

PAPER • OPEN ACCESS

## A Hybrid Approach on Single Image Dehazing using Adaptive Gamma Correction

To cite this article: O V Putra *et al* 2019 *J. Phys.: Conf. Ser.* **1381** 012030

View the [article online](#) for updates and enhancements.

 <p>The Electrochemical Society Advancing solid state &amp; electrochemical science &amp; technology 2021 Virtual Education</p> <p><b>Fundamentals of Electrochemistry:</b> Basic Theory and Kinetic Methods Instructed by: <b>Dr. James Noël</b> Sun, Sept 19 &amp; Mon, Sept 20 at 12h–15h ET</p> <p>Register early and save!</p>	
--	--

# A Hybrid Approach on Single Image Dehazing using Adaptive Gamma Correction

O V Putra\*, A Musthafa, and F R Pradhana

Universitas Darussalam Gontor, Ponorogo, Indonesia

\*oddy@unida.gontor.ac.id

**Abstract.** Since the last eruption of Mt. Kelud, a surveillance has been conducted using camera to observe the crater lake and its surroundings. The key point of this observation is based on the captured haze-free images. However, these images suffer from hazy condition because of degassing. Degassing obscures the camera vision so that the observer barely maintain to keep track of lake phenomenon. Furthermore, even many dehazing techniques have been proposed to tackle this such problems, it still leaves some other problems such as oversaturation, color distortion, and halo effects. In this paper, a hybrid method is proposed. This work incorporates two the state-of-the-art visibility restoration and contrast enhancement methods which are color attenuation prior (CAP) and adaptive gamma correction (AGC). This method is separated into three different modules. They are disparity estimation (DispE) module, transmission map enhancement (TME) module, and hazy image restoration module (ImRec). The DispE module adapts the color attenuation model for its powerful depth estimation for handling outdoor image. Subsequently, the TME module is enhanced using AGC. And the last module is calculated from the modified hazy model. The experimental results are quite impressive. It is able to maintain edge and minimize image distortion qualitatively. And the fog density measured with Fog-Aware Density Estimation (FADE) estimated at 1.448.

## 1. Introduction

Human vision can see through any object in a clear scene condition. An object is visible to human eye because it reflects or scatters the light that come from the sky. The ray propagates from the object through the particle in the air and reaches the eye [1,2]. On the other side, an image which is taken under hazy condition loses its contrast and visibility. Haze often obscure the vision.

Generally, many concept of image dehazing were proposed to overcome the vision problem depend on the portion of the skylight [2–4]. They use outdoor image in a proper composition. The image may consist of three main parts, which are the land, the object, and the sky region. Ideally, these main parts are divided evenly. Thus, the proportion of scene within image is adequate. However, at certain outdoor photograph condition, the proportion may lack something, such as the existence of sky region with. For example, our prior research uses the crater lake images as subject for visibility restoration [5]. The image is captured using CCTV. Prior to the application of CCTV, the Ministry of Energy and Mineral Resources of Indonesia conducted the program for volcano disaster mitigation [5]. This observation is



Content from this work may be used under the terms of the [Creative Commons Attribution 3.0 licence](https://creativecommons.org/licenses/by/3.0/). Any further distribution of this work must maintain attribution to the author(s) and the title of the work, journal citation and DOI.

in purpose of monitoring the lake activity. At certain time, the sulphur dioxide starts to emerge and diffuse with particle in the air [6,7]. This process is mainly caused by the volcanic activity. With the degassing moving upward, the camera visibility is obscured. Obviously, one of the solution is to restore the camera visibility.

By the camera is directly facing toward the lake, it does not cover the sky region. Another problem is that the restored scene radiance color is affected by global color luminance. Which results the restored color tends to be bluish. This condition compared to other outdoor images makes the dehazing difficult to handle. Since most of the dehazing is relied upon the light source. Restoring the visibility is not only haze removal but also color adjustment.

In this paper, an adaptive dehazing method using gamma correction is proposed to restore the visibility and adjust the color of hazy image. By incorporating the concept of dark channel prior (DCP) for atmospheric light estimation, color attenuation prior (CAP) [8] for the depth estimation, and adaptive gamma correction [9] for color adjustment, we can restore the hazy scene images.

The main contribution of this paper is the adaptive gamma correction incorporated with DCP and CAP to improve the previous works [8,10,11] including the conference version [5]. Our new method is able to preserve the color of restored images. Thus, the image is no longer affected by global scene radiance.

