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Haze Removal Algorithm for Optical Remote Sensing Image Based on Multi-Scale Model and Histogram Characteristic

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ABSTRACT Optical imaging remote sensing technology is an important technical means to obtain information of ground objects, but it is restricted by bad weather such as clouds, rain, and haze. In haze weather condition, optical images often have poor contrast and blurred details, which has a great impact on subsequent applications and interpretation. If the acquired images are processed, not only their quality can be improved, but also their visual effect and utilization value can be improved, so as to reduce the impact brought by haze. In general, the haze is removed from the view of image processing. In this paper, through in-depth analysis and study of existing algorithms and characteristics of optical remote sensing images, a new idea is proposed to solve this problem from the view of combination of image content and auxiliary information. Furthermore, a new haze removal algorithm is proposed based on the Retinex multi-scale model and the histogram characteristics of remote sensing images. Because the new method combines multi-scale model (MSM) and histogram characteristics (HC), it is referred to as MSMHC algorithm in this paper. The advantage of the new method is that the content and type of image are considered in the whole process, and then two processing schemes are set for haze removal. In the test experiments, one hundred groups of image data were used to carry out comparative experiments. At the same time, single-scale Retinex (SSR) algorithm, multi-scale Retinex (MSR) algorithm, dark channel priori (DCP) method, brightness preserving dynamic fuzzy histogram equalization (BPDFHE) algorithm, histogram equalization (HE) method, and homomorphic filter (HF) algorithm were used for comparative experiments with the MSMHC method. Five parameters, including standard deviation (SD), information entropy (IE), peak signal to noise ratio (PSNR), structural similarity (SSIM), and image contrast (IC), were used to quantitatively evaluate the test results. The experimental results and the parameter values showed that the MSMHC algorithm could not only effectively remove haze from remote sensing images, obtain high contrast and high definition images, but also have better generalization ability.

INDEX TERMS Haze removal, multi scale model, histogram characteristics, Retinex theory, dark channel prior method, remote sensing image.

I. INTRODUCTION

The imaging remote sensing technology is an indispensable technical means for earth observation and deep space exploration. Remote sensing techniques generally refer to the acquisition of electromagnetic information of a target without touching it. It includes not only remote sensing images acquired by traditional aircraft, satellites and ground platforms, but also images acquired by ordinary cameras, mobile phones and video cameras. Therefore, remote sensing has entered the era of multi-sources. At the same time, various types of imaging remote sensing satellites have been successfully launched, remote sensing image data acquisition is no longer a problem, and remote sensing data processing has entered the era of big data. Acquiring optical images is greatly affected by bad weather, such as fog, haze, rain, smoke, snow

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and sand storms, which all will affect the image quality. For example, under conditions of haze weather, the quality of the acquired image is dramatic decline, the details are blurred, the contrast is reduced, the color is offset, and the whole image appears gray-white. The heavier the haze is, the more serious the image degradation is. These degraded images are not only distorted in color, but also have poor visual effects, which have a great impact on subsequent image processing and applications, such as target information extraction, target tracking monitoring, and image classification, recognition, interpretation and application. So it has important social value and application prospects to remove haze or to reduce the impact of haze.

Image haze removal is essentially a matter of image restoration or image enhancement. Its purpose is to remove or reduce the impact of haze on the scene imaging, restore the original scene and improve the visual effect and useful value of the image. Therefore, there are two main ideas for image haze removal. The first is to use image enhancement strategy to remove haze; the second is to restore the image, so as to achieve the purpose of removing haze. Image enhancement methods mainly include histogram equalization (HE) method [1], filtering enhancement method [2], [3] and the Retinex algorithm [4]–[7]. Image restoration method is to restore the original image scene by analyzing the causes of image quality degradation, establishing a degradation model and using relevant prior knowledge. The typical method is the dark channel prior (DCP) method proposed in [8]. This method has been widely used, and on the basis of it, many improved methods and theories have been put forward [9], [10]. Other two typical model methods were proposed by Tan [11] and Fattal [12], respectively. These methods based on atmospheric scattering model need to set up assumptions and then to estimate the relevant parameters, which is the common point of model-based methods.

