15.1: *Invited Talk:* Spatial Comparisons: The Antidote to Veiling Glare Limitations in HDR Images

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Abstract: *Veiling glare is a physical limit to HDR image acquisition. Multiple exposures improve quantization, but cannot overcome the glare limit to dynamic range. Human visual optics have much greater glare than cameras, yet outperforms conventional photography in recording details in shadows. This paper measures glare limits in HDR test targets and reviews display algorithms that mimic human vision to get better HDR performance.*

Keywords: HDR imaging; veiling glare; calibration of multiple exposure techniques; spatial algorithms.

Introduction

There is considerable interest in the design and manufacture of High Dynamic Range (HDR) displays. The popular HDR technique using multiple exposures[1] attempts to extend cameras' range in recording darker scene regions. This paper describes measurements that demonstrate two points. First, image dynamic range is limited by the camera's veiling glare (uncontrolled spread of an image-dependent fraction of scene luminance caused by unwanted scattered light in the camera). Second, multiple exposures can increase sensor flux and improve digital quantization, but cannot improve the dynamic-range record beyond the camera's scene-dependent glare limit, since each exposure has the same scene- and lens-dependent glare.

Multiple exposure techniques for rendering High Dynamic range (HDR) scenes go back to the earliest days of negative–positive photography. H.P. Robinson's 1858 composite print "Fading Away" was made using five glass negatives with different exposures.[2] Kenneth Mees's long career (1902-1956) studying photographic sensitometry at University College London and Kodak established standards for high-dynamic range image capture on the negative and high-slope rendering on prints. [3,4] In 1939 Ansel Adams's zone system established three sets of procedures: first, for measuring scene radiances; second, for controlling negative exposure to capture the entire scene range, and third, spatial control of exposure to render the high-range negative into a low-range print.[5] In 1968, Land demonstrated the first electronic (analog) HDR rendering in his Ives Medal Address to the OSA.[6] Here the intent was to render HDR images using spatial comparisons. In 1980 Frankle and McCann patented a very efficient digital spatial-comparison HDR algorithm.[7] In 1984&5 McCann described HDR image capture using low-slope film[8] in Siggraph courses. In 1997 Debevec and Malik used multiple exposures and least square fits to solve for camera response function and the radiance of each pixel in the scene.[1] Here the rendering intent is to accurately determine the scene luminance of each pixel for processing and display.

ISO 9358:1994 Standard, " Veiling glare of image forming systems"[9] defines veiling glare and describes two standard techniques for measuring it. It describes how veiling glare is the sum of individual stray light contributions to a single pixel from all other light from the scene, even from light beyond the field of view of the camera. Stray light reflected from lens surfaces, sensor surfaces and camera walls causes veiling glare. The ISO standard defines the glare point spread function (GSF), which is a measure of the amount of stray light as a function of angle from a small very bright light source. Veiling glare is measured by ISO9358:1994 as the fraction of a very large white surround scattered into a small opaque central spot. For commercial camera lenses veiling glare values are in the range of 1 to 10 %, depending on the lens and the aperture.

While ISO 9358:1994 provides a standard to compare different lenses and apertures; we wanted to measure the effects of veiling glare on the HDR imaging. We used a single calibrated test target (dynamic range = 18,619:1). Using opaque masks to cover the surrounding portions of the scene, we photographed three sets of HDR test images with different amounts of glare. The experiment compares camera digits with measured scene luminance over a very wide range of luminances and exposure times. This experiment measured the extent that veiling glare distorts camera response in situations common with HDR practice.

We made photographs using a typical compact, high-quality digital camera (Nikon Coolpix 990) with manual, mid-range aperture (f 7.3) and exposure time controls. The experiment consisted of making 3 sets of images. The first was the image seen in Figure 1, called *4scaleWhite*. The only mask was an opaque black strip placed 1 inch in front of the lightbox to have a sample of 0 luminance. The second set *4scaleBlac k* used an opaque mask that blocked all light from the white surround. Only the 4 scales with pie shaped luminance sectors were visible. The third set

(*1scaleBlack*) used additional opaque masks to cover everything except one 10-step scale with the 3.0 neutral density filter - the lowest luminances in the display.