## 2. Related Works

A number of dehazing researches have been conducted for about 20 years. Many approaches and assumptions are built during these development. Fattal *et al*, have been proposed a dehazing technique based on Independent Component Analysis (ICA) [3]. He assumed that the transmission medium and surface shading are locally uncorrelated. Fattal also refined the hazy image model which used in [1]. The vector of constant albedo  $R$  and scalar  $l$  are added to the hazy model. These variables redefine the non-haze image. By using Gauss-Markov random field, Fattal's algorithm can be used for transmission map estimation. The white light proportion which reflected by the surface is estimated using this algorithm. Finally, the transmission map can be refined along with estimation of albedo scene. However, the shortcomings of this method are the long process of refinement and the weakness for handling dense haze.

Not only the global contrast is higher on clear scene compared to hazy scene but also the local contrast. Tan *et al* has proposed a dehazing method based on Markov Random Field (MRF) [12]. The local contrast of a scene is maximized using his method. Restoring the visibility of hazy scene is quite a problem. This is due to the non-existence of atmospheric light. The overcast caused the light dimmer. On the other side, the light globally remains constant. Instead of estimation the atmospheric light, the remaining task is focused on light chromaticity estimation. There are several conditions that must be met in order to dehaze a hazy scene. First, the haze-free image must have higher contrast than the hazy one. Second, the depth image affects the atmospheric light variance. Therefore, at some patches, the atmospheric light and the depth are likely to be similar. Third, the outdoor hazy images usually disrupted by bad weather. Therefore, the recovered image must satisfy the clear image features. The restored image yields good result but susceptible to oversaturation. This is caused by high distinct contrast in adjacent block window patches.

At some colors in most patches of natural outdoor scene, there is one color channel which has low intensity. Some colorful outdoor object such as tree leaves, yellow flowers, and green bushes have low intensity from one channel of their RGB color space [2,13] When the color channels are observed from the green leaves, the green color obviously has higher intensity than the remaining two channels. This observation also valid for the other colorful objects. The low intensity channel within colorful object is called the dark channel. This assumption was introduced by He *et al*. He called this as the dark channel prior (DCP). One of the concept of dark channel is that its capability for estimating the light source. If the colorful object at least has one channel with low intensity then the light source has high intensity on each channel. This claim can be proven by using the dark channel assumption. The DCP takes a certain patch size. From each patches, it takes the minimum intensity color channel within a patch to make a block-like window sliding throughout the image. The side effect of this process will create some block artifacts for the restored image. To handle this problem, He utilized the soft matting algorithm to refine the restored image. However, the soft matting take long time to process. In the next two years, He

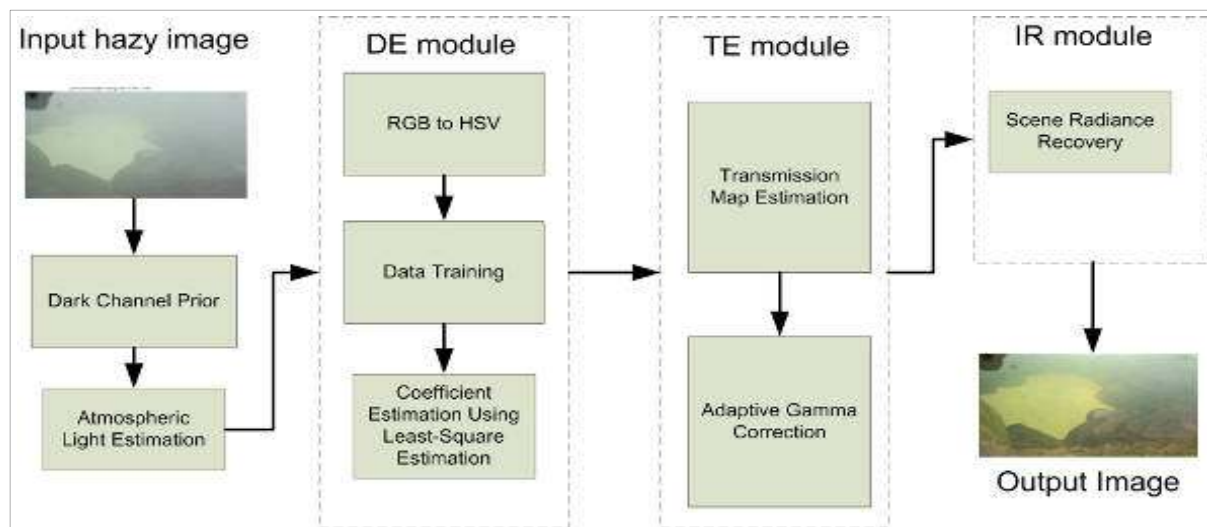


Figure 1. Proposed method using AGC

proposed an image filter method called guided image filter [14]. This method works faster than soft matting. The DCP gives impressive result on dehazing of hazy images. It can handle denser haze. However, it may results oversaturation when there is exist an object whose color intensity similar or equal to the light source.

