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Tone Mapping of HDR Images: A Review

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***Abstract*—Real world contains a wide range of intensities that cannot be captured with traditional imaging devices. Moreover, even if these images are captured with special procedures, existing display devices cannot display them. This paper presents a comparative study of most famous tone mapping algorithms. Tone mapping is the process of compressing high dynamic range images into a low dynamic range so they can be displayed by traditional display devices. The study implements six tone mapping algorithms and performs a comparison between them by visual rating. Independent participant were asked to rate these images based on a given rating scheme. The study concluded that Reinhard tone mapping operators are the best in term of visual pleasure and maintaining image integrity. In addition, exponential tone mapping operators have achieved better rating compared the logarithmic operators.**

Keywords-tone mapping; dynamic range; image visualization; intensity mapping

I. INTRODUCTION

Light intensity in the real world span a wide range from dim to very bright (direct sunlight) [1]. Traditional imaging devices can capture limited range of intensities; a normal camera has a 24-bit depth per pixel which means it has 256 discrete intensity levels for each color channel of the image. This is far less than the real world dynamic range and as a result, some parts of the image appears dark while others may appears bright [2]. Image dynamic range is the number of discrete levels that its intensity takes. Normal images or low dynamic range images (LDR) has 256 intensity levels for each color channel of the image. Recently, the demand for high dynamic range (HDR) images has been driven by the need to capture real world images as well as the availability of powerful computing power that can easily process the HDR image. HDR imaging is used in many applications to create visually pleasing images specially scenes that contains dark and bright areas together such as taking a photograph that includes indoor parts and outdoor parts [3]. Normally the indoor part will look dark and the outdoor part will look bright. HDR imaging technologies will create an adaption from multiple image shots and create a visually pleasing image similar to the one seen by the observer eyes [4–7].

High Dynamic Range (HDR) images are created by taking multiple LDR images at different exposures and then fusing them in a way that maintain the image details. At short exposure time, the sensor will have less time to saturate so the image will appear dark. Low exposure is used with bright areas of the scene in order to make it less illuminated. In contrast, at larger exposure time the sensor will fully saturate and as a result, the image appears bright. Larger exposure time is used for rendering dark areas of the image [8]. There are various methods for combining multiple differently exposed LDR images. These methods can be classified into global method and local methods. Global HDR blending techniques compute the global normalization factor that penalizes the whole image without considering its spatial information. On the other hand, local blending techniques groups local similar regions in the image and process them together [8], [9]. Human visual system uses local control sensitivity in the retina in order to capture HDR images. Within seconds, the retina control exposure time of different parts of the image in order to generate a high dynamic range image that contains more details. HDR imaging is used in many applications specially in the area of computer graphics and image processing. Figure 1 shows an outdoor/indoor scene; when taking a normal image of the scene, outdoor area become bright while indoor area become dark because of the dynamic range of the camera which cannot accommodate the whole real world dynamic range [10].

Figure 1. The HDR image problem: left is LDR image and right is the actual image [2].

This paper presents an evaluation of six different tone mapping algorithms. The evaluation is performed by presenting these tone mapped images to a fare evaluators who rated them based on a given schema. The rest of this paper is organized as follows. Section II presents related prior art of tone mapping and HDR imaging. Section III discusses the tone mapping techniques. Section IV discusses the tone evaluation of some HDR images. Finally, Section V provides a brief summary of the main findings and future direction that can be taken in this research.

II. PRIOR ARTS IN TONE MAPPING

High dynamic range imaging has been an active research for many years and many techniques have been developed in that direction. Fatal and his colleague [11] developed a gradient based tone mapping operator by compressing the gradient of the image luminance component and then constructing the LDR image by solving a Poisson equation on the compressed gradient image. Reinhard et al. [12] used the zone system for mapping HDR world image into LDR ones. In the Zone system, the photographer firstly selects the middle grade key in the image and then selects the darkest and brightest points in order to compute the dynamic range. This process is done manually by photographers then the image is corrected using dogging (darkening) or burning (brightening) process. Reinhard and his colleagues work on automating this system by firstly mapping the whole image using a local averaging logarithmic operator. Then they implemented an automated dodging and burning algorithm that uses a circular Gaussian operator at multiple scales and convolves it with the entire image to correct the bright and dark regions of the image.

