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Preservation of edges:
The mechanism for improvements in HDR imaging

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ABSTRACT

There are a number of modern myths about High Dynamic Range (HDR) imaging. There have been claims that multiple-exposure techniques can accurately record scene luminances over a dynamic range of more than a million to one. There are assertions that human appearance tracks the same range. The most common myth is that HDR imaging accurately records and reproduces actual scene radiances. Regardless, there is no doubt that HDR imaging is superior to conventional imaging. We need to understand the basis of HDR image quality improvements. This paper shows that multiple exposure techniques can preserve spatial information, although they cannot record accurate scene luminances. Synthesizing HDR renditions from relative spatial records accounts for improved images.

Keywords: HDR imaging, visible dynamic range, simultaneous contrast, veiling glare, tone-scale LUT curves.

1.0 INTRODUCTION

The problem of rendering light values from real-life scenes has been studied since the Renaissance.[1] The primary issue is that the scene has a range of luminances that far exceeds the range possible in the reproduction media. There are two different approaches to solve this problem and to make images that reproduce scenes. The first approach used by painters, photographers and scientists was to synthesize low-dynamic-range (LDR) images that contained the equivalent visual information as the scenes high dynamic range (HDR) of luminances. The goal of this type of HDR image generation is appearance, not accurate scene luminance reproduction. Painters do not use light meters to create their art. The second, more recent, approach is the use of registered, multiple exposures of scenes to capture scene luminance[2] and render that physical record of the scene with a tone-scale map to transform it into the range of the reproduction media.[3] This approach to HDR has stimulated considerable interest, particularly in the computer graphics community.

These two approaches can be characterized by the techniques they use. The first, traditional HDR, is designed to capture and render the spatial information in the scene. The absolute value of individual pixels is not as important as the relationship between pixels. Traditional HDR puts major emphasis on preserving edge information in its renditions. Regarding the second, more recent HDR approaches use Tone-Scale Maps to process the captured information one pixel at a time. These lookup tables replace each digital value in the captured scene with new value that improves the appearance of the image. The two underlying principles of traditional spatial HDR and recent pixel based Tone-Scale Mapping are very different.

Tone-Scale Mapping gets it name from Kenneth Mees who coined the term to describe Hurter and Driffield's input/output functions for film.[4] These maps behave as photographic film had to. For every light exposure, film has the same response measured in developed silver density. Everywhere in the image the response to constant exposure is constant response. Tone-Scale Maps do the same. Every input pixel with a particular value will be transformed to a new value regardless of the content of the rest of the image. Traditional HDR, by preserving edge information, distorts the values of individual pixels to maintain spatial information between pixels. Photographic dodging and burning is an excellent example.[5] The output value for a pixel depends on the input value of that pixel and those from the rest of the scene. Thus, the important differentiation between traditional and Tone-Scale Mapping HDR is the spatial processing versus single pixel processing.

2. MEASUREMENTS OF HDR RANGES

The goal of this paper is to understand why HDR images are superior to conventional images. To do this we need background data. This data includes measurements of light ranges in real life scenes, the range of camera responses and the range of luminances human can see in scenes.

2.1 Accuracy of scene capture using multiple exposures

Jones and Condit studied the range of light from scenes and the range of information captured by cameras.[6] They compared the camera's response range to the inherent film range, limited by signal to noise. They described the details of how veiling glare of camera lenses limits the range of captured information. This limit depends on the camera, the lens and the scene. Multiple exposures change the camera response, but have no influence on the veiling-glare-limited dynamic range. A number of recent papers have measured digital and film responses to a test target with six-log-unit dynamic range. These papers demonstrate again that scene dependent glare determines the range of captured information.[7,8,9] For most scenes and lenses, single exposures of conventional color film negatives can capture the entire dynamic range of film-plane images, while digital cameras have a lower dynamic range. Multiple digital exposures can capture the same range as single negative exposures.