At the same year when the guided filter was proposed, a new adaptive method was also proposed by Meng *et al* [15]. He modified the hazy image model geometry. Two new components was added prior to the model. They are the boundary constrain C0 and C1. This method is used for transmission map estimation and based on L1-norm for weighting the contextual regularization. The concept of contextual regularization is originated from observation that neighboring pixels share same depth at local patch. Meng's method refines the DCP. However, it may fail on recovering the halo effect. The new prior was proposed by Zhu *et al*[8] was called color attenuation prior (CAP). Zhu has found the depth model for outdoor hazy image. He found a correlation between saturation and brightness. The correlation is based on observation of outdoor image. He took samples of different distance from an outdoor image. The samples was separated into three patches. Each patches represents the image depth. The first to the third patch represents near, mid, and far distance respectively. They are observed in the HSV color space. From this observation, the saturation gradually decreased along with the distance. And vise versa, the brightness statistically increased. In near distance, we can clearly distinguish objects with different color. The colorfulness of object represent high saturation. When we see objects in far away, it is hard to see them because of the obscuring haze. Therefore, the depth of image, the concentration of haze, and the brightness are positively correlated. The depth model was trained using maximum likelihood estimation (MLE). He gathered data from Google dan Flickr. The CAP algorithm is the fastest compared to the previous state-of-the-art algorithms and able to preserve edge information. However, there is a shortage of this algorithm. When an object close to the camera, the restored object is darker.

In the next year, Chen *et al* [11] proposed a gain intervention refinement (GIR) filter for transmission refinement. This filter idea came from the shortage of DCP which are the halo effect. As mentioned earlier, the main problem of dehazing is the halo effects and block-like artifacts [11,13]. The use of filters such as softmatting and guided filter avoids the generation of halos and artifacts. However, the computational intensifies because of the overlapping window in local linear model. Compared to the previous two filter of DCP, soft matting and guided filter, GIR utilizes the gain intervention of the dark channel images. This filter surpassed the previous filter in term of transmission map refinement due to its fast computation. However, oversaturation exists when dealing with an object that as bright as the light source.

In our previous work [5], an incorporated haze removal was implemented using DCP and CAP. The result is quite impressive. However, the restored images tend to be bluish.

### 3. Proposed Works

According to previous research, dehazing problem mainly focused on restoring the visibility. This issue works well when there is no influence of global color radiance. Since the global color mostly affects the restored image, the remaining problem is adjusting the restored color. We will discuss this issue more details later.

Mostly, the previous state-of-the-art methods [2,8,12] recover the obscured image with proper proportion of the background. This proper proportion is composed by objects and sky. Since the camera Field of View (FOV) covers only the lake and its surroundings, our data does not contain the sky region. With this condition, it is quite problematic for estimation of the atmospheric light.

The output dehazed images come in different issue according to the method. Almost every dehazing algorithms can bring up the vivid color of hazy images. However, a problem may come when dehazing problem only depends on haze removal and is affected by the global luminance. The restored image does not show its original color.

Occasionally, the surrounding lake color varies. The green color appears when it is cloudy. The yellow color also appears when the weather is clear. Sometimes, it becomes dark brown when it is overcast. In order to overcome this problem, in this paper, a hybrid single image haze removal using CAP dan Adaptive Gamma Correction (AGC) is proposed. This method is applied to the CCTV images of the lake crater of the mountain Kelud. The proposed method shows impressive results.

The proposed method consist of three modules as seen in **Error! Reference source not found.**. The first module is the disparity estimation module (DispE). The second module is the transmission enhancement (TME) module. And the last module is the image recovery module (ImRec). These three modules will be elaborated later.

