HDR Rendering: An Overview

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***Abstract*— High-dynamic-range (HDR) rendering techniques are becoming more relevant with the popularization of HDR-ready cameras and displays. Although the recent increase of interest, the reproduction of scenes with a high range of luminances has a five-century history that includes painting, photography, electronic imaging, image processing and, more recently, rendering. HDR images are, knowingly, superior to conventional images. This work summarizes the theoretical background and results of previous works with the aim of assisting graduate engineer students on grasping relevant concepts of HDR rendering.**

I. INTRODUCTION

The Renaissance introduced a hole new set of questions, ideas and solutions to society, one of these solutions was the use of perspective and chiaroscuro techniques on representing real worlds scenes on oil paintings. Leonardo Da Vinci is credited as the father of chiaroscuro technique, that was later mastered by many dutch painters, such as Gerrit van Honthorst, whose painting Childhood of Christ is presented on figure 1.

Fig. 1. Childhood of Christ, Gerrit van Honthorst, 1620

The painting on figure 1 illustrates the difficulty in creating images that simulate the human vision perception of scenes with a high range of luminances, such as the lit candle and the two girls talking on the right.

Human perception has it's owns limitations. Knowing these gives us a powerful tool for constructing algorithms and solutions that produces nice perceptual effects, more about human limitations will be discussed later.

Main concepts involved on a HDR rendering will be presented and explained on the text.

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The actual implementation of many ideas presented here is a main concern in this article, that means, explanations about implemented solutions and comments on positive and negative points will be present.

II. CONCEPTS

There are numerous concepts behind HDR imaging and rendering. The next subsections are an attempt on highlight and explain the most fundamentals ones.

Before jumping on main topics, it's necessary to consolidated some nomenclatures and fundamentals concepts. What is dynamic Range from High Dynamic Range (HDR)?

Dynamic Range is the ratio between the largest and the smallest quantity under consideration. And which quantity is under consideration? Since there is interest on scenes that have bright light sources in contrast with regions of low bright sources the quantity to be considered should be luminance.

Luminance is a photometric measure of the luminous intensity per unit area of light travelling in a given direction. The SI unit for luminance is candela per square metre (cd/m^2).

The High from HDR stands for great differences in the order of magnitude from different light sources in the scene, as figure 2 indicates.

Another important point to be considered is that, today, the pixel resolution in ultra high definition (UHD) imaging is not the key limiting factor. The problem is the restricted color gamut and the constrained luminance/contrast ranges found on most cameras and file formats. Figure 2 gives an example o the limited gamut, relative to the human visual perception, found on a screen.

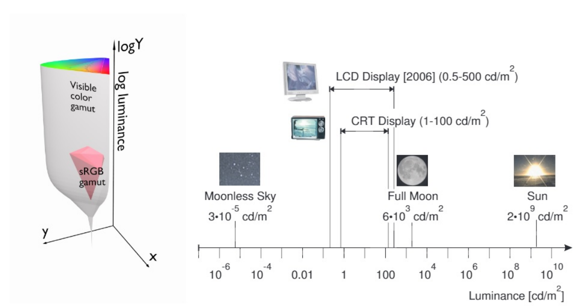

Fig. 2. Difference of Color Gamut space between a camera (red) and the human perception (gray) and different Luminance values for different sources

A. Pipeline

There are several ways of obtaining a HDR image, it is possible to photograph or film a real scene with a HDR-ready device, render a scene as HDR, get a HDR file format, transform an LDR (Low Dynamic Range) image on a HDR image. Those possibilities are presented on figure 3 with correspondent actions.

B. Human Vision

The human vision is capable of perceiving great discrepancies in luminance, ranging from daylight to nightlight luminance levels. This is possible due the different physiologic receptors, the rod and the cones. Rods are responsible for perception of luminance differences, but have no capability to distinguish different colors. Cones are responsible for color vision. The range of illumination covered by the rods is denominated scotopic, for the cones, photopic. Figure 4 illustrates this concept.

