An Adaptive Image Dehazing Algorithm based on Dark Channel Prior

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Abstract: Traditional dehazing algorithm based on dark channel prior may suffer weak robustness against the variation of hazy weather and may fail in bright regions. To resolve these issues, this paper proposes an improved adaptive dehazing algorithm based on dark channel prior. Our method can adaptively calculate dehazing parameter, such as the degree of haze removal. Here the dehazing parameters are local, rather than global variables. We compute the local dehazing parameter automatically according to haze distribution, which makes our method being able to handle different dehazing degrees under various weather conditions, and makes haze removal more robust. We also propose a new method to optimize the rough transmission paramters, which can help to remove the distortion in bright regions. Experiments confirm the advantages of our method, such as robustness against different scenes, high color fidelity of the restored images and greatly enhanced details of the hazy regions.

Key Words: Image dehazing, dark channel prior, atmospheric scattering model, adaptive

1 INTRODUCTION

Nowadays hazy weather is quite common. Images captured in hazy days may be severely degraded due to the influence of atmospheric light. Hazy images will be grayish and blurred in edges, which can significantly damage their detectability. Especially in the thick hazy situation, too much details may be missed and it is quite difficult to process these hazy images, which may yields false vision decision.

Recently, researchers have put a lot of energy on image dehazin. Many effective methods have been put forward. There are lots of methods based on image enhancement, such as global histogram equalization[1], local histogram equalization[2], Retinex[3] including Single scale Retinex(SSR)[4] and Multiple scale Retinex(MSR)[5]. These methods are simple and do little effect in haze removal, therefore researchers established some methods based on physical model of haze imaging, such as Tan at el[6], Tarel at el[8], He at el[7] and Meng at el[9] and so on. These methods proved to be good performance in haze removal but they often has a large computational complexity.

Tan[6] argues that haze-free images usually have high contrast, and the dehazed images are generated by maximizing local contrast. However, the restored images usually suffer from oversaturation in color and halos at edges.

He et al[7] proposes a theory, which is called dark channel prior (DCP), to guide the work of dehazing. The DCP is a regular pattern found in general haze-free images. In most non-sky patches of the haze-free image, at least one color channel has some pixels whose intensity are very low and close to zero. That is to say, the minimum intensity in such a patch is close to zero. Conversely, this pattern do not exist in hazy images. The dehazing algorithm based on DCP is simple and effective, even if the haze is dense or depth changes intensively, so the algorithm becomes the focus as soon as it is proposed. However, the DCP fails in the bright regions (sky etc.), which leads to distortion in restored images, we will discuss this later in detail.

Tarel et al[8] assumes that the variation of the atmospheric dissipation function was flat in local areas, and the transmission was estimated by median filter instead of minimal filter introduced in the algorithm of He at el[7]. Tarel's algorithm is simpler than that of He at el[7], and the processing speed is shortened a lot. However, the median filter does not keep edges well, and halos appear when the scene depth changes rapidly. And there is another shortcoming that limits its application: parameters needing manual control are too many.

Based on dark channel prior[7], this paper proposes an improved algorithm mainly consisting of two novel methods: dehazing parameter adaptive method and new transmission optimization method. A dehazing parameter adaptive method is proposed to enhance the robustness of haze removal. We calculate the dehazing parameter locally according to haze distribution, so the restored images always have a clear vision. We also proposes a new method to optimize transmission, avoiding the DCP's failure in bright regions. Experiments show that our method can not only greatly enhance the ability of haze removal but also improve the robustness to adapt different haze conditions, and the visual perception is realistic and natural.

In the second section we will introduce our method in detail. The experiment results will be showed in third section. Section 4 is the summary.

2 Improvement Based on Dark Channel Prior

Although the DCP algorithm[7] has a good performance on haze removal, it fails in some special scenes (such as

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the bright sky regions) so that the reconstructed image will produce unacceptable distortion in color. The other problem of DCP algorithm is that dehazing parameter, which determines how much haze will be removed, is constant (He at el[7] choose it 0.95)with no changes corresponding to haze distribution, the greater it takes, the more haze will be removed. In fact, different distribution of haze needs different parameters, excessive power in dehazing creates distortion in color, and insufficient haze removal makes image blurred. In order to solve the two problems above, two improved methods are proposed in this paper: dehazing parameter adaptive method and new transmission optimization method.We first would like to review the DCP dehazing algorithm briefly, and the two improvements will be introduced after that.