Since haze has a great impact on the visual effect and application of images, the research work on this aspect has begun as early as the 1950s. With the development of modernization and urbanization in the world, the frequency of bad weather such as haze has increased, resulting in an increase in the number of remote sensing images affected by haze, so the haze removal is an important part of remote sensing image preprocessing. The work of image haze removal has probably gone through three stages or processes. The first stage was to remove haze by using multiple images [13], [14]. The second stage was to filter haze by using the auxiliary information of images [15]. The third stage was to directly use single image to achieve dehazing [16]–[20]. Because there are some difficulties for the former two to meet the requirements of real-time processing, almost all current methods use a single image as the processing object to complete the removal of haze phenomenon.

There are many literatures and methods about image haze processing, and many new theories are still being put forward and applied [21]–[26]. These theories or methods can be roughly classified into four categories. The first is based on image enhancement theory [1], [2], [5]–[7], the second is based on hypothesis and prior knowledge [8]–[12], the third is based on fusion of different methods [18], [26], [27], and the fourth is based on machine learning and artificial intelligence theory [24], [25]. These methods usually process a haze image from a certain angle to minimize the impact of haze and restore the scene as much as possible. Because their applications have obvious purpose and limitation, the advantage of them is to achieve the purpose of processing, and the disadvantage is that their universality is not strong. Moreover, the influence of haze on the image is a dynamic change, which further weakens their universality. Through the research and analysis of related methods and work, we got the following conclusions. The dark channel prior method proposed in [8] is an effective, excellent and widely used physical modeling method. But its shortcoming is also very obvious, because the use of soft matting algorithm, resulting in too much computation, long running-time, especially when the image size is large, poor real-time; at the same time, it is also affected by white objects, and the processing effect of the sky area is not ideal, easy to produce distortion phenomenon. Aiming at the defects of the dark channel prior method, many scholars have proposed some corresponding improved algorithms [19], [28]. Under two premises that the contrast of sunny image is higher than that of haze image and the ambient illumination is related to distance, Tan proposed a haze removal algorithm based on Markov random field (MRF) [11]. The contrast of an image can be significantly improved by this method, but it tends to over compensate the contrast of the image, leading to color distortion and halo effect at the sudden change of depth of field. Fattal proposed a physical model haze removal method under the assumption that the surface chromaticity and medium transport are locally statistically relevant [12]. Because the algorithm relies on locally hypothetical statistics, it not only has a large amount of computation, but also was ineffective in dense haze region. In addition to the above typical model-based physical methods, there are many other improved methods. They remove haze from the viewpoint of imaging principle and atmospheric scattering physical model. The key technology of them is the estimation of atmospheric ambient light value and atmospheric transmittance, so different estimation methods will produce different results. Some fusion algorithms of different methods or different scales are appeared [26], [27], [29], [30]. Usually, the fusion processing will increase the complexity and consume more time, which not only increases the real-time challenges, but also sometimes the processing effect does not improve much, because the determination of fusion weights will bring impact. Similarly, the machine learning method based on a single image to remove haze, because of a large number of training sample feature sub-images [24], making the processing process more complex, slow speed, poor real-time.

