffused light coming from the LCD panel. We measured the ramps for red, green and blue channels of the LCD setting the DLP channels to their maximum values. Fifty-two measurements were performed for each of LCD panel and DLP channels from digital level 0 to 255 in intervals of 5 units. The data captured for both LCD panel and DLP were later interpolated to have the spectral radiance for all 256 levels.

### *Verification of Colorimetric Accuracy between Measured HDR Display ($XYZ_{HDR}$) and Reference ($XYZ_r$) Tristimulus Values*

We generated 100 sextuplets randomly as a verification set for the forward model. This random set was built in order to comprise 20 sextuplets that have DLP digital values above the threshold to activate white channel. We measured the XYZ tristimulus values of the random colors displayed on LCD with the same set-up as the LCD panel red, green and blue ramps measurement. An additional verification set with 280 colors was generated to test the inverse transformation. It consisted of a collection of 14 spectrally flat neutrals that results in luminance values that span most of the measurable dynamic range of the display from 0.5 to 1400 cad/$m^2$, 4 octaves of 24 colors of the GretagMacbeth ColorChecker generated from its measured spectral reflectances and finally 170 object colors from Vrhel database.[29] All color samples were rendered and evaluated using 2 degree observer and CIE D65 standard illuminant. XYZ tristimulus values were also taken with the spectral measurements with same measurement geometry used in the calibration and the luminance for the white was used to determine the coefficient K in the colorimetric calculations shown above.

### *Verification of Colorimetric Accuracy between Measured LDR ($XYZ_{LDR}$) and HDR Display ($XYZ_{HDR}$) Tristimulus Values*

Although we can infer from our calibration procedure that we can match colorimetrically in-gamut images shown in both HDR and CRT displays, we decided to perform a verification using 55 randomly generated XYZ tristimulus values that are inside the dynamic range and color gamut of both displays. The CRT display inverse model was used to derive triplets of RGB from XYZ values. The HDR display inverse model was used to derive sextuplets from XYZ values. Uniform regions are shown in the center of both displays with the estimated triplets and sextuplets values. We measured the XYZ tristimulus values from the both displays using the PhotoResearch PR-650 spectroradiometer in a dark environment. The lens tip of the spectroradiometer was set 45 cm apart from the display, for both display measurements, pointing perpendicularly to its center.

### *Verification of Colorimetric Accuracy between Measured HDR Scene ($XYZ_m$) and Reference ($XYZ_r$) Tristimulus Values*

A HDR scene was produced inside a Macbeth SepctraLight III light booth comprised of a GretagMacbeth ColorChecker under D65 illuminant and a mini ColorChecker inside a dark tunnel cavity. A dark cardboard window frame was built in front of the light booth in order to reduce flare and to provide same viewing field as the image displayed on the HDR display. The linear data was captured using a Pixim video camera with CMY CFA and 5 to 50 mm lens 1:1.4 Pelco 1/3 inch CCTV CS CE ASPHERICAL lens. The iris of the lens was all open and the distance from the tip of the lens to the front of the light booth was 90 cm. The captured linear image was processed to produce XYZ image. Colorimetric measurements were taken using a PR-650 spectroradiometer, from the same geometry used for imaging.

## Results

### *Results for the Verification of Colorimetric Accuracy between Measured HDR Display ($XYZ_{HDR}$) and Reference ($XYZ_r$) Tristimulus Values*

#### *Forward Model Accuracy*

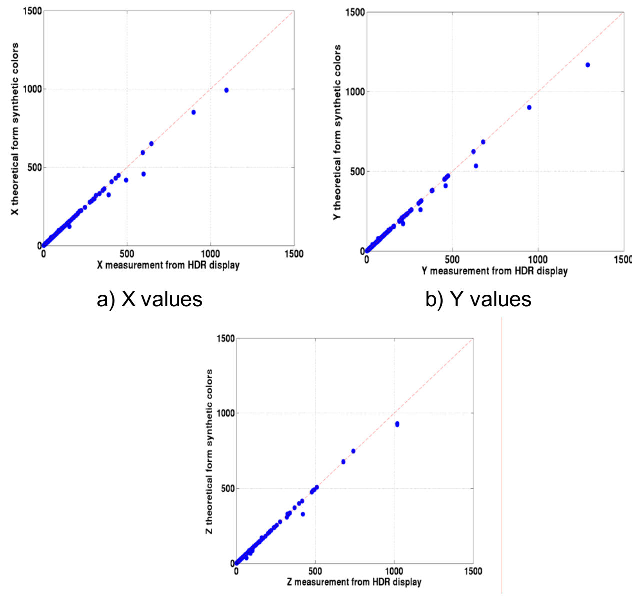
When we compared measured 100 random color values, the estimated XYZ tristimulus values correlated well with measured values, except for colors correspond to bright and saturated yellow and orange colors. It shows that our model is inaccurate in this region of color space. The average and maximum CIEDE2000 was respectively 2.1 and 11.6. The forward model was reasonably accurate except in very bright and chromatic yellow and orange colors. Further details can be found in Ref. [24].