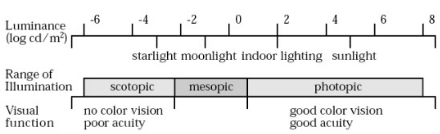

Fig. 4. Range of Luminance for human photoreceptors

Even with different photoreceptors, the pupil plays a crucial role on iluminance data acquisition since it can adjust it's size to permit a certain light passage level.

Another topic of interest in human vision is the spatial influence contribution on discriminating tones and luminance levels. This characteristic is critical to determine perception of color, since our discrimination response comes from an average image intensity. The examples presented in figures 5 and 6 illustrates this concept, where on figure 5, equal color squares have different color perceptions to human eye, based on the brighter/darker surrounding. In figure 6 the gray dots appear to be present on the intersections but when focused, they dissapear. Both illusions can be found on [4], with further information and others examples

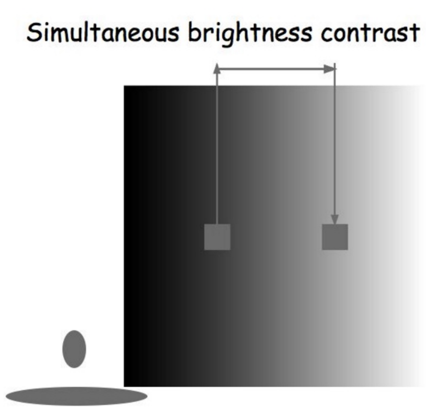

Fig. 5. Example of different perception of tonalities based on surroundings impact

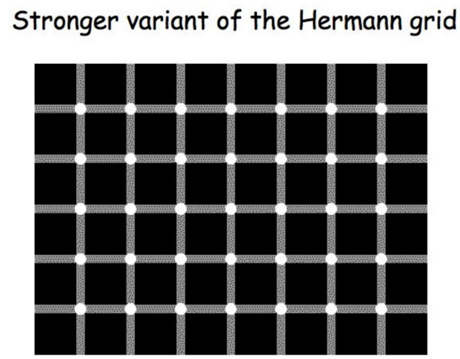

Fig. 6. Herman Grid and his imaginary gray dots that disappeared when looked at

To demonstrate the effect of discrimination influence, as a result from the spatial influence, figure 7 is presented. It's easily seen that the retina has only a diminutive range of dynamic luminance compared to the actual discrimination range encountered on humans.

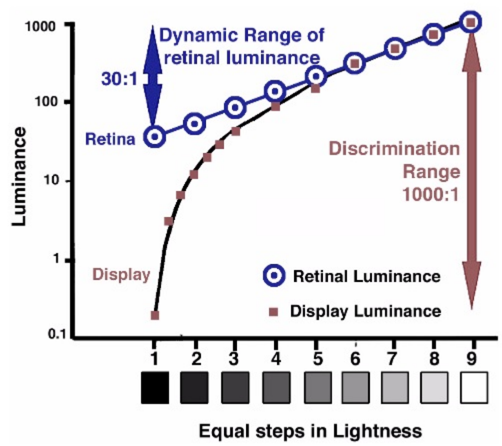

Fig. 7. Differences in range for retina dynamic luminance differentiation and discrimination levels

The human visual optical system presents, as any optical system, limitations, due to intrinsically present physics and physiology, being them most important the Veiling Glare effect.

Veiling glare is a scene-dependent physical limit of the camera and the lens. Multiple exposures cannot accurately reconstruct scene luminances beyond the veiling glare limit.

Veiling Glare is caused by reflections between surfaces of lens elements and the inside barrel of the lens. It is a strong predictor of lens flare, image fogging (loss of shadow detail and color) that can degrade image quality in the presence of bright light sources in or near the field of view. It occurs in every optical system, including the human eye.