Using the way of image enhancement can effectively remove haze and get good results, but it does not consider the reason of image degradation. There are many methods for image enhancement. For example, the histogram equalization method is often used for image haze removal. This method is not only simple and reliable, but also has the lowest cost and fast processing speed. For these images with little change in scene distance or low haze, it can achieve good dehazing effect. The insufficiency of histogram equalization algorithm is easy to cause the phenomenon of image over-enhancement and color distortion. Aiming at the deficiency of histogram equalization method, many improved methods were proposed, such as brightness preserving bi-histogram equalization (BBHE) [31], dynamic histogram equalization (DHE) [1], brightness preserving dynamic histogram equalization (BPDHE) [32], brightness preserving dynamic fuzzy histogram equalization algorithm (BPDFHE) [33], which is an improved version of BPDHE algorithm. Another commonly used enhancement method for haze removal is the Retinex algorithm, which is a model method based on color invariance. It can not only effectively remove the haze in the image and improve the image quality, but also has good applicability. Land [34] proposed a single scale Retinex (SSR) algorithm based on the center function, also called the surround function. Since the selection of scale has a great influence on haze removal, Jobson [6] proposed a multi-scale Retinex (MSR) algorithm, which improves the contradiction between the detail and the whole processing in SSR algorithm. Similarly, facing the problem of color distortion in MSR algorithm, many scholars have proposed some improved algorithms for color restoration [35], [36]. Although Retinex algorithm can well remove the haze in the image, the dark-gray phenomenon occurs in the processed image, which leads to the loss of some color information. At the same time, it is difficult to enhance the details of the brighter part in the haze image.

These algorithms have been proposed and applied to solve the haze problem in outdoor color images. However, remote sensing images are different from outdoor images. Outdoor images generally refer to color photographs. Remote sensing image includes single-band gray images (panchromatic images) and multi-band composite color image, as well as the RGB color image directly obtained. Outdoor images are usually obtained directly from the ground. Therefore, outdoor images generally contain the sky background, especially the distant scene; at the same time, most outdoor images have large depth-of-field spans. So the emphasis of outdoor image processing is in the distant scene part. The remote sensing image usually refers to the image which contains ground scene information acquired from the aerial platform such as airplanes or satellites. Therefore, the remote sensing image not only has no sky background, but also has a relatively small span. Moreover, the spatial resolution of remote sensing image is much lower than that of outdoor photo image. Obviously, those methods for processing outdoor image are directly applied to remote sensing image, as is very difficult to achieve the desired effect. Aiming at the shortcomings of the existing algorithms and the characteristics of remote sensing images, from the viewpoint of image enhancement, this paper proposed a new haze removal algorithm based on multi-scale model (MSM) and histogram characteristic (HC), which is abbreviated as MSMHC algorithm. The proposed algorithm mainly includes three parts. Firstly, the input haze remote sensing image is preprocessed so as to obtain the corresponding auxiliary information and preliminary content information. Secondly, two kind of remote sensing image processing schemes based on MSR method are set up, and then the histogram and fusion processing operations are carried out. Thirdly, according to the prior information of the input image, it decides whether the image needs to be converted or not. The advantages of MSMHC algorithm include the following aspects. (1) It can process different types of remote sensing images like gray images and color images, so it has wide applicability and practicability. (2) It can not only effectively remove haze and improve image quality, but also keep abundant geometric details. (3) The degree of distortion is relatively small in terms of color and brightness.

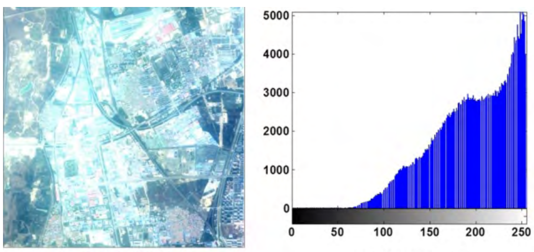
The main contributions of this paper include the following contents. (1) From the content of remote sensing images, different processing ways are designed for different types of images. (2) Retinex theory and histogram equalization algorithm are optimized to reduce color offset and detail information loss. The result of Retinex method is that the dynamic range is compressed and the tone of the image is usually darker. The result of histogram equalization is to stretch the dynamic range, and the whole tone is brighter. The combination of them will complement each other and make the result closer to the original scene. (3) The influence of the number of scale parameters on the MSR algorithm is discussed in detail, and two different MSR algorithms with different numbers and values of scale parameters are designed. It not only increases the adaptability of the new algorithm, but also ensures the effectiveness of the algorithm. (4) Using multi-scale wavelet decomposition theory fuses different results to improve the accuracy of processing. (5) Setting multi-scale concepts and processing modes by three times, which makes the image more information, more complete details and closer to the original scene.