Dargo et al. [13] proposed and adaptive logarithmic for compressing the luminance values by adaptively varying the logarithmic bases. They used contrast enhancement to improve the contrast of dark areas in image. Duan et al. [14] used histogram adjustment technique to enhance the visualization of the image obtained using global tone mapping operators. They segmented the image into smaller segment then they adaptively adjusted the contrast of each segment using a global histogram operator. Guangjun and Yan [15] used a logarithmic normal distribution for tone mapping instead of normal distribution. Li et al. [16] decomposed the HDR image into base layer which contains the overall luminance of the image and detailed local luminance layer. They used a statistical-based histogram adjustment to map the base layer into low dynamic range while the detailed layer is mapped using a spatial filtering approach.

III. TONE MAPPING OPERATORS

Tone mapping is the process that reduces a high dynamic range image into low dynamic one so that it can be displayed in conventional display devices while maintaining the image integrity. This section gives a brief introduction about HDR image blending then it defines different tone map operators and explain their effects.

A. High Dynamic range Image Blending

HDR image is generated by fusing multiple LDR images captured at different exposures. The main idea of image blending is to first compute the camera response function which relates pixel intensities to the log of exposure time. Some techniques uses linear camera response curve while other uses nonlinear camera response functions. Detailed description of image blending is beyond this study and more details can be obtained from [2], [3], [17–19]. To give a clue about how LDR images can be blending into a HDR image, let's consider the images in Figure 1 which has been captured at different exposures. If we look at the histogram of each image, we can observe that at low exposure time, majority of pixel lie in the low intensity range and the image generally appears dark. With increasing the exposure time the images gets bright and majority of the pixels tends to fall the high region of the histogram. At a large exposure time the image become very bright and most of the pixels tend to fall in the high region of the histogram. Short exposure gives clear view to the bright regions of the image such as outdoor areas in the Figure 2. On the other hand, longer exposure gives clear view to the dark areas of the image such as indoor regions in Figure 2.

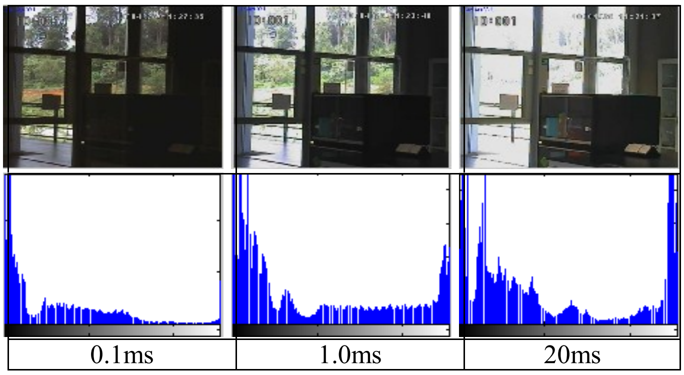

Figure 2. LDR images with different exposure time.

B. Tone Mapping Operators

Tone mapping operators are classified into four parts based on the way they process the images. The categories are global operators, local operators, frequency operators and gradient operators. Global operators apply standard compression on the whole image while local operators use different compression ratio for different parts of the image [2] . Frequency operators compress the spatial frequency domain of the selected part of the image and gradient operators compress the gradient image [11]. In this study seven well-known tone mapping operators were studied and their effect has been compared.

1) Logarithmic (LTM)

It uses a logarithmic function to compress the luminance component of the HDR image using Equation (2) where $\max(I_{HDR})$ is the maximum luminance value, $I_{HDR}.R$ is the Red color channel in the HDR image and I_{LDR} is the compressed LDR image. Then gamma correction algorithm is used to compress each channel in the RGB image using equation (3) where s is the gamma gain [2].

$$L_{HDR} = 0.27 I_{HDR}.R + 0.67 I_{HDR}.G + 0.06 I_{HDR}.B \quad (1)$$

$$L_d = \frac{log_{10}(1 + L_{HDR})}{log_{10}(1 + \max(I_{HDR}))} \quad (2)$$

$$\begin{bmatrix} I_{LDR}.R \\ I_{LDR}.G \\ I_{LDR}.B \end{bmatrix} = L_d \times \left(\begin{bmatrix} I_{LDR}.R \\ I_{LDR}.G \\ I_{LDR}.B \end{bmatrix} \Big/ L_{HDR} \right)^s \quad (3)$$