C. Tone Mapping

Tone mapping is the process of rendering scenes of high contrast and potentially wide color gamut on a destination medium of limited contrast and color reproduction. It can have multiple objectives, they are:

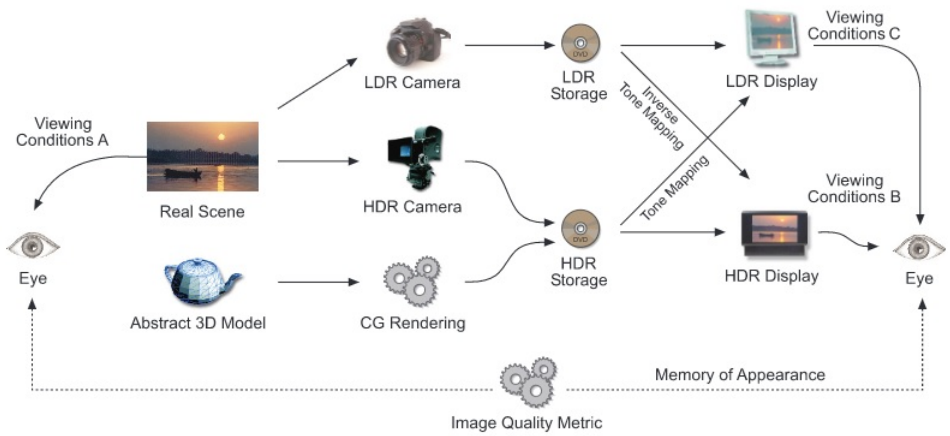

Fig. 3. Imaging pipeline and available HDR technologies

- Visual system simulators (VSS) - simulate the limitations and properties of the visual system.
- Scene reproduction (SRP) operators - overcome the limitation of the output medium and try to achieve the best match given the limited gamut and dynamic range
- Best subjective quality (BSQ) operators - designed to produce the most preferred images or video in terms of subjective preference or artistic goals

The focus of this paper will be the second item, i. e. generating better images for a constrained display based on a HDR scene. Since tone mapping is a extensively researched subject, many approaches and solution have been proposed on literature, on the next subsections an overview of major approaches are commented, this division is proposed by [2].

1) Illumination and reflectance separation: Reflectance is responsible for texture, shape and color information, it is mostly invariant to the conditions in which the object is observed. In contrast, illumination can vary greatly depending whether, for example, an object is observed indoors or in the sunlight.

Since a) illumination is the main contributor for the large dynamic range, b) humans have a visual system that discount the effect of illumination and c) in the majority of diffuse objects, the pixel values can be regarded as a product of incoming illumination and the surface reflectance.

A tone mapping approach that apply only on the illumination factor (assuming that it's possible to split reflectance from illumination) without distorting the reflectance is the main purpose of this set of solutions.

Some known approaches are: Low-pass filter decomposition, Bilateral filter decomposition, Retinex algorithms and Gradient and contrast based methods. [2]

2) Forward visual model: Human connection between visual cortex and optic nerve has a limited range of transmission, therefore the human vision system execute an effective dynamic range compression. The main idea behind these approaches is an attempt to mimic this human compression method. Although the approach may be effective in reducing the dynamic range, this compression results in an abstract internal representation of the visual system. These solution can cause certain confusion, since the eye expect to see luminance instead of an abstract internal representation, but, in general, the results are pleasing.

Such a forward-only approach to tone-mapping can be considered as inspired by a perception, rather than perceptually plausible. This model can be visualized in figure 8.

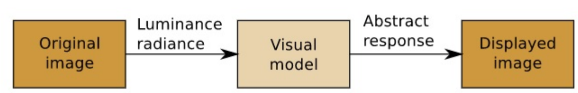

Fig. 8. Typical processing pipeline of tone-mapping based on a forward-only visual model. The original image is transformed into abstract representation using a visual model and then sent directly to a display.[2]

3) Forward and inverse visual models: Since the forward model only accounts for the observation of original scenes and not a tonne-mapped image, where the stimulations are different, an alternative approach has been proposed, one which accounts for the forward and inverse visual model, as illustrated on figure 9.