The rest of this paper is organized as follows. In section II, the related theories and work are briefly introduced. The proposed MSMHC algorithm is described in detail in section III. In section IV, the experimental settings and the results are discussed, including different parameter settings and comparison of different methods. Finally, section V concludes this paper and mentions the future work.

II. RELATED WORK AND THEORY

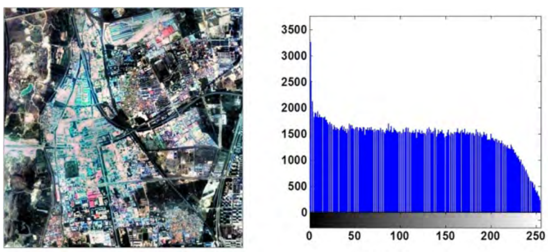
A. HISTOGRAM EQUALIZATION METHOD

The histogram equalization method is a common method for image enhancement. Because of its simplicity, reliability and fast processing speed, and the maximum amount of information after histogram equalization processing, it is often used to enhance images. Due to the influence of haze scattering and atmospheric light, the gray value of remote sensing images acquired under haze weather conditions generally increases, the contrast decreases, the detail information is blurred, the distribution range of image histogram is narrowed and concentrated, which is shown in Fig. 1. The image shown in Fig. 1(a) was obtained by the QuickBird satellite and was affected by haze, and Fig. 1(b) was the corresponding histogram. According to the experiment and prior knowledge, if the image gray distribution is wider and more uniform, the more information it contains, the clearer the detail information is. Therefore, stretching the gray distribution range of an image can make the gray distribution uniform, and achieve the purpose of enhancing the image effect. This method is called the image histogram equalization enhancement. Fig. 2(a) was an image of Fig. 1(a) after haze removal. Fig. 2(b) was the corresponding histogram of Fig. 2(a). Histogram equalization processing includes two ways, one is the global histogram equalization and another is the local histogram equalization.



(a) Original image (b) Histogram

FIGURE 1. **Haze image and its histogram.**



(a) Images of haze removal (b) Histogram

FIGURE 2. **Image and histogram after removing haze.**

Histogram is a description of the statistical features of an image, which represents the frequency of occurrence of gray values of each pixel in the image. Suppose that a gray image has L gray level, $P(r_k)$ denotes the frequency of the gray value r_k of the k^{th} level, n_k denotes the number of pixels of the k^{th} level gray, n represents the total number of pixels in an image, the definition of image histogram can be described by equation (1).

$$P(r_k) = n_k/n \tag{1}$$

The above expression represents the histogram of a gray image. For a color image, firstly three channel sub-images can be obtained, namely R, G and B images, then the histogram P_l of single channel image is got separately, finally, weighted sum is used. The mathematical model is shown in equation (2).

$$P(r_k) = \sum w_l \cdot P_l \tag{2}$$

Here, $l \in \{R, G, B\}$, w_l represents the weight of a channel sub-image, P_l denotes the histogram of the image, in general, $w_l = 1/3$. Certainly, you can also convert color images to gray images, and then get its histograms. There is little difference between them.

For haze images with little change in scene, the histogram processing method can achieve better results, but details information is often not well processed. At the same time, the contrast of the image is easy to be over-enhanced, which makes the color of the image brighter and leads to image distortion.

B. RETINEX METHOD AND DEGRADATION MODEL

The Retinex theory is an image enhancement theory proposed by Land and McCann [37]. It consists of Retina's first five letters and Cortex's last two letters, called the retina cerebral cortex theory, and is a theory based on color constancy. The so-called color constancy refers to the human eye's perception of the color of external objects will not change with the illumination changes, always being a constant perception on color. According to the Retinex theory, images of the human eye perception are composed of the ambient light incident and object surface reflection. Using the idea of color constancy, the inhomogeneous influence of the ambient light incident is removed, and only the object surface reflection is obtained, which achieves the purpose of enhancing images. Based on the above thinking, the influence of haze on image is essentially the influence of the incident intensity of ambient light. According to the Retinex theory, the image captured by the sensor can be regarded as the product of ambient incident light and object reflection, and its mathematical model can be expressed by equation (3).