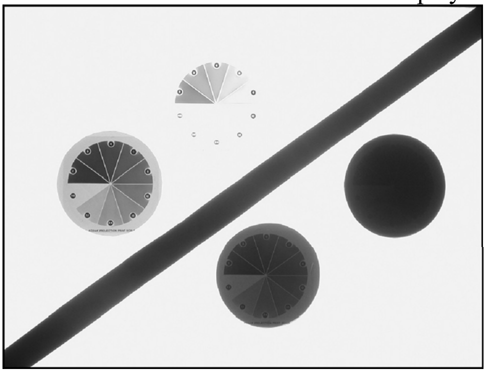

Figure 1 is a photograph of the lightbox with 4 identical 10 sector Kodak R-26 Scales (range=16:1) mounted on top of 0.0 [A], 1.0 [B], 2.0 [C] and 3.0 [D] uniform neutral density circles. The luminance range is 18,619:1 [2049 to 0.11 cd/m^2]. Each sector luminance was individually measured (Konica-Minolta LS-100C). In the above 1/8 sec photograph, half of ScaleA is overexposed, ScaleB is good, ScaleC is low–contrast dark, and ScaleD is uniformly dark. The original scales have identical contrast.

Figure 2 plots the camera digits for 10 Scale D luminances (0.11 to 1.79 cd/m^2) from all three photographs. The punctual luminance values at each wedge sector remain unchanged in the scene. A 16 sec exposure of the *1scale Black* target shows a typical camera response with digits from 37 to 201. Veiling glare has a small, but significant incremental effect on camera response to *4 scales Black*. Veiling glare overwhelms the camera response to *4 scales White*. The intent of multiple exposures in HDR imaging is to synthesize a new image with a significantly greater dynamic range record of the scene. The idea is simply to assume that scene flux [(cd/m$^{2)}$ * sec] generates a unique camera digit. Longer exposures collect more scene photons, and can move a dark portion of the scene up onto a higher region of the camera response function. This higher exposure means that the darker portions of the scene have better digital segmentation, more digits for better quantization of luminances. The HDR multiple exposure proposal[1] claimed to extend the cameras range by calibrating flux (luminance * time) vs. camera digit. This assumption is correct up until unwanted veiling glare distorts the camera responses.

We measured the influence of veiling glare using 16 scene exposures. Using a fixed lens aperture, we photographed the all four scales (A,B,C,D) with the three surrounds discussed above using a series of different exposure times. The plots of camera digits resulting from calibrated scene luminances are shown in Figure 3.

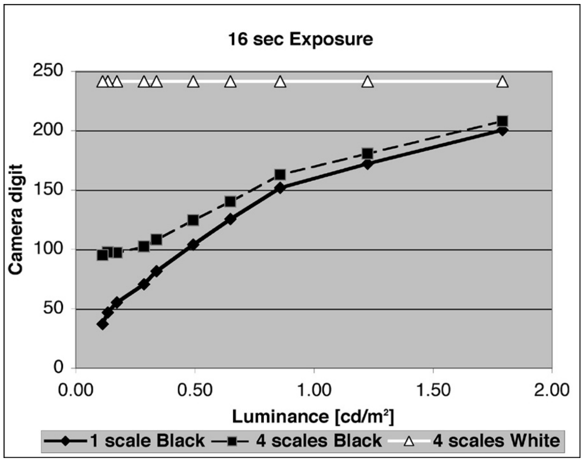

Figure 2 shows the surround's effect on camera digits. It plots the digits from ScaleD with a 16 second exposure. Diamonds plot (*1scaleBlack*) digits for 10 luminances. Squares plot *4scaleBlack* digits for the same luminances when the higher luminance scales [A, B, C] are unmasked. Their glare increased camera digits. The darkest sector went from digit 40 to 98. The triangles plot *4scaleWhite* digits with white surround. All camera responses equal 242.

The *1scaleBlack* photographs have the lowest veiling glare and are an accurate measure of the camera sensor response function. The only sources of glare are the test patches themselves (range 16:1).

In *4scaleBlack* the camera's digit responses to four 10-step scales attempt to capture a combined dynamic range of 18,619:1. This target measures the minimum glare for a scene with this range, because it has an opaque black surround. The only source of glare is the test patches that vary from 2094 to 0.11 cd/m^2.