2.2 Ability of humans to see wide range images

The Human Visual System (HVS) has optics that is subject to veiling glare limitations. Glare is an uncontrolled spread of an image-dependent fraction of scene luminances. Tyndall scattering by macromolecules [10] in the eye scatters light is a physical limit to HDR image acquisition on the retina.[9,11,12,13] These papers measured veiling glare limits in the human optical system They performed magnitude estimation experiments with human observers, using the same HDR test targets shown in figure 1. They used pairs of identical film transparencies to make single- and double-density test targets. Figure 1 shows the arrangement of 20 pairs of slightly different gray test patches surrounded by different backgrounds, 100% black pixels (left), 50% white pixels and 50 % black pixels (center), 100% white pixels (right).

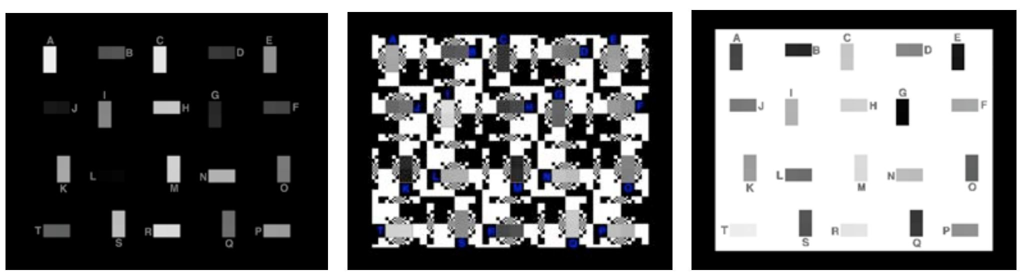

Figure 1 shows test targets with different background and twenty gray pairs of luminance patches. All gray pairs are close in luminance, but some edge ratios are larger than others.

Magnitude estimation measurements of observed lightnesses are plotted in Figure 2. In the black surround with no glare from the surround, observers can discriminate lightnesses over a range of 5 log units. When 8% of the surround contributes maximum glare, the range of usable luminances is only 2.9 log units. When 50% of the surround contributes maximum glare, the range of usable luminances is only 2.0 log units. With 100% maximum glare in the surround the range is only 1.5 log units.[12]

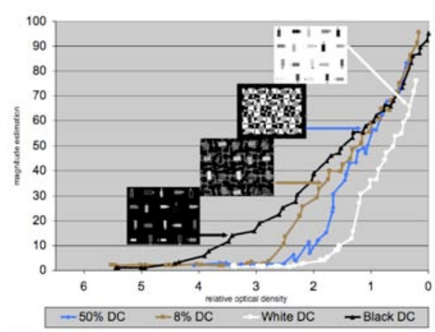

Figure 2 plots log display luminance against the magnitude estimate reported by the observers with all the backgrounds.

There is a second very important observation from the data in Figure 2. Magnitude estimates of 50 are by definition middle gray. Middle gray was observed from distinctly different log luminances for each surround. Appearance of middle gray depends on the image content, not the luminance of the pixel.

3. WHY ARE HDR IMAGES BETTER?

We have presented two different approaches to HDR imaging. The traditional approach uses mechanisms that preserve spatial information. Tone-Scale Mapping HDR uses pixel transforms to bring out details and enhance images. Both techniques provide better images than their controls. Our goal here is to understand how each techniques gets these results and evaluate how well each approach can be applied to all images.

3.1 Tone-Scale Mapping

Figure 3 has two images and three LUTs for Tone-Scale Mapping. The left image is a low-contrast photograph of a design in a rug. The right image is a high-contrast scene of sunlight coming through a stand of trees. Both images were combined within a single histogram. The histogram of the combined images can be seen behind the LUT plots. The top row was printed using the LUT on the left. This LUT makes output equal input -- a slope 1.0 Tone-Scale map.

The middle row introduces a LUT designed to improve the image of trees. It significantly increases the midtone values and moderately increases the darker tones. This LUT reduces the apparent contrast of the image and allows better discrimination between midtone values. The reduction of apparent contrast makes the rug image still lower in contrast.