$$I(x, y) = L(x, y) \cdot R(x, y) \tag{3}$$

In equation (3), $I(x, y)$ represents the captured image, affected by haze, and degraded images. Here (x, y) is pixel point of an image, namely spatial location of pixel. $L(x, y)$ denotes incident ambient light, which is the image interference information to be eliminated. $R(x, y)$ denotes the object surface reflects light, which is the image information to be retained. In order to effectively separate the incident part and the reflective part from the acquired image, and then to achieve the purpose of image enhancement and haze removal by changing the ratio between them, the logarithmic operation on both sides of equation (3) performs and equation (4) is obtained.

$$\log[I(x, y)] = \log[L(x, y)] + \log[R(x, y)] \tag{4}$$

Reorganize the equation (4), and equation (5) is got.

$$\log[R(x, y)] = \log[I(x, y)] - \log[L(x, y)] \tag{5}$$

The detailed explanation of the principle can be found in reference [33].

At present, the imaging model widely used to process haze images is the atmospheric scattering model proposed by McCartney [38]. For two-dimensional images, the specific expression is as follows.

$$I(x, y) = J(x, y) \cdot t(x, y) + A \cdot [1 - t(x, y)] \tag{6}$$

Here $I(x, y)$ denotes images affected by haze, namely these images are obtained under conditions of haze weather. Here (x, y) denotes the spatial coordinates of a pixel in an image. $J(x, y)$ denotes image acquired without haze. A is ambient light value and $t(x, y)$ is the atmospheric transmittance. By adjusting equation (6), the following expressions can be obtained.

$$J(x, y) = \frac{I(x, y) - A}{t(x, y)} + A \tag{7}$$

It can be seen from equation (7) that the haze removal based on atmospheric scattering model is actually to estimate the image unaffected by haze with the observing image. Essentially, like the Retinex theory, it is to reduce the influence of ambient light. However, the atmospheric scattering model should estimate two parameters, ambient light value A and atmospheric transmittance $t(x, y)$. The image haze removal methods based on scattering model almost all work hard on this parameter estimation, and different estimation values will bring different results. The dark channel transcendental method proposed in [8] is a typical representative. The formula for calculating the parameters $t(x, y)$ is shown in equation (8).

$$t(x, y) = e^{-\beta d(x,y)} \tag{8}$$

Here β is the coefficient of atmospheric light scattering. $d(x, y)$ is the depth of field. For remote sensing images, the depth of field distance is relatively small, which can be ignored. However, for outdoor photo images, the span of depth of field is generally large, and accurate estimation is needed to obtain accurate processing results. It can be seen from the principle of atmospheric scattering model that it is not suitable for dealing with haze in remote sensing images, and is more suitable for dealing with haze in outdoor photo images.

C. SINGLE SCALE RETINEX ALGORITHM

Based on the Retinex theory proposed by Land [4], Jobson and Rahman proposed a single scale Retinex (SSR) algorithm [5]. The SSR algorithm used the Gauss function to calculate the ambient incident component in the image, and the expression of the Gauss function is as follows.

$$G(x, y) = \frac{1}{2\pi\sigma^2} \exp\left(-\frac{x^2 + y^2}{2\sigma^2}\right) \tag{9}$$

The σ in equation (9) is not only the standard deviation of the Gauss function, but also is its scale parameter. At the same time, the incident component of an image can be expressed by equation (10) [33].

$$\begin{aligned} r(x, y) &= \log [R(x, y)] \\ &= \log [I(x, y)] - \log [G(x, y) * I(x, y)] \end{aligned} \tag{10}$$

Equation (10) does not consider color images; for the processing of color images, it uses equation (11).

$$\begin{aligned} r_i(x, y) &= \log [R_i(x, y)] \\ &= \log [I_i(x, y)] - \log [G(x, y) * I_i(x, y)] \end{aligned} \tag{11}$$

Here $r_i(x, y)$ represents the reflected component image after processing, $I_i(x, y)$ denotes the haze image input by the i^{th} color channel, and the number of channels in the input image is N. When $N = 1$, it indicates that the input image is a gray image; When $N = 3$, it is a color image. The symbol $*$ in the formula represents the convolution operation.