2.1 Dehazing Algorithm Based on Dark Channel Prior

There is a regular pattern[7] in most outdoor haze-free images: In the nonsky patches, at least one color channel has some pixels whose intensity are very low and close to zero. Equivalently, the minimum intensity in such a patch is close to zero. The DCP dehazing algorithm is based on the atmospheric scattering model[10] that describes the relationship between hazy image and haze-free image captured in one same scene, the model divide the light from two part: the attenuation of the incident light part[11] and the atmospheric light imaging part[12]. The model is described as follows:

$$I\left(x\right)=J\left(x\right)t\left(x\right)+A\left(1-t\left(x\right)\right) \tag{1}$$

where $J\left(x\right)$ is haze-free image in the same scene with hazy image which is $I\left(x\right)$, $t\left(x\right)$ is the transmission that is corresponding to scene depth, and A is atmosphere light measuring the influence of surrounding light.

He at el[7] assume that the transmission is constant in local patches. Then minimum the equation(1) on both sides:

$$\min_{y\in\Omega(x)}\left(\min_{c}\frac{I^c\left(y\right)}{A^c}\right)=t'\left(x\right)\min_{y\in\Omega(x)}\left(\min_{c}\frac{J^c\left(y\right)}{A^c}\right)+1-t'\left(x\right) \tag{2}$$

Since the dark channel of haze-free image tends to be zero, He at el[7] treats it as 0 directly, and A^c is positive, where c is one of the channels, so we have:

$$\min_{y\in\Omega(x)}\left(\min_{c}\frac{J^c\left(y\right)}{A^c}\right)=0 \tag{3}$$

Putting this into equation(2), we can get the transmission:

$$t'\left(x\right)=1-\min_{y\in\Omega(x)}\left(\min_{c}\frac{I^c\left(y\right)}{A^c}\right) \tag{4}$$

In fact, even in sunny weather the atmosphere is not free with haze, the particle hovers in air at every time, so the haze exists all the time. That is to say, we need not to remove all the haze, the remaining haze will keep the vision perceptual well and looks naturally. So He at el[7] introduces a dehazing parameter $\omega\left(0<\omega<1\right)$ to control the degree of haze removal, and then the transmission becomes:

$$t'\left(x\right)=1-\omega*\min_{y\in\Omega(x)}\left(\min_{c}\frac{I^c\left(y\right)}{A^c}\right) \tag{5}$$

The value of ω is corresponding to the haze condition, it should be larger if the haze is dense and be smaller when haze is thin. In particular, haze is removed thoroughly when $\omega=1$ and no haze been removed when $\omega=0$, He at el[7] chooses it as 0.95 to match most conditions despite it leads to unpleasant effect sometimes.

However, block effort is serious if we just use $t'\left(x\right)$ in equation(5) to restored image by equation(1), He at el[7] then optimizes the rough transmission by soft matting[7], however, this optimization has unacceptable computational complexity, so they proposed guide filter[13] to optimize the rough transmission $t'\left(x\right)$ later. Finally, the optimized transmission is used to restore haze-free image through equation(1).

The dehazing algorithm based on DCP, proposed by He at el[7], succeeds in removing haze thoroughly, and the result looks natural and has a great enhancement in details. Although it performs almost perfect, there still remains some problems need to be settled. The first defect we can see is that the dehazing parameter ω is a constant no matter how haze distributes. That sometimes makes haze removed too much, image with not a little haze often leads an unreal feeling of vision. The second problem is that the DCP fails in bright regions(sky etc.), the estimated transmission there differs a lot from real scene transmission, the deviation of transmission yields a distortion in color or even distorts the structure of objects.

2.2 dehazing parameter adaptive method

Note that the DCP algorithm[7] introduces a global parameter to compute the transmission: the dehazing parameter ω, that adjusts the degree of haze removal so that the restored image retains a certain amount of haze, which makes image look naturally. However, the constant dehazing parameter, which should change corresponding to haze distributes, makes the algorithm lower robustness. If the haze is thin, it often removes too much haze and makes image unnatural. In this paper, a dehazing-parameter adaptive method is proposed, which can automatically adjust the value of dehazing parameter according to the distribution of haze. The method is based on the following two facts:

- Haze image generally has a lower contrast compared with the haze-free image when captured in a same scene, and the deviation is correspondingly lower. Especially the thicker the haze is, the smaller the deviations is;
- In hazy image, as we know, the haze distribution depends on scenes depth, so different regions have different density of haze. The local contrast of dense haze region is lower and the intensity is higher than that of mist region. The distribution of haze is related to not just the global information (such as haze-free, mist, dense haze etc.), but also the local information (specific depth distribution, etc.).