The bottom row uses a LUT designed to improve the rug image. This LUT increase the output of light grays and decreases the output of dark grays. This LUT brings out differences in the rug image, but obfuscates the differences in the trees image.

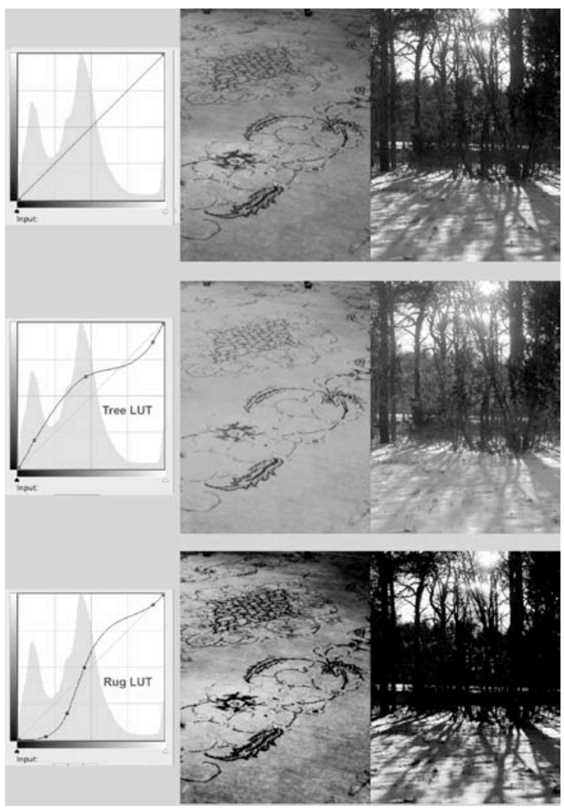

Figure 3 shows a pair of images taken with the same camera. The top pair is printed with a straight-line, slope 1.0 LUT. The middle pair uses a contrast lowering LUT chosen to improve the trees image, while the bottom pair uses a contrast enhancing LUT chosen to improve the rug image. The effects of tone-scale LUTS are independent of scene content. They perform the same transform on all pixels within an image and all pixels in all images.

The pixel based Tone-Scale Map approach is a powerful tool in manipulating images and enhancing the aesthetic intent of the image maker. Its greatest power is in the ease of implementation in digital systems. The same techniques were developed for film based photography, but were much more difficult to use. Black and white print papers had different contrast emulsions for red, green and blue light. By choosing the color of the enlarger light, one determined the contrast of the print. The growth of the photographic industry required the opposite approach. Namely, the industry used one - best compromise - tone scale. This made it possible for photography to change from the time consuming hobby of skilled amateurs to the mass consumption of point and shoot cameras.[5]

Conventional color negative-print film is an interesting example. Mees's colleagues at Kodak made extensive studies of the light range of scenes, the limits of camera optic and the signal to noise of silver halide films.[6] They designed the negative so it could capture the range of camera's film plane luminances for most scenes and lenses. If their prints followed the same design scheme, then their images would look like they were taken in heavy fog. They used a high contrast print paper so that the system response has an S-shaped Tone Scale response to scene luminances. Extensive consumer-preference research verified that their Tone Scale was the best universal compromise for all scenes. It is difficult to improve on the design of the negative as an image capture media with its more than 3.5 log unit dynamic range. The limitations of color film Tone-Scale systems are in the universal application of one function to all scenes. Low dynamic range scenes are enhanced in contrast and in chroma. High-dynamic-range scenes exceed the range of the print. The introduction of the S-shaped Tone Scale is a powerful tool. Whereas a straight-line function make the range limits obvious, curved functions maintain image detail at lower print contrast. In other words, the curve of the Tone Scale preserves image details near white and near black. This response prevents visible artifacts, but does not render accurate luminance information.