#### *Inverse Model Accuracy*

Figure 3 shows the correlation between reference $XYZ_r$ and measured $XYZ_{HDR}$ tristimulus values when the estimated sextuplets from inverse transformations were displayed on HDR display. It is possible to observe from Figure 3 that most of the measured XYZ tristimulus values matched well with the original XYZs. Not surprisingly, there were mismatches for the yellow, orange and orange-yellow colors from the brightest octave of the color checker that were underpredicted because these correspond to the color region in which the forward model had accuracy problems besides the fact that some of these colors are also out-of-gamut of this HDR display. There were also two XYZ tristimulus values corresponding to the brightest color checker white and brightest neutral that were also underpredicted. We discovered that our refinement search finds local minima for those very bright colors. Further optimization procedures may overcome this problem. Excluding 7 of these outliers, the CIEDE2000 was respectively 2.4 and 7.7 for average and maximum values. The inverse transformation also provided reasonable performance except for out-of-gamut and very bright colors.

### *Results for the Verification of Colorimetric Accuracy between LDR ($XYZ_{LDR}$) and HDR Displays ($XYZ_{HDR}$) Tristimulus Values*

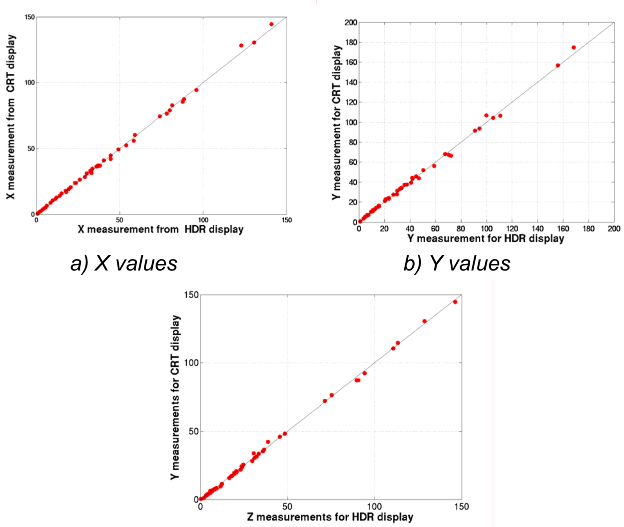
A comparison between XYZ tristimulus values measured for CRT and HDR displays are shown in Figure 4. We can observe that both CRT and HDR displays give approximately the same colorimetric values for this independent data. We also verified image visual matches between CRT and HDR displays. We used two images from ISO 12640 CMYK/SCID standard colour image data. The CIELAB images for the musicians and fruit basket shown in Figure 5 were converted to XYZ images under D65 and 2 degree observer and these XYZ images were further rendered on CRT and HDR displays using the processing flow shown in Figure 1. The rendered images were displayed simultaneously on HDR and CRT displays and both matched visually very well in luminance and color.




a) X values b) Y values

c) Z values

*Figure 3. Comparison between reference and measured XYZ tristimulus values from sextuplets obtained by inverse transformation from the reference XYZ values.*




*a) X values* *b) Y values*

*c) Z values*

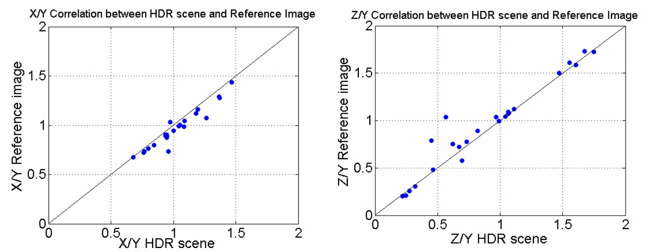
*Figure 4. Comparison of measured XYZ tristimulus values between CRT and HDR displays.*

### *Results for the Verification of Colorimetric Accuracy between Measured HDR Scene ($XYZ_m$) and reference ($XYZ_r$) Tristimulus Values*

The uniform regions of the reference images were averaged to obtain $XYZ_r$. One problem encountered in this experiment was flare that reduces the dynamic range of captured image. In order to check the preservation of chroma and hue X/Y and Z/Y ratios were compared as shown in Figure 6.