The work flow proposed by this method is explained. The original HDR image is first processed by the forward visual model, then, the result of the visual model can be optionally edited, for example to reduce the dynamic range or improve the visibility of details. In the next step, the abstract response is converted back to luminance or trichromatic values with an inverse display model while assuming adaptation to a particular display. Finally, the physical luminance or trichromatic values are transformed to pixel values using an inverse display model.

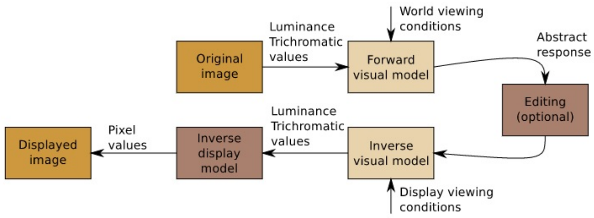

Fig. 9. Typical processing pipeline of tone-mapping based on forward and inversevisual models. The original image is transformed into abstract representation usingthe forward visual model, optionally edited and then transformed back to the physicalimage domain via an inverse display model. [2]

4) Constrained mapping problem: Tone mapping can be considered an optimization problem, since the rendering on an output device is a tradeoff between preserving certain image features at the cost of the others. An algorithm with adjustable parameters corrected by an error estimation can be employed on such map. This approach has gained the name of Constrained Mapping Problem.

The main difficulty occurs on finding a reliable visual metric that captures the real dissonance between the original scene and the tone-mapped image. The comparison methods will be discussed next.

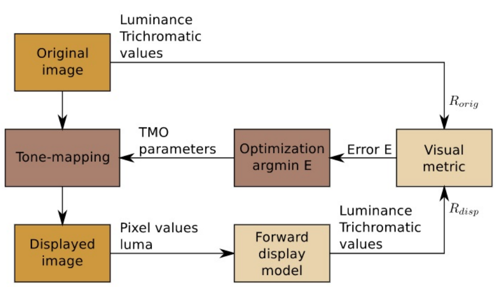

Fig. 10. Typical processing pipeline of tone-mapping solving a constrained mapping problem. An image is tone-mapped using a default parameters. Then the displayed image is compared with the original HDR image using a visual metric. The scalar error value from the metric is then used in an iterative optimization loop to find the best tone-mapping parameters. Note that in practice the solutions are often simplified and formulated as quadratic programming or even have a closed-form solution. [2]

D. Comparisons

Comparing images generated by different tone mapping algorithms is a subjective analysis, because different people have different perception (physically and psychologically) on which image ”looks better”. In an attempt to approximate this subjectively realm from mathematics, two main laws are usually employed on such tasks: Thurstones Law of Comparative Judgement and Torgersons Law of Categorical Judgement. A more profound discussion about these laws can be found on [11], since such discussion is not in the scope of this paper.

Attempts on comparing different tone mapping algorithms are found in literature, such as [9].

Methods that attempt to compare images with an objective visual metric are being proposed, as [12] demonstrates.

III. IMPLEMENTATION

Rendering scenes with luminance levels equal or proportional to the real world is the main idea behind representation of real dynamic range luminance level scenes.

In order to represent the different luminance values outside the [0, 1] (default on OpenGL) range it’s necessary to define a color framebuffer with floating point values, this can be done by the following command.

```
glBindTexture(GL_TEXTURE_2D, colorBuffer);
glTexImage2D(GL_TEXTURE_2D, 0, GL_RGBA16F, SCR_WIDTH, SCR_HEIGHT, 0, GL_RGBA, GL_FLOAT, NULL);
```

Fig. 11. Framebuffer declaration with Floating point values. Extracted from [6]

The main idea behind the actual rendering is expressed in the figure 12. The original scene is rendered (with it’s actual luminance levels) on a framebuffer that support floating point luminance levels, as demonstrated above, after that, a new set of shaders is used to perform the tone map algorithm and render a 2D quad scene as the final result. It’s important to highlight that this method works as deferred shading, with the difference that the light calculation is done in the first step and not in the second, where, here, the tone map algorithm is executed.

```
glBindFramebuffer(GL_FRAMEBUFFER, hdrFBO);
    glClear(GL_COLOR_BUFFER_BIT | GL_DEPTH_BUFFER_BIT);
    // [...] Render (lighted) scene
glBindFramebuffer(GL_FRAMEBUFFER, 0);

// now render hdr colorbuffer to 2D screen-filling quad with different shader
hdrShader.Use();
glActiveTexture(GL_TEXTURE0);
glBindTexture(GL_TEXTURE_2D, hdrColorBufferTexture);
RenderQuad();
```