3.2 Spatial Image Processing

As observed earlier in the paper, the appearance middle gray has different log luminance in different surrounds. The optical system in the human eye introduces one kind of image transform caused by glare. Human appearance mechanisms use spatial image processing to overcome glare. White surrounds, with the most glare, make test patches appear darker than in black surrounds, with less glare. Vision uses two spatial mechanisms that tend to cancel each other. Before we can accurately evaluate the post-retinal image processing we need accurate information about the retinal image. While this is difficult to measure, we can use the glare spread function of the eye to calculate the retinal image.

3.3 Calculated Retinal Luminance

We calculated retinal luminance taking into account intraocular glare.[13] We calculated the veiling glare contribution from all other pixels using the standard CIE Glare Spread Function. We added glare to the pixel's luminance to obtain relative retinal luminance. We perform this calculation for displays with 100% white, 50% white and 0% white backgrounds. Plots of appearance vs. log retinal luminance show three different, surround dependent, linear functions. Although increasing the amount of white in the background decreases the dynamic range of the retinal image because of glare, increasing white in the background increases the apparent contrast of the image.

We will use the calculated retinal luminance for the white surround to analyze the high glare- high contrast case. Figure 1 (right) shows the original image for the test target with 100&% White in the surround. This image has been scaled so that digit 255 represents OD 0.0, or 100% transmission; digit 0 represents OD 5.6, or 0.00025% transmission.

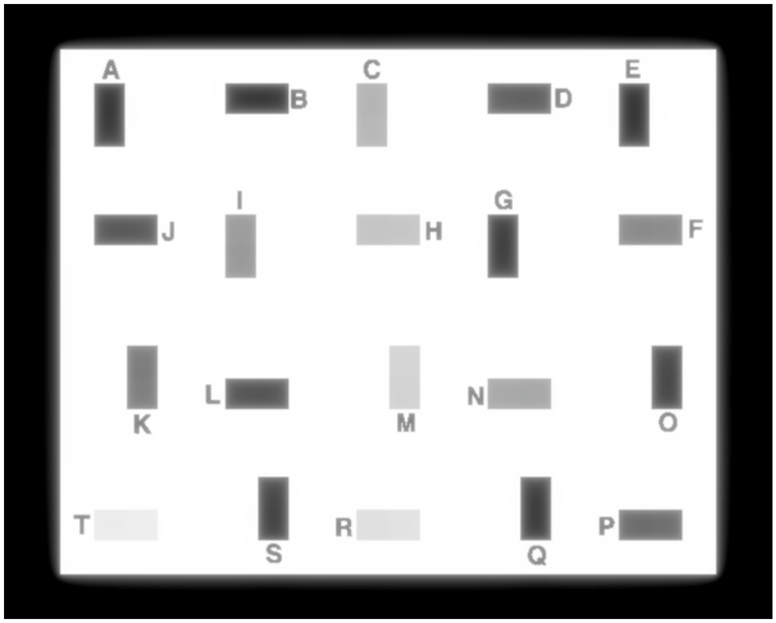

Figure 4 shows the calculated retinal image for the test target with 100% White in the surround. This image has been scaled so that digit 255 represents OD 0.0, or 100% transmission; digit 0 represents OD 2.0, or 1% transmission.

For our analysis we will describe in detail five test areas in the calculated retinal image: the area T (near white), area N (middle gray), area D (dark gray), area A (near black), and area B (near black). Their average optical densities, and the differences in density for each half of the test areas (delta OD) are shown in the second and third columns of Table1. As well, the average observer MagEst and the differences in MagEst for each half are shown in the fourth and fifth columns of Table 1. The final column lists the ratio [delta Lightness (MagEst) / delta Optical Density]. We recall that each area is composed of two very similar but not identical patches.