2) Modified logarithmic (MLTM)

It adopts a separate luminance function for each image channel. The luminance is computed for each channel of the RGB image using Equation (4) then the same luminance gain is used for compressing the said channel of the RGB image as shown in Equation (5) [1].

$$\begin{bmatrix} L_d.R \\ L_d.G \\ L_d.B \end{bmatrix} = \begin{bmatrix} 0.27 I_{HDR}.R \\ 0.67 I_{HDR}.G \\ 0.06 I_{HDR}.B \end{bmatrix} \Bigg/ \begin{bmatrix} log_{10}(1 + \max(I_{HDR}.R)) \\ log_{10}(1 + \max(I_{HDR}.G)) \\ log_{10}(1 + \max(I_{HDR}.B)) \end{bmatrix} \quad (4)$$

$$\begin{bmatrix} I_{LDR}.R \\ I_{LDR}.G \\ I_{LDR}.B \end{bmatrix} = \begin{bmatrix} L_d.R \\ L_d.G \\ L_d.B \end{bmatrix} \times \left(\begin{bmatrix} I_{LDR}.R \\ I_{LDR}.G \\ I_{LDR}.B \end{bmatrix} \Bigg/ \begin{bmatrix} 0.27 I_{HDR}.R \\ 0.67 I_{HDR}.G \\ 0.06 I_{HDR}.B \end{bmatrix} \right)^s \quad (5)$$

3) Exponential (ETM)

An exponential function is used for mapping the luminance instead of the logarithmic function [1]. The exponential gain is computed using equation (6) where L_{av} is the average luminance. After computing the compression gain, the gamma correction is done using Equation (3) as shown previously in the logarithmic operator.

$$L_d = 1 - exp\left(-\frac{L_{HDR}}{L_{av}}\right) \quad (6)$$

4) Modified exponential (METM)

Similar to the modified logarithmic method, a separated luminance mapping is generated for each channel of the RGB image [1].

5) Reinhard global operator (RGTM)

It is a modified version of the exponential operator where the luminance is compressed in a controllable fashion using a low luminance key and high luminance key. Firstly, an initial luminance scaling is generated using equation (7). Then high luminance region is compressed using high key as shown in Equation (8) while the low luminance regions are mapped using low key using Equation (9) where $L_{white}$is the smallest luminance value to be mapped as white [12].

$$L_m = \frac{a}{L_{av}} L_w(x,y) \quad (7)$$

$$L_d(x,y) = \frac{L_m(x,y)}{1 + L_m(x,y)} \quad (8)$$

$$L_d(x,y) = \frac{L_m(x,y)\left(1 + \frac{L_m(x,y)}{L_{white}^2}\right)}{1 + L_m(x,y)} \quad (9)$$

6) Reinhard local operator (RLTM)

This operator firstly applies a spatial blurring on the image using a Gaussian filter shown in Equation (10). Then it computes the largest area that has a relatively low contrast by maximization Equation (11). After that, it uses the Gaussian operator to blur the region of the selected size to compute the luminance gain. Finally, the image is compressed using Equation (12).

$$L_s^{blur}(x,y) = L_m \otimes R_s \quad (10)$$

$$V_s = \frac{L_s^{blur} - L_{s+1}^{blur}}{2^{\phi} a/s^2 + L_s^{blur}} \quad (11)$$

$$L_d = \frac{L_m}{1 + L_{s_{max}}^{blur}} \quad (12)$$

7) Garrett operator (GTM)

This operator is developed based on the image appearance model (iCAM) which considers the surrounding of the pixel during the mapping process. The derivation steps of this operator are slightly complex and more details can be obtained from [20].

IV. Evaluation of Tone Mapping Operators

The previously described tone mapping operators have been applied on different test images and then presented to 12 independent observers who were asked to rate these images based on a given schema as shown in Table I. The highest score is 6 which means excellent while 1 is the lowest score.

TABLE I. RATING SCALE FOR HDR IMAGE EVALUATION [27]

Value	Rating	Description
6	Excellent	Extremely high quality, as good as you could desire.
5	Fine	High quality, providing enjoyable viewing.
4	Passable	An image of acceptable quality.
3	Marginal	Poor quality image; you wish you could improve it.
2	Inferior	A poor image, but you could watch it.
1	Unusable	An image so bad that you could not watch it.