Table 1: η - ω

Standard Variance Ratio η	global dehazing parameter ω_0
(0,0.5)	0.9
(0.5,1)	0.8
(1,1.5)	0.7
(1.5,2)	0.5
(2,∞)	0.4

Therefore, we proposed a method combined with global and local information of hazy image to calculate the dehazing parameter, and each pixel gets its own dehazing parameter rather than global one.

We assume that the image to be dehazed is $I(x)$, the haze-free image to be restored is $J(x)$, and the atmospheric light A is known. Firstly, we calculate the $t(x)$ roughly by equation(5). Then we dehaze the minimum channel of haze image $I^{min}(x)$, using minimum of atmospheric light A^{min} and $t'(x)$,to obtain the dehazed image $J^{min}(x)$:

$$J^{min}(x) = \frac{I^{min}(x) - A^{min}}{max(0.1, t'(x))} + A^{min} \tag{6}$$

Haze usually leads to low contrast, that is to say, the variance is lower. Therefore, we use the ratio η, which is quotient of standard variance of $I^{min}(x)$ and $J^{min}(x)$, to measure the global haze condition: $\eta = \sigma\left(I^{min}\right)/\sigma\left(J^{min}\right)$. η indicates the global haze information, the haze is dense when η is small. We introduce a global dehazing parameter ω_0, it is the minimum value of final local dehazing parameter. The value of ω_0 is shown in table1.

Since ω_0 indicates the haze condition roughly, through which we can only know whether the haze is thin or dense, and the realistic haze distribution varies with depth and is nonuniform, we need calculate the detailed dehazing parameter which is locally. We know that regions with dense haze have lower local variance and higher intensity, then the local dehazing parameter $\omega(x)$ is computed:

$$\omega(x) = \omega_0 + \omega_0 * (1 - \omega_0)\left(1 - \frac{\sigma_\Omega(x)}{\sigma_\Omega^{max}(x)}\right)\frac{I^{min}(x)}{A^{min}} \tag{7}$$

where Ω is the neighbouring of pixel x (the radius takes 5 in general), $\sigma_\Omega^{max}(x)$ is the max of $\sigma_\Omega(x)$, which is the standard variance in patch Ω. Then the transmission $t(s)$ is computed:

$$t_1(x) = 1 - \omega(x)\min_{y\in\Omega(x)}\left(\min_c \frac{I^c(y)}{A^c}\right) \tag{8}$$

2.3 new method of transmission optimization

The success of DCP dehazing algorithm[7] is the valid of dark channel prior, it has been proved that the DCP is valid in most conditions. Unfortunately, there are some regions, say sky, do not meet the law. When there is a bright region, DCP fails and the restored image has a great distortion in colors.

Analyzing the DCP dehazing algorithm we can find the key leading DCP's failure: the DCP considers the dark channel of haze-free image to be 0 when compute transmission, so the obtained transmission $t(x)$ will be smaller than correct value. In fact, the dark channel is beyond 0 greatly at the sky region(maybe 30% or even 80% of atmospheric light A), making it 0 causes great deviation and induces distortion in color. To solve this problem, we proposed a new method for the optimization of transmission, which avoids the failure of the DCP dehazing algorithm in those special regions, the estimated transmission reflects the real value of the scene and the restored image looks more natural.