Fig. 12. Implementation idea to render using framebuffer with floating point values

A. Tone Mapping operators and shaders

In order to compare different approaches on tone mapping, it’s proposed 4 types of operators based on [3].

1) Linear mapping

$$Color = a \cdot \frac{L_w}{\overline{L_w}} \tag{1}$$

where L_w is World Luminance and $\overline{L_w}$ is a logarithmic average of pixel luminances fromt the scene

2) Reinhard mapping

$$Color = \frac{L_{scaled}}{1 + L_{scaled}} \tag{2}$$

where $L_{scaled} = a \cdot \frac{L_w}{\overline{L_w}}$

3) Modified Reinhard’s mapping

$$Color = \frac{L_{scaled} \cdot (1 + \frac{L_{scaled}}{L_{white}^2})}{1 + L_{scaled}} \tag{3}$$

where L_{white} is the luminance from white color on display.

4) Adaptive Logarithmic Mapping

$$Color = \frac{a}{log_{10}(\overline{L}_w + 1)} \cdot \frac{log(L_w + 1)}{log(2 + ((\frac{L_w}{\overline{L}_w})^{\frac{log(0.7)}{log(0.5)}}) \cdot 8)} \quad (4)$$

The tone mapping operators presented before are implemented by the code present on figure 13.

IV. RESULTS

A proposed scene present in [6] is used to test the tone map algorithms proposed on a HDR scene. The result can be visualized on figure 14.

The result shows a illuminated back of the structure (corridor) along whit three directional lights, one red, one green and one blue. The difference on the intensities were from 200.0 in the square on the back to 0.1 on the directional lights, i. e., a three order of magnitude difference. To illustrate the improvement the image without Tone Mapping is presented on figure 15.

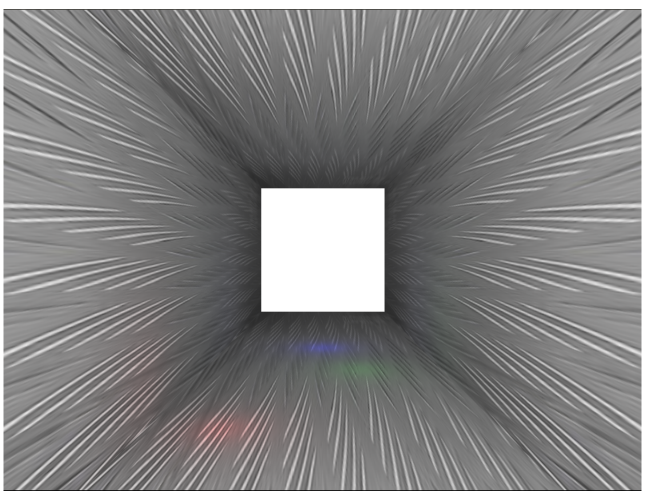

Fig. 15. Scene rendered without the use of Tone Mapping

Since the values from the back square all exceed greatly one, OpenGL clampled this values to one, therefore the result is a white square. The three lights are all lightly seen.

Since the result presented has subtle differences, the result, for the same operators, present on the paper [3] is displayed here, on figure 16, in order to a broader comparison can be made.

It's possible to note that tone mapping different techniques have more impact in scenes with a higher degree of complexity and can have different impact depending on the type of scene chosen to be rendered. Regardless of the scene, tone map operators successfully compress the dynamic range presented on the original scene in a way that is possible to observe the details of both bright and dark regions.