A. Test Case 1: Standard HDR Images

Tone mapping operators have been tested on well-known HDR images obtained from the literature. Figure 3 shows the rating obtained for these types of HDR images. Reinhard tone map operators (RGTM and RLTM) obtained the highest grading followed by the exponential (ETM) operator. The rated images can be seen in Table II at the Appendix. The image for RGTM, RLTM and ETM are clear and good details are preserved although there are some dark regions at the low luminance range (top left corner of the image). The METM operator obtained lower grade because the image has excessively bright regions as well as dark regions. GTM operator shows colors imbalance that is why it scores low rating. Logarithmic operators (LTM and MLTM) have obtained very low score because as it is clear in Figure 6, the compressed image is very dark and almost nothing is visible.

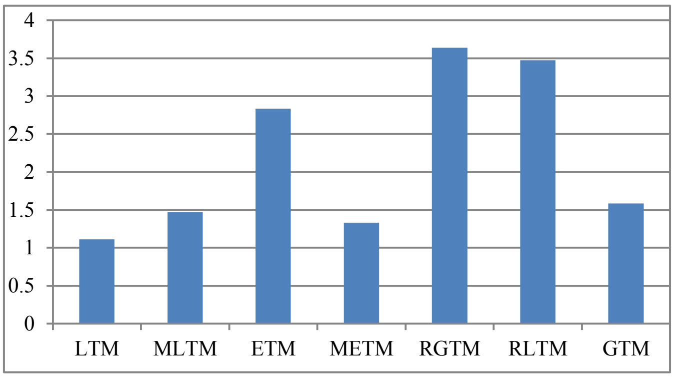

Figure 3. Rating obtained for standard HDR images.

B. Test Case 2: HDR Images with Linear Camera Curve

In this part, the tone mapping operators were applied on HDR images generated using a linear camera response curve. Similar to the previous case, Reinhard operators (RGTM and RLTM) achieved the best score followed by the exponential operator (ETM) as shown in Figure 4. These three operators preserve good details compared to the reference image which has been generated using Photomatic ® Software. In this Set, Garrett operator (GTM) obtained high rating compared to the previous set however it is still less than the score attained by Reinhard operators and exponential operator. Logarithmic operators (LTM and MLTM) along with the modified exponential operator (METM) achieved low rating because the compressed image quality is very bad and the image has colors imbalance and tends to be purplish as in Table III.

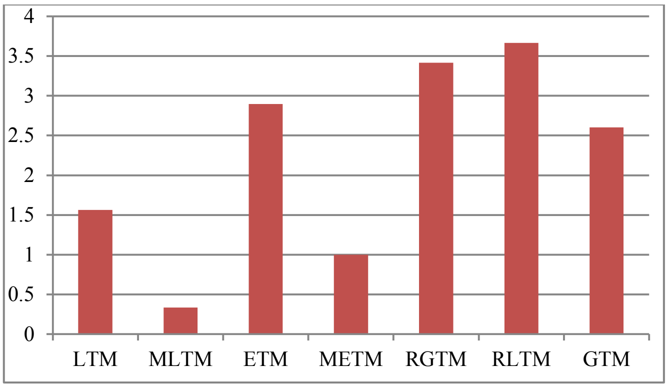

Figure 4. Rating obtained for HDR images generated using linear camera curve.

C. Test Case 3: HDR Images with Nonlinear Camera Curve

In this part, tone mapping operators were applied on HDR images generated using a nonlinear camera response curve. In this case, the modified exponential operator (METM) attained the highest score followed by the Reinhard operators (RGTM and RLTM). Unlike the previous cases, the logarithmic operator (LTM) achieved a higher score and in fact the image has a better visualization as shown in Table IV compared to the other operators. The images obtained by the Garrett operator (GTM) is very grayish and the images obtained by the modified logarithmic (MLTM) and modified exponential (METM) operators is very purplish. In general, the image obtained in this case has less quality compared to the previous test cases and it has colors imbalance in the green component.