Assuming that the atmospheric light A and the rough transmission $t_1(x)$ (obtained by equation(8)) are known, the specific steps of the algorithm are as follows:

1. using the atmospherical scattering model to dehaze the haze image $I(x)$, we get the one iteration dehazed image $J_1(x)$:

$$J_1^c(x) = \frac{I^c(x) - A^c}{max(0.1, t_1(x))} + A^c, c \in (r,g,b) \tag{9}$$

2. calculate the minimum channel $J_1^{min}(x)$ from $J_1(x)$
3. calculate the optimized transmission $t_2(x)$:

$$t_2(x) = \frac{A^{min} - I^{dark}(x)}{max\left(1, A^{min} - J_1^{min}(x)\right)} \tag{10}$$

4. get the refined transmission map $t(x)$ guide filtered by $t_2(x)$

Since the denominator will cause overflow when it is too small, we use 0.1 as its lower bound in equation(9). Similarly, we use 1 as the lower bound of denominator in equation10, in case of unpleasant case created by noise. Note that guide filter is used in step4, which makes transmission more refined and accurate and with no block effort.

Now we would like to prove the valid of our optimization above. In fact, we can use the deformation of step1,2,3 above to get the transmission reach the real transmission of scene, even with no deviation, that is:

$$J_i^c(x) = \frac{I^c(x) - A^c}{max(0.1, t_i(x))} + A^c, c \in (r,g,b) \tag{11}$$

$$J_i^{dark}(x) = \min c \in (r,g,b)\left[\min x \in \Omega\left(J_i^c(x)\right)\right] \tag{12}$$

$$t_{i+1}(x) = \frac{A^{min} - I^{dark}(x)}{A^{min} - J_i^{dark}(x)}, i \in N^* \tag{13}$$

It can be proved that iterative calculation of equation(11)(12)(13) makes transmission $t_i(x)$ reach the real transmission $\hat{t}(x)$, which depends on scene depth, and the deviation tends to 0 when the iteration times gets large, that is, $t_i(x)$ converges to real transmission $\hat{t}(x)$(suppose it exists). The prove of this is following:

1. When the iteration time i is 1. Since $J_0^{dark}(x) = 0$(DCP's conclusion), then $J_0^{dark}(x) \leq or \leq J_1^{dark}(x)$, and we also get $t_1(x) \leq t_1(x)$ through equation(13).

2. Assume that iteration time is i, it content the inequality: $t_i(x) \leq t_{i+1}(x)$, then we can reference from equation(11)(12) that $J_i^{dark}(x) \leq J_{i+1}^{dark}(x)$

3. When the iteration time is i+1, we can reference from equation(13) and conclusion of 2:$t_{i+1}(x) \leq t_{i+2}(x)$

4. In summary, the sequence of $t_i(x)$ and $J_i(x)$ is increment sequence of i.

5. As $J_0^{dark} = 0$, we simply get $t_1(x) \leq t(x)$ and $J_1(x) \leq J(x)$(suppose $J(x)$ is restored by $t(x)$). If we consider the sequence $t_i(x)$ do not converge to $t(x)$, that is to say, there exist a positive integer j, when $i < j$,$t_i(x) \leq t(x)$, and $t_i(x) \geq t(x)$ when $i \geq j$. We just consider i=j, then $J_{j-1}(x) \geq J(x)$(by equation(8)). Bring it into formula(6), the conclusion, that is $t_{j-1}(x) \geq t(x)$, is against the assumption above, so we can get the conclusion that $t_i(x)$ converges to $t(x)$. Similarly, the sequence $J(x)$ converges to $J(x)$.

Seeing the proof above, we know that the calculated transmission $t_i(x)$ will close to real transmission in scene with the iteration increasing, and so does the restored image. Multiple iteration makes the restored image close to real scene without haze, and the result will look naturally, the intensity and details is greatly enhanced.

Although multiple iteration of equation(11)(12)(13) makes a good performance, it slows down the speed of processing because of its high computation. To increase the speed of processing while the dehazing ability reduces in an acceptable range, we deformed the equation(11)(12)(13) that just one iteration is computed and the dark channel $J_1^{dark}(x)$ is replaced by minimum channel $J_1^{min}(x)$(Since $J_1^{min}(x)$ is somehow close to $J_n^{dark}(x)$after n times iteration), this is introduced in the front of this section.

3 Experimental Results

We compared our algorithm with some classical dehazing algorithms, say, Multiple scale Retinex(MSR)[5], He at el[7], Tarel at el[8], Meng at el[9]. We dehaze in different scenes that have thin , moderate, dense or even no haze, the images will be dehazed by different algorithms mentioned before respectively. In particular, we choose 0.95 for the dehazing parameter introduced in He at el[7].