In SSR algorithm, different values of the scale parameters σ will have a great impact on the performance of the algorithm. By choosing the appropriate scale parameter values, the SSR algorithm can achieve the desired results. However, the selection of scale parameter values is a key step. Generally, satisfactory results and corresponding parameter values can be obtained through repeated experiments. In Section IV, different effects of different scale parameter values will be discussed in detail. When the value of scale parameter σ is larger, the smaller the mask radius is, the less influence by the surrounding pixels is. The estimated incident component of the image is smoother, and the color characteristics of the processed image will increase obviously. Because the dynamic compression range of the image is reduced, the detail part of the image is not displayed enough, and the enhancement effect of the detail is poor. The values of the scale parameter σ are smaller, the larger the mask radius is, the greater the influence between adjacent pixels is, the worse the image integrity is, the poor color fidelity of the image is, and the distortion phenomenon will occur. But it increases the dynamic range compression characteristic of the image, makes the detail information of the image better and the information entropy of the image higher.

D. MULTI-SCALE RETINEX ALGORITHM

The SSR algorithm is often not ideal for directly processing haze images, because the selection of scale parameters has a greater impact on the processing results. At the same time, it is very difficult for image details and color fidelity to coordinate best. To overcome these problems, Jobson et al. proposed a multi-scale Retinex (MSR) algorithm [6]. The processing idea of MSR algorithm is to perform the weighted sum of the results of multi-component processing, which is as a new processing result. The mathematical model of MSR algorithm is as follows.

$$\begin{cases} r_{ni}(x, y) = \log [I_i(x, y)] - \log [G_n(x, y) * I_i(x, y)] \\ r_{mi}(x, y) = \sum_{n=1}^{N} w_n r_{ni}(x, y) \end{cases} \tag{12}$$

Here i is the number of color channels, corresponding to the R, G and B channel of a color image. N is the number of scale parameter values, and its value is usually set in three grades: low, medium and high. $r_{ni}(x, y)$ represents the reflection component of the i^{th} color channel at the n^{th} scale. $r_{mi}(x, y)$ denotes the reflection component of the i^{th} color channel processed by the Retinex algorithm, and w_n is the weight of the scale parameter value.

The MSR algorithm can effectively remove or reduce the influence of haze and improve the image quality, but sometimes it will produce halo phenomenon. This is related to the selection of scale parameters, and often occurs in the region where the pixel gray value changes greatly. When the scale parameter value is large, the halo phenomenon can be effectively avoided, but the effect of haze removal is weakened. When choosing smaller scale parameter values, the haze removal effect is good, but there will be halo phenomenon. Generally, the MSR algorithm is better than the SSR algorithm in removing haze. Although the effect of removing haze by MSR algorithm is obvious, the image color fidelity is not ideal, and the tone of the image will be darker.

III. PRINCIPLE AND IMPLEMENTATION OF MSMHC ALGORITHM

At present, most of the theories and methods about haze image enhancement and restoration are mainly proposed for outdoor images, and a small number of scholars have studied removing haze from remote sensing images [3], [14], [16], [20], [29]. When they deal with haze in remote sensing images, the idea is basically the same as outdoor image processing. However, there are great differences between remote sensing images and outdoor images. Therefore, we consider the problem of haze removal from the content and characteristics of remote sensing images. Based on the advantages and disadvantages of existing algorithms and their application scope, a new MSMHC algorithm for haze removal in remote sensing images is proposed. The MSMHC algorithm adopts the image enhancement theory based on Retinex method and histogram characteristics, instead of the scattering model and hypothesis conditions. The reason is that both Retinex algorithm and histogram method are suitable for the characteristics of remote sensing image, which is conducive to improving the effect of remote sensing image processing. The dark channel priori method is not only based on atmospheric scattering model, but also a method for outdoor image statistical experimental results. Therefore, it is suitable for outdoor image processing, but far from the characteristics of remote sensing images, especially single-band gray image. The flow chart of MSMHC algorithm principle is shown in Fig. 3.