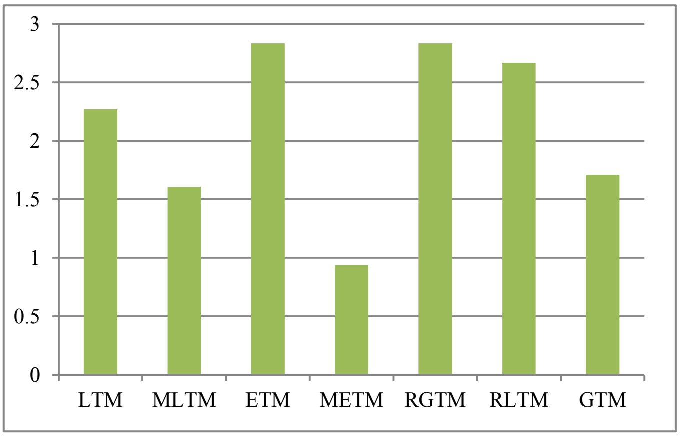

Figure 5. Rating obtained for HDR images generated using nonlinear camera curve.

D. Results and Dsicussions

Based on the previous test cases, Reinhard tone mapping operators (RLTM and RGTM) are the best in term of producing visually pleasing LDR images the maintain all the features of the origional HDR image. The exponential tone mapping operator (ETM) has good results close to the one achieved by the Reihanrd operators. The close coupling between these operators is very clear because the RGTM and RLTM are based on the exponential operator (ETM). In Table V, additional tone mapping results have been shown for these three operators. The Figure shows results of five different images where the obtianed LDR images is visually pleasing. In all the five images, RGTM operator is better than the other two in term of image details as we all rating atained by the evaluators. The other four operators failed to achieve visually pleasing results in all images. Garrett operator (GTM) sometimes produces grayish images. the modified exponential operator (METM) has color imbalance in all the test cases and it always produces a purbilish image. similar comments can be said about the modified logarithmic operator (MLTM). The lgoratithmic operator (LTM) sometimes produces dark images such as in the first test case and sometimes it produces a grayish image. Standard HDR images achieved higher socres that the HDR image generated by authors. Among the non-standard HDR images, the linearly generated image are more visually pleasing and the atained higher socres than the nonlinearly generated images.

V. Conclusion and Future Directions

In this paper, we presented a comparative study of seven well-known tone mapping techniques used for compressing HDR images in order to be compatible with printing and display devices. The evaluation is performed by appling these operators on multiple images and presenting them to a rational evaluators who rate these images based on a given schema. The study concluded that exponential based tone mapping operators have the best scores and the produces more visually please images than the logarithmic based operators. Among the studied operators, Reinhard tone mapping operators (RGTM and RLTM) are the best followed by the exponential operator (ETM). Modified exponential operator (METM) and the logarithmic operators (LTM and MLTM) have poor results.