#### 3.1. DispE Module

The hazy image degradation model is proposed by McCartney [16]. Later, this model is further improved by [1]. The image degradation formula can be written as:

$$I(j) = \Phi(j)(t(j)) + A(1 - t(j)) \quad (1)$$

where  $I(x)$  is the output hazy image which is formed by the right term in equation **Error! Reference source not found.**. The  $\Phi(x)$ ,  $A$ ,  $t_0(x)$ , and  $x$  in right term are the haze-free image, the atmospheric light, the transmission medium, and the position within images respectively. The main objective of dehazing is to extract  $\Phi(x)$  from equation 1. The haze-free image can be achieved once the remaining variables  $I(x)$ ,  $A$ , and  $t_0(x)$  are satisfied. The physical model of hazy image can be seen in Figure 2.

The transmission map can be regarded as image transparency level [2]. There is another definition of transmission map according to [3,10,17]. It is defined as unscattered portion of light that reaches the camera. Mathematically, the transmission map is formulated as:

$$t_0(j) = \exp\left(-\int_0^m \beta(z)dz\right) \quad (2)$$

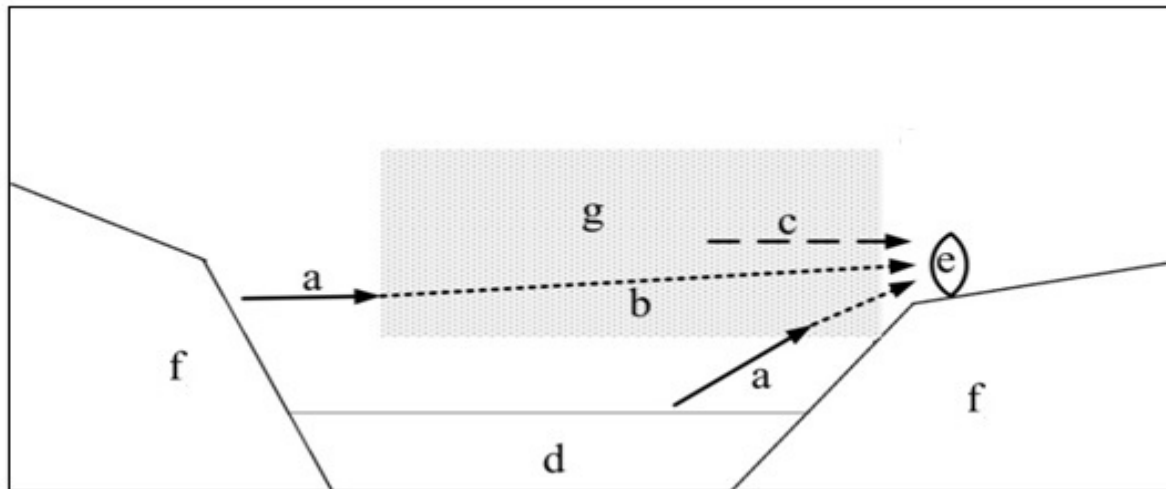


Figure 2. The physical model of image degradation. Where **a** is the propagating light, **b** is the attenuated light, **c** is the airlight, **d** is the lake water, **e** is the observer camera, **f** is the lakeside, and **g** is the haze above the lake

where  $t_0$  is the transmission map. It represents a portion of light that passes through particles in the air and finally reach the observer,  $\beta$  is the light scattering coefficient, and  $d$  represents the depth map. From equation **Error! Reference source not found.**, we get:

$$t_0(j) = e^{-\beta d(z)} \quad (3)$$

where the remaining problem in determining the transmission map is relied on the depth image  $d(x)$ . The depth image is an image in graylevel which its pixels hold intensity value. In fact, each pixel represent the distance between point object or background to the observer.

Measuring the depth image is quite challenging [2,5,8]. Some tools such as Microsoft Kinect and stereo camera can be utilized for estimating the depth for measurable distance object. However, some outdoor scene it is troublesome to measure its depth.

A new outdoor depth model was introduced by [8]. It is formed from three coefficients which are positively correlated. They are brightness, saturation, and difference between them. The depth value is directly proportional to the difference between brightness and saturation. By this definition, the correlation can be modelled as:

$$d(z) \propto v(z) - s(z) \quad (4)$$

where  $d$  is the disparity,  $v, s$  are the value and saturation in HSV color domain respectively and  $z$  is the pixel position.