It can be seen in Fig. 3 that the MSMHC algorithm mainly includes the following steps.

(1) Input remote sensing images. The input remote sensing images can be either color or panchromatic gray images.

(2) Obtain relevant auxiliary information of the input image. The auxiliary information here mainly includes two aspects. The first is whether the image is a color or gray image; the second is whether the image coverage area is mainly urban or country areas.

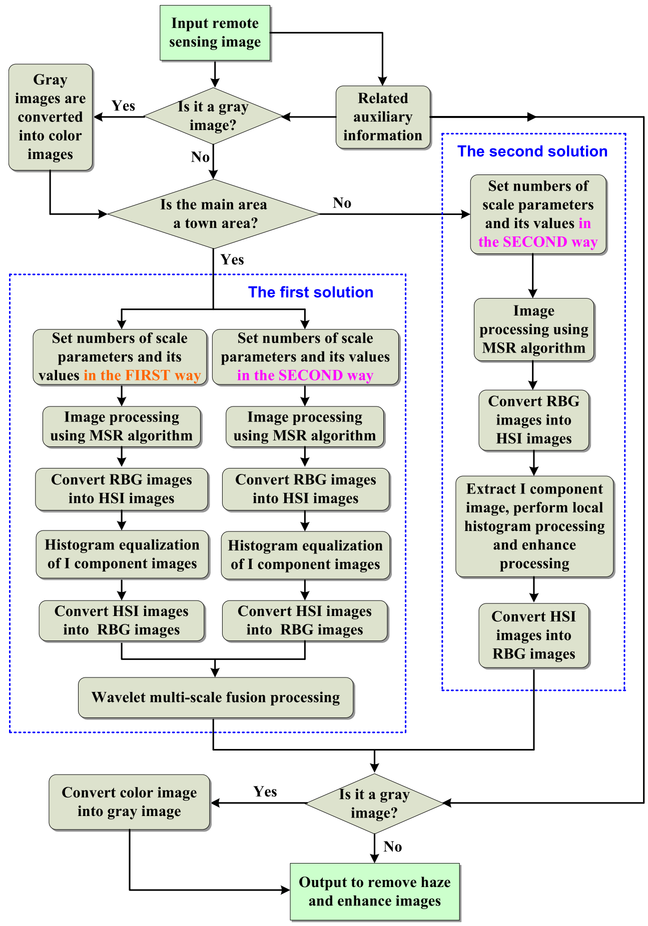


FIGURE 3. Flow chart of MSMHC algorithm.

(3) Preprocess the input gray images. If the input image is a gray image, in order to carry out the same process as the color image, the gray image needs to be preprocessed, and the gray image will be converted into a false color image. Suppose that $I(x, y)$ is the gray image and $C(x, y)$ is the false color image, and then the gray image $I(x, y)$ is assigned to three channels of the color image, respectively, namely

$$\begin{cases} C_r(x, y) = I(x, y) \\ C_g(x, y) = I(x, y) \\ C_b(x, y) = I(x, y) \end{cases} \tag{13}$$

Generally, the methods based on atmospheric scattering model cannot process gray images, such as dark channel prior method and its improved algorithm. The reason is that the objects processed by these methods are RGB color images, and their three channel values are different. However, according to equation (13), the three channel values of a false color image converted from gray image are equal. Therefore, the method based on atmospheric scattering model or hypothesis cannot process such images, which is an obvious limitation of these algorithms. On the contrary, MSMHC algorithm can well process the gray remote sensing images, as shows its advantage and wider application range.