V. CONCLUSIONS

This article is capable of introducing HDR to a broad audience that doesn't require many prior knowledge on the subject. An introductory overview for HDR rendering is present as a series of concepts in human vision, HDR motivation and capabilities, Tone Mapping approaches and comparison methods. The implementation implications and final results are, also, presented to demonstrate concrete examples of all concept discussion. More discussion about selected topics can be found on the references.

FUTURE WORKS

New tone map approaches, improve in parameter adjustment, new objective and subjective visual metric comparisons, real time HDR rendering are all subjects open to improvements and further research.

ACKNOWLEDGMENT

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```
void main() {
    const float gamma = 2.2; float i, j; int n = 0;
    vec3 sum = vec3(0.0);
    for (i = 0.0; i < 1.0; i = i + 0.1) {
      for (j = 0.0; j < 1.0; j = j + 0.1) {
        sum = sum + texture(hdrBuffer, vec2(i, j)).rgb;
        n++;
      }
    }
//Logarithm average of all pixels luminance on a scene
    vec3 lw_complement = exp(sum/n);
    vec3 lw = texture(hdrBuffer, TexCoords).rgb;

//Linear
        float a = 0.5;
        //TODO compute a key value based on image
        //float a = max(vec3(0.0), 1.5-(1.5/(lw_complement*0.1 +vec3(1.0)))) + 0.1;
        vec3 l_scaled = a * (lw/lw_complement);
        vec3 result =  l_scaled;

//reinhard
        vec3 result = l_scaled / (l_scaled + vec3(1.0));

//reinhard modified
          float white_lum = 2.5;
        vec3 result = (l_scaled*(vec3(1.0) + l_scaled/pow(2.5, 2))) / (l_scaled + vec3(1.0));

//exposure
        vec3 result = vec3(1.0) - exp(-l_scaled * exposure);

//Adaptive logarithm
        vec3 result = ( a / (log(lw_complement + vec3(1.0)) / log(10.0)) ) * ( log(lw + vec3(1.0)) / log(2 + ((vec3(pow(lw.x/lw_complement.x, log(0.7)/log(0.5)), pow(lw.y/lw_complement.y, log(0.7)/log(0.5)) , pow(lw.z/lw_complement.z, log(0.7)/log(0.5))) )*8)));