*a) Fruit basket* *b) Musicians*

*Figure 5. ISO 12640 CMYK/SCID standard colour images used for the visual match experiment.*




*a) X/Y ratio* *b) Z/Y ratio*

*Figure 6. Comparison between HDR scene and estimated reference image.*

From figure 6, it is possible to see that with the exception of some outliers the X/Y and Z/Y ratios of the reference image correlates well with measurements taken directly from the original HDR scene.

## Conclusion and Discussions

A framework for HDR video sequence rendering evaluation is described. Early experiences with the system demonstrated the need for good color fidelity to enable useful side-by-side comparisons. It is verified that the system has reasonable colorimetric accuracy comparing original scene with XYZ image and this reference XYZ image with HDR display and the LDR display for in-gamut colors. Since we verified that we have a controllable experimental framework with appropriate equipment that are properly calibrated, we can use this system to test different rendering approaches for both still and sequence HDR image. Although further refinements can be performed to improve the model's accuracy we believe that the accuracy shown above is sufficient for our HDR video rendering experiments. The majority of the work to date has focused on ensuring an acceptable level of accuracy while displaying at video frame rates. A remaining challenge is to reduce the amount of time needed to prepare the data for the HDR display, as it currently requires several hours and extensive computational resources. Despite this long turn-around time, the system has proven useful and preliminary experiments suggest that this system will prove to be an invaluable aid when designing future HDR video cameras. Other aspects that have to be mentioned are how to deal with flare that is responsible for reduction in dynamic range during capture and how to deal with spatial correction that is responsible for inaccuracies in the rendering. Future work includes conducting psychovisual experiments for tone rendering algorithm evaluation, and simulations of the video control characteristics when capturing HDR scenes as well as consideration of appropriate video encoding for HDR scenes.[30]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## References