When we removed the black mask covering the lightbox in background we go to the situation with maximal veiling glare (*4scaleWhite*). Nearly 80% of the pixels are making the highest possible contribution to veiling glare.

The data from all three sets of photographs are different. Data from *1scaleBlack* provides an accurate measure of camera sensor response vs. luminance – a single response function. Data from *4scaleBlack* shows variable (non-unique) camera sensor responses vs. luminance. Data from *4scaleWhite* shows many very different camera sensor responses vs. luminance. Camera digits from multiple exposures cannot provide a trustable means of measuring HDR scene flux. Camera digits cannot accurately record HDR scene flux because of glare. Veiling glare is image dependent. We have performed tests also using different cameras, digital and with film, and various changeable lenses, and we obtained similar results.

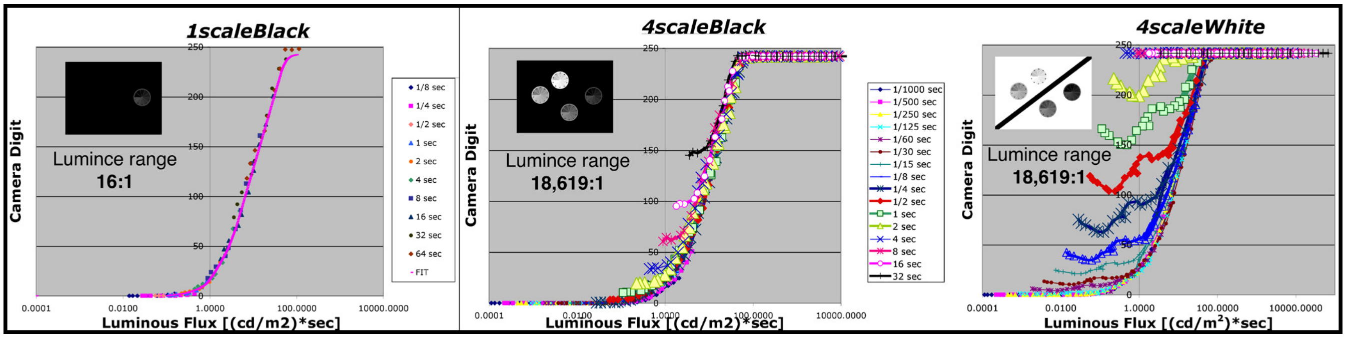

Figure 3 plots camera digits vs. luminous flux for all exposures for the three sets of photographs. (left) *1scaleBlack* (range 16:1) shows the desired coincidence of camera digits and flux. The curve provides us with an accurate camera response function. (center) *4scaleBlack* (range 18,619:1) show the minimal effects of glare for this range and configuration using a black surround between test scales. The effects of glare are seen in low luminance sectors. *4scaleWhite* (range 18,619:1) shows the maximal effects of glare for this range and configuration with a white surround between test scales. Image dependent glare distorts luminance estimates for luminances.

We took the data of Scale D from *1scaleBlack* to generate a lookup table that describes camera digit as a function of flux and its inverse. We then used this camera response lookup table to convert the camera digits from *4scales Black* and *4scales White* to estimated flux. We took the ratio of camera-estimated flux to actual measured flux and plotted the values vs. scene luminance in Figure 4. If camera digit accurately measure scene luminance than all data must fall on a horizontal line (ratio =1.0). The results support that hypothesis from 50 to 2048 cd/m^2 (range 40:1). Below 50 cd/m^2, the *4scaleWhite* data show that veiling glare distorts the ratios, and hence the luminance estimates. The same is true for *4scaleBlack* below 0.3 cd/m^2. The target has a range of 4.3 $\log_{10}$ units. Camera estimates of luminance are accurate over 4.0 $\log_{10}$ units with minimal glare and 1.6 $\log_{10}$ units with maximal glare .