Figure 1 shows the results of non-haze image using different dehazing algorithms respectively. We can see that MSR brightens the color from (a), the details in dark regions is enhanced. Tarel at el[8] makes the image to be block and distortion in sky, more worse, the halos is produced. Meng at el[9] makes great distortion in sky and the smooth region becomes block like. Since the DCP fails in sky, He at el[7] produces heavy distortion in color, and there is some halos between the sky and grove. Our algorithm succeed in retaining the information of scene, and the tone is natural, distortion and block phenomenon is avoided.

Figure 2 is the results of thin haze condition. The Multiple scale Retinex(MSR)[5] does no good with haze removal, it produces heavy distortion in colors. Tarel at el[8]

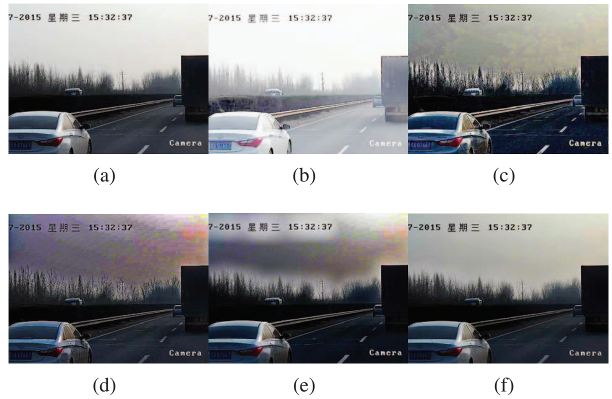

Figure 1: (a) is the source image with no haze,(b) is restored by Multiple scale Retinex(MSR),(c) is restored by Tarel at el,(d) is restored by Meng at el,(e) is restored by He at el,(f) is our result

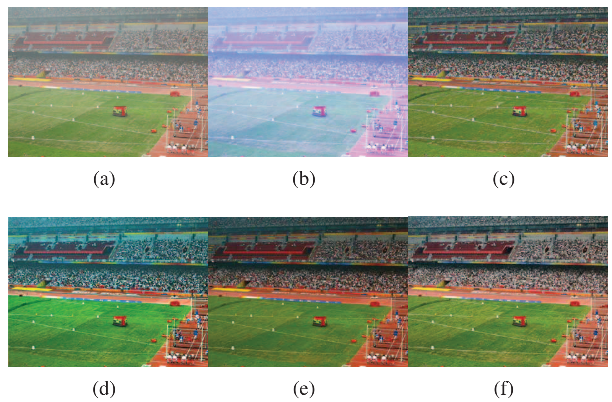

Figure 2: (a) is the hazy image with thin haze,(b) is restored by Multiple scale Retinex(MSR),(c) is restored by Tarel at el,(d) is restored by Meng at el,(e) is restored by He at el,(f) is our result

achieve to remove haze and has a good performance in details enhancing which makes contrast enhanced too. Meng at el[9] remove the haze while distortion involves, colors tend to be blue in the upper left corner, it's worth to say that Meng's way has the highest contrast compared with the other four results. He at el[7] remove the haze thoroughly without any distortion, the picture dehazed has a good perceptual, only one defect, that the intensity is dark, makes the upper left corner blurred. Looking at the last picture, that is, our result, we can see that we removed the haze successfully without distortion and blur, the contrast enhanced greatly and the picture looks naturally.

Figure 3 shows the results of moderate haze image(the first one) restored by five algorithms. Obviously, the MSR[5] does not remove any haze in perceptual, it only enhances the contrast of image, the regions where there is less haze restored to a perfect effect compared with the others, while in the regions with dense haze still retains haze. Although Tarel at el[8] removes haze completely and the restored image has the highest contrast in five images, we can see it is heavily distorted. Meng at el[9] restored a lot