// also gamma correct while we're at it
        result = pow(result, vec3(1.0 / gamma));
        color = vec4(result, 1.0f);
}
```

Fig. 13. Implementation from several tone mappings operators

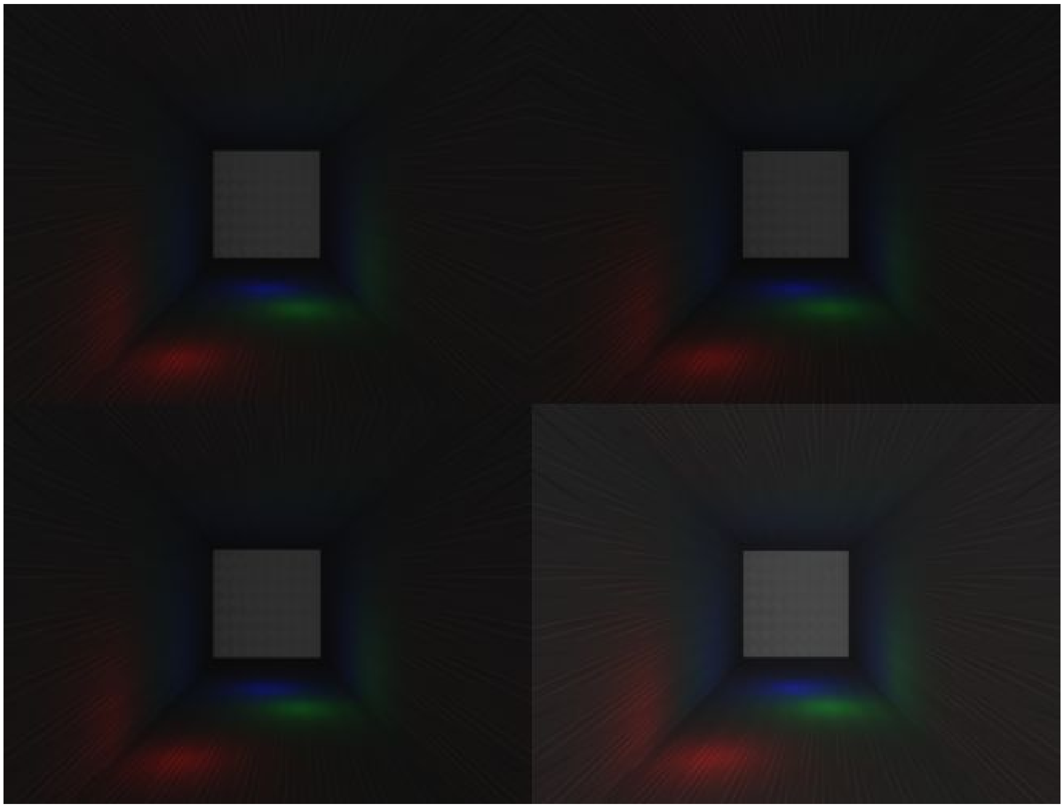

Fig. 14. Result for different tone mapping, on top left: linear, top right: Reinhard, bottom left: Modified Reinhard, bottom right: Adaptive Logarithmic

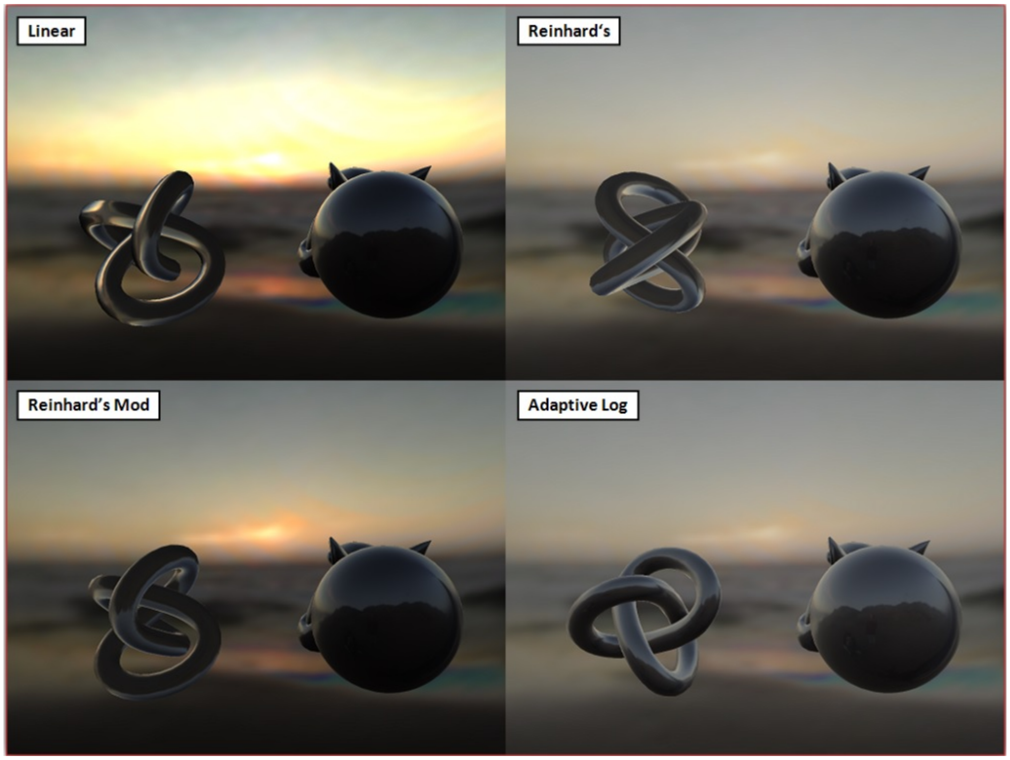

Fig. 16. Result for different tone mapping exhibited on [3], on top left: linear, top right: Reinhard, bottom left: Modified Reinhard, bottom right: Adaptive Logarithmic