100W retinal image	Average OD	delta OD	Average MagEst	delta MagEst	Ratio d Lightness / d OD
T	.024	0.03	74	4.52	150.7
N	.089	0.04	38.5	4.0	100
D	1.59	0.05	8.8	1.32	26.4
A	2.37	0.05	1.6	0	0
B	2.96	0.04	1.8	-0.08	-2

Table 1 compares the change in optical density in the original test target (shown in Figure 1) versus change in lightness for the edges in test areas T, N, D, A, and B. Near white we observe large changes in lightness with small changes in OD. Middle gray and dark grays shoe progressively smaller changes in appearance for the same change in OD. Black shows both no change, and errors in MagEst.

Figure 5 shows 3-D plots of half the areas T, N, D, A, B, listed in Table 1. The right side of Area T is clearly higher luminance than the left. The left side of Area N is higher. Despite greater change in OD that the previous areas, D is minimally higher on the left. Areas A and B appear nearly identical. The MagEst Data in Table 1 correlates well with retinal luminances.

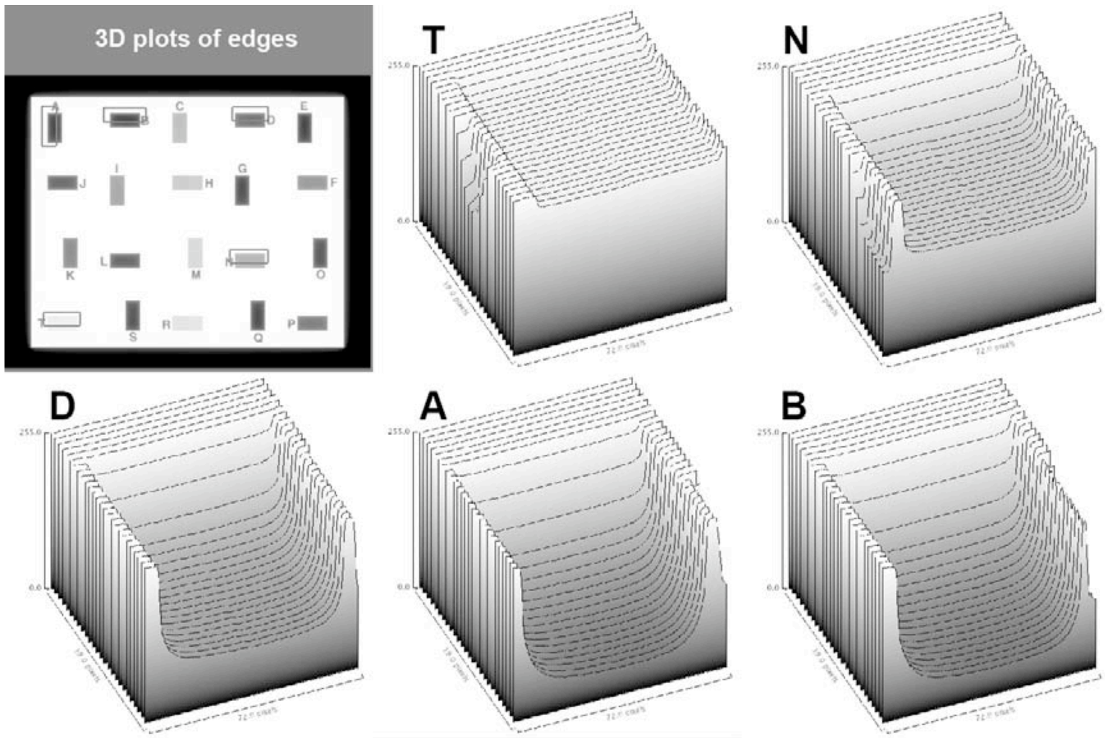

Figure 5 shows 3-D plots of the calculated retinal image for the test areas T, N, D, A, and B with 100% White surround. These images have been scaled so that digit 255 represents OD 0.0, or 100% maximum retinal radiance; digit 0 represents OD 2.0, or 1% maximum retinal radiance.