Since the equation **Error! Reference source not found.** is positive correlation, the mathematical representation can be defined as:

$$d(z) = \lambda_0 + \lambda_1 v(z) + \lambda_2 s(z) + r(z) \quad (5)$$

where  $d, v,$  and  $s$  are the depth, value, and saturation respectively. These are taken from equation **Error! Reference source not found.**  $\lambda_0, \lambda_1,$  and  $\lambda_2$  are the coefficients that must be estimated. And the last is residual  $r$ . In Zhu's works [8], the coefficients of this model was estimated using maximum likelihood estimation (MLE).

To simplify the calculation, the matrix form of **Error! Reference source not found.** are  $\mathbf{K}$  represents the variables  $v_0$  to  $v_n$  and  $s_0$  to  $s_n$ , the vector  $\mathbf{d}$  represents the depth  $d_0$  to  $d_n$ , and the vector  $\mathbf{p}$  represents  $\lambda_0$  to  $\lambda_n$ . By this declaration, we have:

$$K = \begin{bmatrix} 1 & v_0 & s_0 \\ 1 & v_1 & s_1 \\ 1 & \vdots & \vdots \\ 1 & v_n & s_n \end{bmatrix}, p = \begin{bmatrix} \lambda_0 \\ \lambda_1 \\ \lambda_2 \end{bmatrix}, d = \begin{bmatrix} d_0 \\ d_1 \\ \vdots \\ d_n \end{bmatrix} \quad (6)$$

In order to estimate the coefficient  $\mathbf{p}$ , the Least Squared Estimation (LSE) is proposed in this method. From **Error! Reference source not found.**, the estimated coefficients can be estimated by:

$$p = (K^T K)^{-1} V^T d \quad (7)$$

The data training are collected from [18]. The points are accumulated prior to data training. Once the coefficients are estimated, the disparity also can be estimated using equation **Error! Reference source not found.**

### 3.2. TME Module

In case of dehazing, the condition of outdoor images varies. An image may composed of object which act as light source. This object can cause oversaturation for the restored scene. The other problem, global environment color also affects the restored image. This ill-posed nature needs different treatment [13].

A method based on gamma correction is adapted from [4]. This method classify the image intensity into bright and dark. Gamma correction not only is used to increase contrast but also to adjust the intensity of transformation function. Furthermore, this adaptive gamma correction (AGC) preserves the detailed edge. Thus, the modified TME can be formulated as

$$t_1(j) = V_m \left( \frac{t_0(j)}{V_m} \right)^\gamma \quad (8)$$

while  $\gamma$  can be achieved from

$$\gamma = \begin{cases} 1 + \frac{z}{T_{thres}} & , z \geq T_{thres} \\ 1 & , z < T_{thres} \end{cases} \quad (9)$$

where  $t_1$  is the enhanced transmission,  $V_m$  is maximum intensity from grayscale,  $\gamma$  is the adaptive gamma value,  $z$  is intensity value when the cumulative distributed values reach certain threshold, and  $T_{thres}$  is the intensity constraint from  $z$ . We set the value of  $T_{thres}$  at 0.429 when  $z = 0.1$ . This value was obtained from our observation of crater images in various weather condition, such as clear, cloudy, and hazy.

Inspired from [4] in restoring bad weather images, the average of each RGB value is calculated. Therefore, we get

$$\mu_c = \frac{1}{s} \sum_{i=1}^p \sum_{j=1}^q H_c(i, j) \quad (10)$$

where  $\mu$  is the average intensity of each points,  $s$  is the number of pixel,  $p, q$  is the height and width of image respectively, and  $H_c$  is the intensity at  $i, j$ .

From equation **Error! Reference source not found.**, we get:

$$\delta^c = \mu_r - \mu_c \quad , \quad c \in \{r, g, b\} \quad (11)$$

### 3.3. ImRec Module

Finally, last but not least, this module plays as final role. When DispE and TME module has been achieved, the outdoor haze-free image can be obtained from

$$\Phi^c(j) = \frac{I^c(j) - (A^c - \delta^c)}{\max(t_1(j), t_0)} + (A^c - \delta^c) \quad (12)$$

where  $\Phi^c(j)$  is the restored haze-free image,  $I^c(j)$  is the intensity of hazy image at  $j$ ,  $A$  is the atmospheric light,  $\delta$  is a disparity from **Error! Reference source not found.**, and  $t_0$  and  $t_1$  are the boundaries. Typically,  $t_0$  is set at 0.1.