1. W. Bidermann, A. El Gamal, S. Ewedemi, J. Reyneri, H. Tian, D. Wile and D. Yang, A 0.18 µm High Dynamic Range NTSC/PAL Imaging System-on-Chip with Embedded DRAM Frame Buffer, in Proc. of ISSCC, 2003.
2. P. E. Debevec, Rendering synthetic objects into real scenes: Bridging traditional and image-based graphics will global illumination and high dynamic range photography, in Proc. of ACM SIGGRAPH 98, M. Cohen, Ed., 1998, pp. 189-198.
3. J. M. Dicarlo and B. A. Wandell, Rendering high dynamic range images, in Proc. of SPIE image sensors, 1999, pp. 392-401.
4. G. Ward, High dynamic range imaging, in Proc. of IS&T/SID 9th Color Imaging Conference, IS&T, Springfield, VA, 2001, pp. 9-16.
5. F. Durand and J. Dosey, Fast bilateral filtering for the display of high-dynamic range images, in Proc. of ACM SIGGRAPH 02, ACM Press, 2002, pp. 257-266.
6. E. Reinhard, M. Stark, P. Shirley and J. Ferwerda, Photographic tone reproduction for digital images, in Proc. of ACM SIGGRAPH 02, ACM Press, 2002, pp. 267-276.
7. R. Fattal, D. Lischinski and M. Werman, Gradient domain high dynamic range compression, in Proc. of ACM SIGGRAPH 02, 2002, ACM Press, pp. 441-448.
8. G. M. Johnson and M. D. Fairchild, Rendering HDR Images, in Proc. of IS&T/SID 11th Color Imaging Conference, IS&T, Springfield, VA, 2003, pp. 36-41.
9. D. Gadia, D. Marini and A. Rizzi, Tuning Retinex for HDR images visualization, in Proc. of 2nd European Conference on Color in Graphics, Imaging and Vision CGIV 2004, Aachen, Germany, 2004, pp. 326-331.
10. J. Duan, G. Qiu and G. Finlayson, Learning to display High Dynamic Range images, in Proc. of 2nd European Conference on Color in Graphics, Imaging and Vision CGIV 2004, Aachen, Germany, 2004, pp. 524-547.
11. M. D. Fairchild and G. M. Johnson, The iCAM framework for image appearance, image differences, and image quality, J. of Electronic Imaging 13 126-138 (2004).
12. K. Devlin, A review of tone reproduction techniques, Technical report CSTR-02-005, Department of Computer Science, University of Bristol, 2002, http://www.cs.bris.ac.uk/~devlin/tonemapping.html
13. M. D. Fairchild and G. M. Johnson, Imaging appearance modelling, in Proc. of SPIE 5007, SPIE/IS&T Electronic Imaging, B. E. Rogowitz, t. N. Pappas, Eds., Bellingham, WA, 2003, pp. 149-160.
14. S. N. Pattanaik, J. E. Tumblin, H. Yee and D. P. Greenberg, Time-dependent visual adaptation for realistic image display, in Proc. of ACM SIGGRAPH 2000, Computer Graphics Proceedings, Annual Conference Series, ACM Press, 2000, pp. 47-54.
15. J. Kuang, H. Yamaguchi, G. M. Johnson and M. D. Fairchild, Testing HDR image rendering algorithms, in Proc. of IS&T/SID 12th Color Imaging Conference, IS&T, Springfield, VA, 2004, pp. 315-320.
16. P. Ledda, A. Chalmers, T. Troscianko and H. Seetzen, Evaluation of tone mapping operators using a high dynamic range display, in Proc/ of SIGGRAPH 2005, ACM Press, New York, 2005, pp. 640-648.
17. G. M. Johnson, Cares and concerns of CIE TC8-08: Spatial Appearance Modeling & HDR imaging, SPIE/IS&T Electronic Imaging Conference, Bellingham, WA, 2005.
18. A. Yoshida, V. Blanz, K. Myszkowski and H. P. Seidel, Perceptual evaluation of tone mapping operators with real-world scenes, in Proc. of SPIE 5666, Bellingham, WA, 2005, pp. 192-203.
19. H. Seetzen, L. Whitehead and G. Ward, High Dynamic Range Display Using Low and High Resolution Modulators , Society for Information Display International Symposium Digest, 2003.
20. H. Seetzen, W. Heidrich, W. Stuerzlinger, G. Ward, L. Whitehead, M. Trentacoste, A. Ghosh and A. Vorozcovs, High Dynamic Range Display Systems, in Proc. of ACM Trans. Graph. SIGGRAPH 04, ACM Press, 2004, pp. 760-768.
21. Th. Boosmann and B. Hill, Estimation of Control Values for a 6-Primary Display Considering Different Observers, in Proc. of 2nd European Conference on Color in Graphics, Imaging and Vision CGIV 2004, Aachen, Germany, 2004, pp. 242-247.
22. Y. Murakami, J. Ishii, T. Obi, M. Yamaguchi and N. Ohyama, Color conversion method for multi-primary display for spectral color reproduction, J. Electronic Imaging 13 701-708 (2004).
23. P. Ledda, A. Chalmers and H. Seetzen, HDR displays: a validation against reality, in Proceedings of IEEE International Conference on Systems, Man and Cybernetics, 2004, pp. 2777-2782.
24. F. H. Imai, D. Kuo and R. J. Motta, Colorimetric characterization of a HDR display system, in Proc. of the 10th Congress of the International Colour Association AIC Colour 05, Granada, Spain, 2005. pp. 653-656.
25. http://www.videouniversity.com/tvbars2.htm
26. R. S Berns, R.J. Motta and M. E. Gorzinski , CRT colorimetry. I. Theory and practice, Color Res. Appl. 18, 299 314 (1993).
27. D. C. Day, L. A. Taplin and R. S. Berns, Colorimetric characterization of a computer-controlled liquid crystal display, Color Res. Appl. 29, 365-373 (2004).
28. D. R. Wyble and M. R. Rosen, Color management of DLP projectors, in Proc. of IS&T/SID 12th Color Imaging Conference, IS&T, Springfield, VA, 2004, pp. 228-232.
29. M. J. Vrhel, R. Gershon, L. S. Iwan, Measurement and analysis of object reflectance spectra, Color Res. Appl. 19, 4-9 (1994).
30. R. Mantiuk, G. Krawczyk, K. Myszkowski, H. P. Seidel, Perception-motivated High Dynamic Range Video Encoding, in Proc. of SIGGRAPH 04 (Special issue of ACM Transactions on Graphics), ACM Press, 2004, pp. 733-741.


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