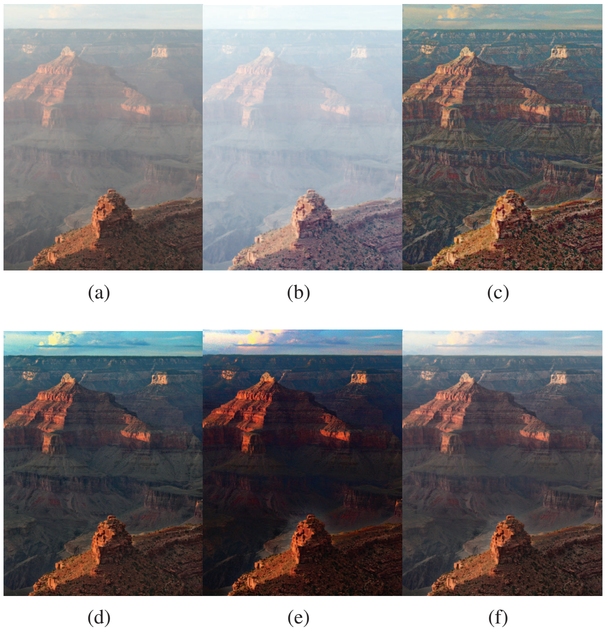

Figure 3: (a) is hazy image with moderate haze,(b) is restored by MSR, the third one (c) is restored by Tarel at el,(d) is the result of Meng at el,(e) is restored by He at el,the last picture (f) is our result

of details, the result has a good perceptual but the whole image tend to be rendered by blue and green tone. He at el[7] restored in a natural tone and looks naturally, the only thing is the lower intensity which leads to lower contrast, especially the distant regions where dense haze distributes. However, our result avoids all the problems above successfully, it has the same tone with the normal scene and looks naturally, the details tend to be more obvious.

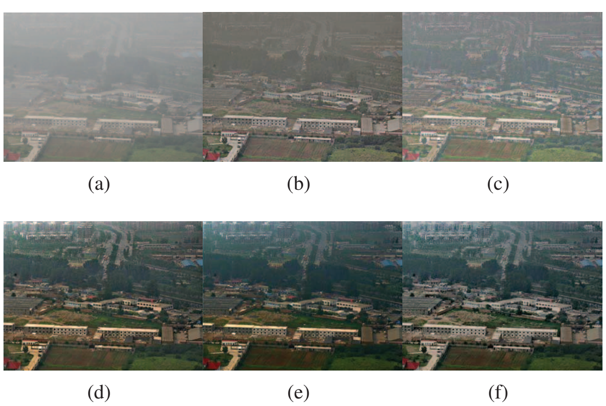

Figure 4: the first picture (a) is the hazy image with dense haze,(b) is restored by MSR,(c) is restored by Tarel at el,(d) is the result of Meng at el,(e) is restored by He at el,the last picture (f) is our result

Figure 4 shows the results of dense haze image(the first one) using the five algorithms mentioned before. The MSR[5] removes haze effectively in the regions with thin haze, while it does nothing with the dense haze.(c) shows the ability on thin haze removal of Tarel at el[8] is good, the contrast enhanced a lot, details looks more clear, but it does little effort on dense haze too, and yields distortion in colors which is the most unacceptable.(d) shows a perfect performance in dense haze removal, the objects restored clearly in the upper left corner and the fresh color contributes to visual feelings. Figure(e) shows He at el's[7] performance in haze removal, it removes haze successfully especially the dense haze though it looks not so good compared with Fig(d) and Fig(f), and the objects in the dense haze regions tend to be rendered by green dye. Our result, showed in Fig(f), tends to overcome all the defects mentioned before, details in the dense haze regions have a great enhancement, the color of scene plays no deviation, say,the roof and road, which tend to be yellow in (d)(e), maintain to be their inherent white after dehazing by our algorithm.

In summary, our algorithm performs well in different conditions of haze removal. Whether the haze is thin or dense or even no haze, we can determine how much haze is going to be removed automatically according to haze distribution, the restored image always has a good clear vision and high contrast. Especially, we have the best power of haze removal in the dense haze regions.

4 Conclusion

In this paper, we propose an efficient method to dehaze while avoiding the defects of DCP dehazing algorithm[7]. The dehazing parameter adaptive method helps to adjust the degree of haze removal according to the haze distribution, by which we remove more haze if the haze is dense and remove less if it is thin. The method is robust and can be used in multiple images haze removal. At the same time, we analyze the reason why dark channel prior fails in some special regions and improve the haze removal using a new transmission optimization method. This novel thought can avoid the unacceptable deviation between estimated transmission and the real one in bright regions. The optimized transmission tends to close to the scene's true transmission and helps to prevent the distortion made by He at el[7] in those bright areas. We have analyzed and proved the rationality of our ideas theoretically, and the efficient efforts have been experimentally verified.

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