Subsequently, equation **Error! Reference source not found.** effectively manage to recover  $\Phi^c(j)$  from  $I^c(j)$ . To sum up, the proposed method is illustrated as in **Error! Reference source not found.**

#### 4. Experiments and Results

Our method were evaluated using generally used hazy images for instance: a hazy soccer field and a castle. This evaluation is intended to measure the performance of our proposed method to other famous dehazing algorithms. They are He [2], Zhu [8], and Chen [19]. The evaluated parameters are fog density (FADE) and entropy.

This experiment was carried out using a PC with 16 GB RAM, Intel Core i7 8<sup>th</sup> gen, and the tested data was captured using CCTV camera model Axis Q1755-E with resolution 1280x720.

##### 4.1. Disparity Estimation using LSE

We gathered outdoor hazy images with their corresponding depth map from [18] the depth map parameters as in equation **Error! Reference source not found.** are estimated using Least-Squared Estimation (LSE). The colored images are converted into HSV color space. Subsequently, only saturation and value are extracted before they used to satisfy equation **Error! Reference source not found.** With its depth images available, finally, the parameters were trained. As results, we found that  $\lambda_0, \lambda_1, \lambda_2$  are equal to 0.126111, -0.043755, and -0.117156 respectively. When these parameters obtained, the next step is TME module.

##### 4.2. Transmission Map Enhancement Results

In this part, a transmission map enhancement is proposed. This method is incorporated from dark channel for airlight estimation, color attenuation for its incredible outdoor depth map estimation, and finally the AGC from image restoration in a bad weather.

This task are quite challenging. In our previous work [5], it still has shortages. The restored image is influenced by global color. This global color causes obstruction to the scene. Furthermore, the haze-free image is leaving a rough amount of haze as well. Therefore, the gamma correction takes place in order to tackle these problems.

Since the condition of the lake suffers from uncertain weather condition, an adaptive parameter of gamma is deployed. This adaptive value relies on the cumulative density function (CDF). In order to optimize the AGC, color intensity distribution, as in equation **Error! Reference source not found.** and **Error! Reference source not found.**, is applied as well. Finally, the enhanced transmission map can be seen in Figure 3.

##### 4.3. Recovery Results

In this part, we evaluated quantitatively using Fog-Aware Density Estimation (FADE) from [20]. As illustrated in Table 1, the proposed method is compared with previous famous dehazing algorithms in various hazy image conditions. In general, our method is able to tackle hazy condition. Even at certain condition, we fail to stand on top of all algorithms, however, the proposed method managed to overpower the other methods. This can be seen that we achieve the average lowest value of FADE at 1.448 followed by He, Chen, and Zhu.

Generally speaking, most of hazy removal techniques are able to tackle such hazy condition. However, another experiment protocol must be used to measure the results in various conditions. Hence, all techniques are forced into these conditions.





Figure 3: Original hazy image and its corresponding transmission map



Figure 4: Comparison of proposed method and the others techniques. (a) is the hazy images, (b) He's result, (c) Zhu's result, and (d) our result.

As illustrated in Figure 4, the difference between the proposed method and the other three methods are quite distinguishable. It can be seen that the He's result contains less haze compared to others. However, even it is achieved such result, it tends to get affected by global blue color. Moreover, the lake color is oversaturated as well, not to mention the halo effects around the lake edge. This halo effects occurred due to the dark channel block patch artifacts. Even Meng's result has slight amount of haze, it is capable of tackling of halo effects, thanks to its adaptive feature of dark channel. Unfortunately, it still remain bluish. Finally, in our result, the proposed method is able to exhibit its ability to preserve edge and reduce oversaturation of lake color.

**Table 1.**FADE Results.

	<i>He</i> <i>DCP</i>	<i>Zhu</i> <i>CAP</i>	Chen HGIR	<i>Our</i> <i>CAPAGC</i>
<b>N1</b>	1.71	2.27	2.14	<b>0.99</b>
<b>N2</b>	0.29	2.56	2.29	<b>1.26</b>
<b>N3</b>	1.90	2.66	2.20	<b>1.32</b>
<b>N4</b>	<b>2.17</b>	3.26	3.02	2.45
<b>N5</b>	1.76	2.43	2.52	<b>1.22</b>

## 5. Conclusion and Discussion

In this paper, a hybrid method was proposed based on outdoor depth estimation from color attenuation and adaptive gamma correction. This method contains three main steps, which are the disparity estimation, enhanced transmission estimation, and finally the haze-free image recovery.