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APPENDIX

TABLE II. TONE MAPPING RESULTS FOR CASE 1 WITH STANDARD HDR IMAGES

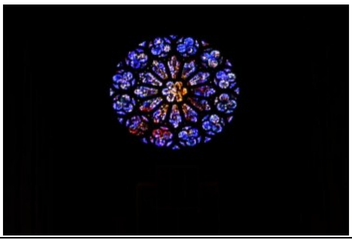
Reference	**LTM**	**MLTM**	**ETM**
			
METM	**RGTM**	**RLTM**	**GTM**
			

TABLE III. TONE MAPPING RESULTS FOR CASE 2 WITH LINEARLY BLENDED HDR IMAGES

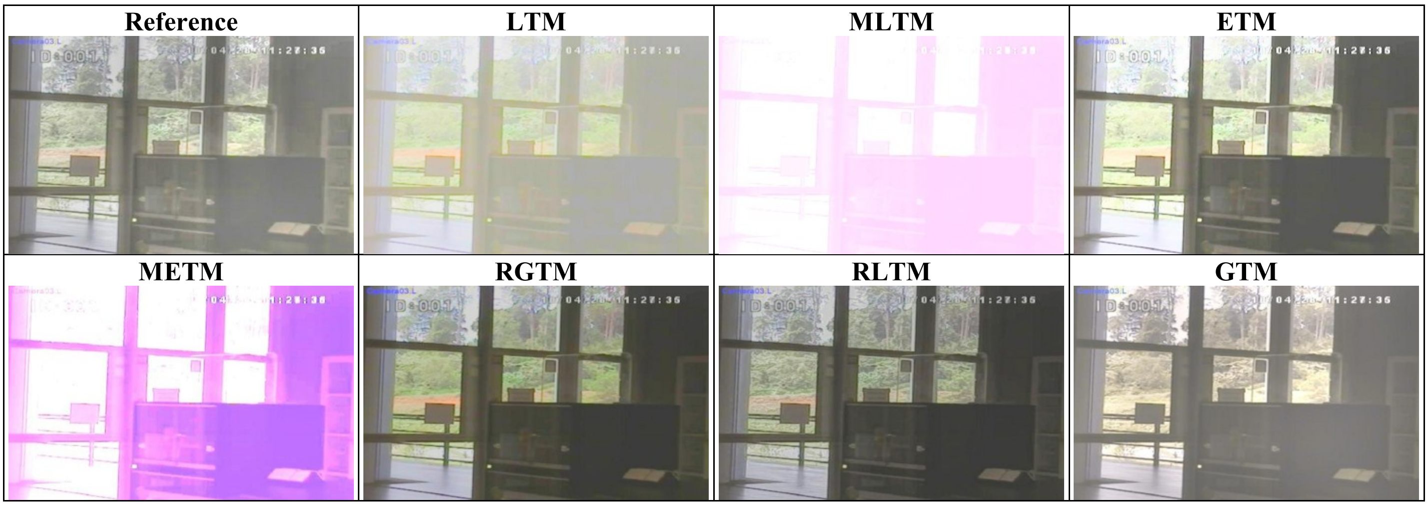


TABLE IV. TONE MAPPING RESULTS FOR CASE 2 WITH NONLINEARLY BLENDED HDR IMAGES

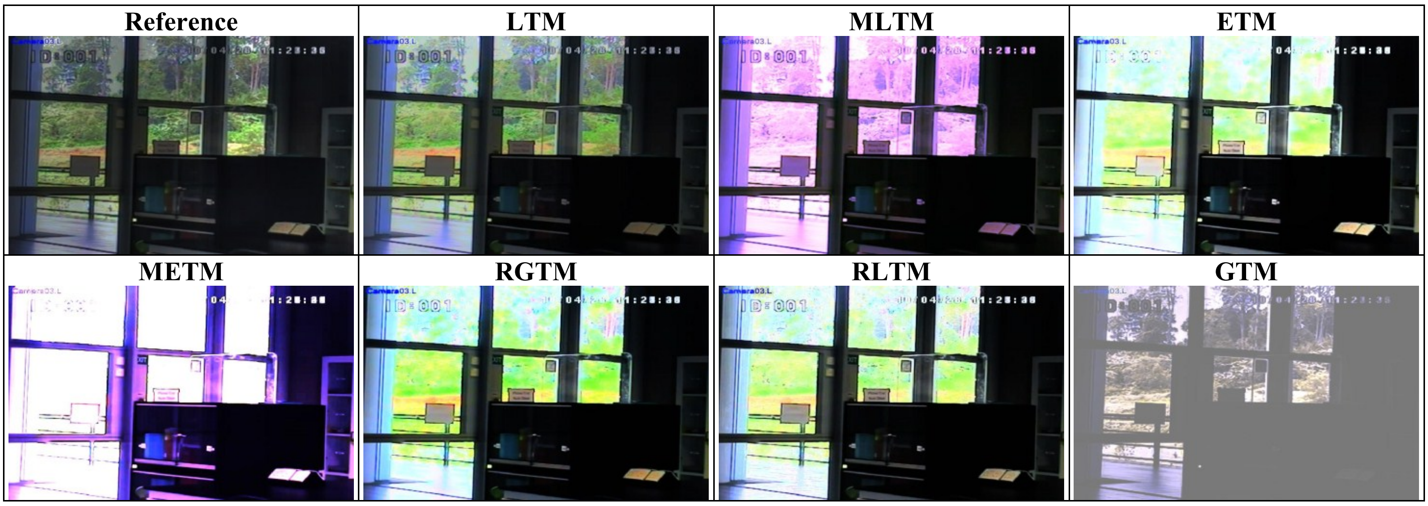


TABLE V. TONE MAPPING RESULTS FOR DIFFERENT HDR IMAGES USING REINHARD AND EXPONENTIAL TONE MAPPING POERATORS