Figure 6 plots the OD values for the display (left), and retinal (right) luminances. These plots illustrate that the OD values covered a range of 3 log units, while the retinal images had only half that range. The display areas T, N, M, A, and B were made of grays with similar difference in OD (0.03 to 0.05). The retinal edge decreased with density. Areas T had the biggest edge, Area N had a smaller one, Area D had a minimal one and Areas A and B were not visible in Figure 6. As well they were not visible in the magnified plots shown in Figure 7.

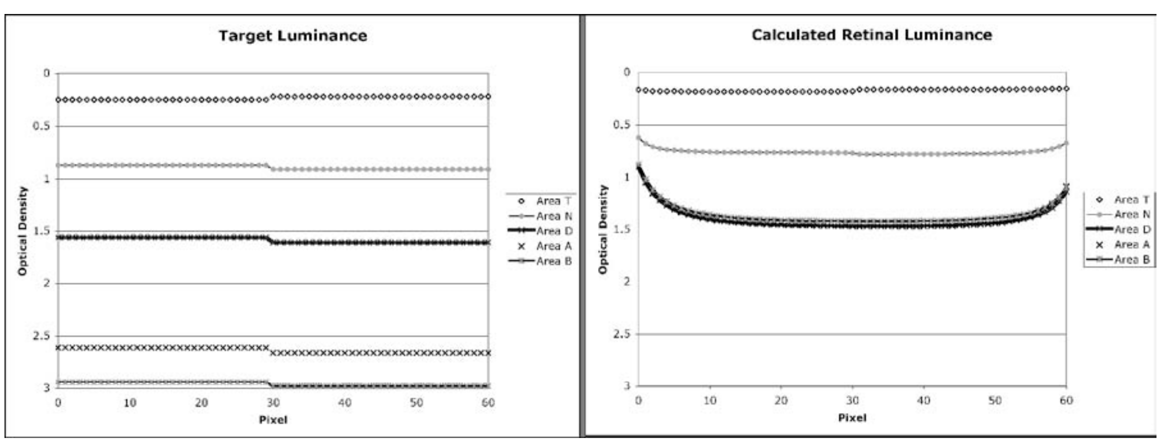

Figure 6 plots the optical densities for both the original target (left) and the calculated retinal image (right) for the test areas T, N, M, A, and B with 100&% White surround. Both vertical axes have been scaled so that OD 0.0 is maximum, and OD 3.0 is the minimum. The effect of intraocular scatter is to reduce the dynamic range of luminance. Further, it reduces dramatically the differentiation between OD 1.5 and OD 3.0.