As a result, our method achieved the lowest value of FADE at 1.448. Furthermore, the restored image is able to maintain edge and help to tackle oversaturation which is the shortage of dark channel prior. However, our result is still far from best condition. There are some issues that need to be put into concern such as accuracy and segmentation in hazy images, especially in using deep learning based algorithms. This has become our future works.

## 6. References

- [1] Narasimhan S G and Nayar S K 2002 Vision and the Atmosphere *Int. J. Comput. Vis.* **48** 233–54
- [2] He K, Sun J and Tang X 2011 Single image haze removal using dark channel prior *IEEE Trans. Pattern Anal. Mach. Intell.* **33** 2341–53
- [3] Fattal R 2008 Single Image Dehazing *ACM Trans. Graph.* **27** 72:1--72:9
- [4] Huang S C, Chen B H and Wang W J 2014 Visibility restoration of single hazy images captured in real-world weather conditions *IEEE Trans. Circuits Syst. Video Technol.* **24** 1814–24
- [5] Putra O V, Prianto B, Yuniarno E M and Purnomo M H 2016 Visibility restoration of lake crater hazy image based on dark channel prior *2016 International Computer Science and Engineering Conference (ICSEC)* pp 1–6
- [6] Hayer C S, Wadge G, Edmonds M and Christopher T 2016 Sensitivity of OMI SO<sub>2</sub> measurements to variable eruptive behaviour at Soufrière Hills Volcano, Montserrat *J. Volcanol. Geotherm. Res.* **312** 1–10
- [7] Gresse M, Vandemeulebrouck J, Byrdina S, Chiodini G and Bruno P P 2016 Changes in CO<sub>2</sub> diffuse degassing induced by the passing of seismic waves *J. Volcanol. Geotherm. Res.* **320** 12–8
- [8] Zhu Q, Mai J, Shao L and Member S 2015 A Fast Single Image Haze Removal Algorithm Using Color Attenuation Prior *IEEE Trans. Image Process.* **24** 3522–33
- [9] Huang Z, Zhang T, Li Q and Fang H 2016 Adaptive gamma correction based on cumulative histogram for enhancing near-infrared images *Infrared Phys. Technol.* **79** 205–15
- [10] Gao Y, Hu H M, Wang S and Li B 2014 A fast image dehazing algorithm based on negative correction *Signal Processing* **103** 380–98
- [11] Chen B H and Huang S C 2016 Edge Collapse-Based Dehazing Algorithm for Visibility Restoration in Real Scenes *J. Disp. Technol.* **12** 964–70
- [12] Tan R T 2008 Visibility in Bad Weather from a Single Image *2008 IEEE Conference on Computer Vision and Pattern Recognition (IEEE)* pp 1–8
- [13] Lee S, Yun S, Nam J-H, Won C S and Jung S-W 2016 A review on dark channel prior based image dehazing algorithms *EURASIP J. Image Video Process.* **2016** 4
- [14] He K, Sun J and Tang X 2013 Guided Image Filtering *IEEE Trans. Pattern Anal. Mach. Intell.* **35** 1397–409
- [15] Meng G, Wang Y, Duan J, Xiang S and Pan C 2013 Efficient Image Dehazing with Boundary Constraint and Contextual Regularization *2013 IEEE International Conference on Computer Vision* pp 617–24
- [16] McCartney J 1976 *Optics of the Atmosphere: Scattering by Molecules and Particles* (Wiley)
- [17] Cai B, Xu X, Jia K, Qing C and Tao D 2016 DehazeNet : An End-to-End System for Single Image *IEEE Trans. Image Process.* **25** 5187–98
- [18] Zhang Y, Ding L and Sharma G 2019 HazeRD: An Outdoor Scene Dataset and Benchmark for Single Image Dehazing
- [19] Chen B H, Huang S C and Cheng F C 2016 A high-efficiency and high-speed gain intervention refinement filter for haze removal *J. Disp. Technol.* **12** 753–9
- [20] Choi L K, You J and Bovik A C 2015 Referenceless Prediction of Perceptual Fog Density and Perceptual Image Defogging *IEEE Trans. Image Process.* **24** 3888–901

## Acknowledgments

Authors would like to give regards to Indonesia Ministry of Higher Education (DIKTI) for this work and Ministry of Energy and Mineral Resources especially Pusat Vulkanologi dan Mitigasi Bencana Geologi Gunung Kelud for supplying data.