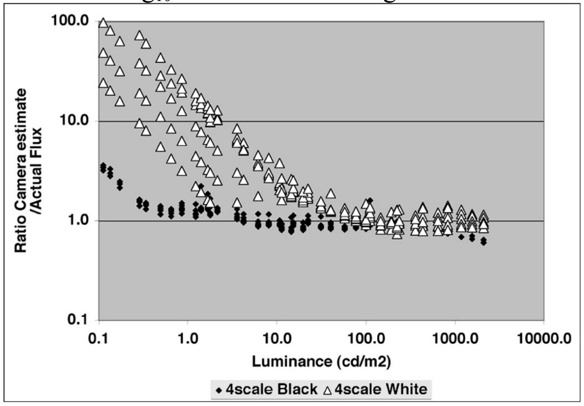

Figure 4 plots the ratio of camera-estimated flux to actual flux for *4scaleBlack* and *4scaleWhite*. Set *4scaleBlack* has minimal glare, yet show 3x distortions. Set *4scaleWhite* (maximal glare) show 100x distortions. All possible backgrounds with Scales A,B,C,D will fall between these data sets. There are different, large glare distortions for the same luminance depending on exposure.

Clearly, accurate luminance recording over the range of captured digits is impossible for the dynamic range studied here. The comparison of white and black surrounds shows dramatic scene dependence with a single camera, using a constant aperture. In addition, the camera flux estimates, when compared with actual flux, show a different error with each exposure. It may be tempting to look for some type of average-flux curve that represents data with smaller errors, but that idea is in conflict with the fundamental aim of the process, namely recording accurate scene luminance. Multiple-exposure HDR is limited by veiling glare that is scene-, exposure-, lens-, aperture-, and camera-dependent. The range of accurate scene luminances will vary with all these parameters.

Some HDR algorithms attempt the inverse calculation. [10] Given the response of the camera, calculate the luminances in the scene. The glare spread functions of commercial lenses falls off very rapidly with distance to a very small number. Intuitively, one would think that such small values couldn't distort distant pixels with veiling glare. The problem is that there are millions of pixels in the image, and the veiling glare for each pixel is the sum of scattered light from all other pixels. The sum of a very large number of small contributions is a large number.

Cameras with multiple elements lenses, small camera bodies (intra-camera reflections), and reflective sensor surfaces have considerable veiling glare distortions of flux. To do this calculation rigorously, one would need the GSF for each pixel in the images (off-axis angle dependence), for each camera aperture. Even then, as pointed out by the ISO standard, one would need to know the luminance of each pixel in the scene. That is the very information we are trying to calculate in the first place. ISO 9358:1994 Standard states unequivocally that: "the reverse [deriving luminance from response] calculation is not possible"[9].

Human vision has a much greater scene dynamic range than camera systems. Humans can see details in highlights and shadows much better than conventional films and electronic cameras. Camera response functions are tuned for low-contrast, uniform-illumination scenes. They generate high-contrast renditions of low-range scenes. The intent of Land and McCann's electronic HDR imaging was to render high-dynamic range scenes in a manner similar to human vision. [5] They made the case for spatial comparisons as the basis of HDR rendering in the B&W Mondrian experiment. There, a white paper in dim illumination had the same radiance as a black paper in high illumination. All tone-scale adjustments designed to improve the rendering of the black do so at the expense of the *white in the shade*. As well, improvements to white make the *black in the sun* worse. Land and McCann made the case that spatial algorithms can automatically perform spatial rendering shown by Adams to compress HDR scenes into the limited range of prints. Such rendering is not possible with tone-scale manipulations in which all pixels are modified by a single tone–scale function.

Veiling glare for human vision is much worse than for cameras. [11]. Earlier HDR algorithms[12] never attempted to determine actual scene luminance, since luminance is almost irrelevant to appearance.[13] Instead, these spatial algorithms mimicked vision by synthesizing HDR visual renditions of scenes using spatial comparisons. These images correlate with appearance, but not with scene luminance. This approach has shown considerable success in experimental algorithms [14,15] and commercial products.[16]

Recent multiple-exposure HDR algorithms that claim to capture scene luminances, or colors[17], are severely limited by scene and camera veiling glare. Nevertheless, the resulting images are considerably better than conventional images with limited range. Since HDR imaging works so well, there must be reasons, other than accurate luminance, that explains the improved images. The multiple exposure technique does significantly improve digital quantization. When human vision looks at high-dynamic range displays, it processes them as it does real life scenes. The improved digital quantization and improved range allows displays to present more spatial information to humans. Humans see more detail in the shadows because of preserved local spatial information. Since humans have more veiling glare than cameras, human spatial mechanisms are not adversely affected by departures from accurate radiance images on their retinas. They see details in shadows because of spatial information at low luminances. [12,18]

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