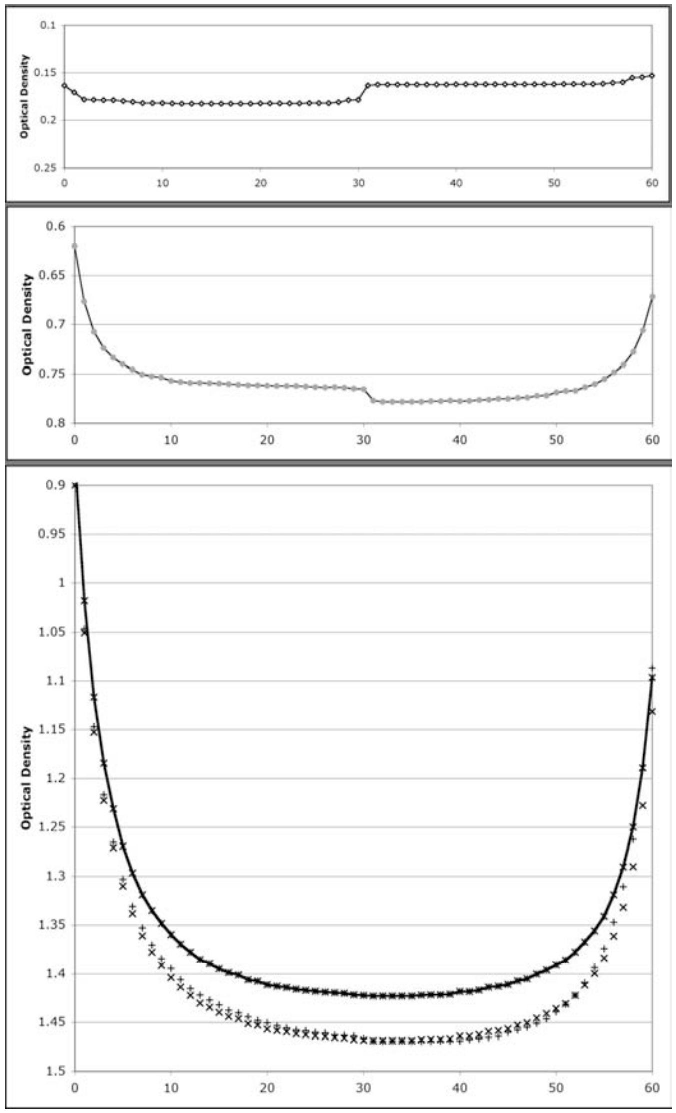

Figure 7 shows expanded plots of the optical densities for the calculated retinal image (right) for the test areas T, N, D, A, and B with 100% White surround. The vertical axis has been magnified to 0.05 OD per division. The three plots allow us to see the sharp edge in the retinal luminance of area T (top), and Area N (middle). The retinal luminances for Areas D, A, and B are very similar. The edges in the center are extremely small compared to the gradient across the pair of uniform areas. Area D has an OD on the left of 0.9 and 1.42 at the center. The invisible gradient changes by 0.52 OD, (0.3 : 1).

3.4 Lessons from the retinal image

There are two very obvious facts about the retinal image. First, intraocular glare uses luminance from other pixels to reduce the possible range on the retina. As well, the magnitudes of the edges get smaller as the areas get darker.

Second, in order to make retinal edges larger, they have to be at higher luminance. When one preserves edges at higher luminances one sees successful HDR renditions. Examples can be seen in paintings by Rembrandt, photographs by Ansel Adams, Retinex and Ace image processing[9, 15] and even in Tone-Scale HDR images. However, there are two reasons that Tone-Scale Mapping is successful. First, the multiple digital camera exposures extended the range of capture of edge information, and second Tone-Scale LUT changed the output luminances to be distinguishable in the retinal image. There is little experimental evidence that recent Tone-Scale HDR techniques have extended the range of scene capture. As well, HDR rendition does not require the increase of dynamic range beyond that found in transparency films. Additional display luminance range cannot be detected by the eye except in images of stars, where there is no limiting scatter from surrounding pixels.

4. DISCUSSION

This paper compares two very different approaches. Traditional HDR puts major emphasis on preserving spatial edge information, whereas Tone-Scale HDR approaches process one pixel at a time. Recently, due to the many limitation of the global approach, a number of algorithms have implemented image-processing techniques described as "Local Tone Scale" processing. This terminology can be very confusing. Tone-Scale, by Mees's definition, and as used for most of a century, is a global lookup function. It transforms every pixel with the same digital value to the same new digital value. The term "Local Tone Scale" implies that tone scale varies for each local region of the image. In fact, what most of these algorithms do is modify the input image sent to the tone scale. In other terms, many "Local Tone Scale" processes perform traditional HDR spatial manipulations, before rescaling them with a global LUT.

5. CONCLUSIONS

HDR techniques using film negatives and multiple-exposure digital images are able to capture scene information over the scene's maximum dynamic range. The maximum range is determined by the interplay of the scene and the camera's lens. Unwanted camera glare varies with scene content. Similarly, the range of luminances visible to humans is controlled by each scene's intraocular scatter. HDR imaging is superior to conventional imaging because it extends the range of HDR information that is visible in LDR rendering. A variety of different approaches are successful in HDR rendering. They include: paintings, photographs, Retinex and ACE image processing, and even in Tone-Scale HDR images. Tone-Scale Mapping is successful when Tone-Scale LUT changed the output luminances to be distinguishable in the retinal image.

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