(4) Make the preliminary judgment on the content of remote sensing images. This paper mainly judges whether the scene covered by a remote sensing image is a natural environment area or a city and town area. For natural scene areas, such as villages, farmlands, deserts, grasslands and mountains, their demand for detail recovery is lower. But for urban areas, such as cities, towns, ports and airports, they have higher requirements for image details recovery. This is related to the number of scale parameters and the setting of their corresponding values when removing haze from remote sensing images with Retinex theory. In MSMHC algorithm, the visual interpretation method is used to determine the content type of remote sensing image.

(5) Set the number of scale parameters and the corresponding values. The key technology of image enhancement using Retinex theory is to set the scale parameter number and their corresponding values. In MSMHC algorithm, two ways are used to set the parameters of MSR algorithm. There were six scales set in the first way, and their values were shown in Table 1. When the scale parameter value is small, it is advantageous to protect the details. Therefore, the values of scale parameters are set relatively small in this way.

TABLE 1. Scale parameters setting table of the first way.

Scale parameter (σ)	First scale	Second scale	Third scale	Fourth scale	Fifth scale	Sixth scale
Parameter value	20	40	60	80	100	120

In the first way, to protect more details, the scale parameter values are smaller. But in the second way, to better remove haze and avoid the halo phenomenon, and to make the image color as true as possible, some larger scale parameter values were designed, as were shown in Table 2, and there are nine different scale values. In section IV, it will be discussed in detail why two different scale parameters should be set up.

TABLE 2. Scale parameters setting table of the second way.

Scale parameter (σ)	First scale	Second scale	Third scale	Fourth scale	Fifth scale
Parameter value	32	64	128	256	512
Scale parameter (σ)	Sixth scale	Seventh scale	Eighth scale	Ninth scale	
Parameter value	1024	2048	4096	8192	

(6) Set the compensation coefficient. Although multi-scale Retinex algorithm can effectively remove haze and enhance the image, for color images, the phenomenon of color distortion will occur. To minimize the color distortion of the image, it is necessary to compensate the color of the image processed by the Retinex algorithm. The mathematical model is as follows.

$$r_i^*(x, y) = C_i(x, y) \cdot r_i(x, y) \tag{14}$$

$$C_i(x, y) = \beta \log \left[\frac{I_i(x, y)}{\sum_{i=1}^{3} I_i(x, y)} \right] \tag{15}$$

Here $C_i(x, y)$ represents the color compensation coefficient of the i^{th} color channel. β is a compensation constant. Like the scale parameter σ, the compensation coefficient β is another important parameter in MSR algorithm, and its value has a great influence on the processing result. Under other conditions unchanged, the bigger the $C_i(x, y)$ value is, the larger the color distortion of the image is, the better the haze removal effect will be, and the image is dark; when the value is small, the effect of haze removal is poor and the image is bright. For different scenes, the degree of influence is different. After a large number of experiments and comparative analysis of the experimental results, $C_i(x, y) \in [10, 30]$ is more suitable for different scene images and good results can be obtained. In MSMHC algorithm, its value is set to 20, namely $C_i(x, y) = 20$.

(7) Carry out histogram equalization processing. After an image is processed by MSR algorithm, the tone of the whole image is darker, but after it is processed by histogram equalization method, the tone is brighter. Therefore, they can complement each other by processing images together. This is a notable highlight of the MSMHC algorithm. Without histogram processing, the standard deviation of images processed by MSR method is low, which indicates that the detail information is not abundant; after histogram processing, the standard deviation and the entropy of information are significantly increased, and the running time is almost same. This issue will be discussed in detail in section IV.

Histogram processing of images does not directly deal with RGB color images. Although this direct processing method will enhance the image, improve the image quality and the visual effect, it often makes the image color distortion. So the RGB image is transformed into HSI model image, and three channel images are obtained, namely H, S and I component images. Since I component image does not involve the color attribute, processing it will not cause the image color distortion result. So I component image is processed by histogram equalization. In MSMHC algorithm, local histogram processing is used instead of global histogram processing. After processing, it is converted to RGB image again.

(8) Use wavelet multi-scale decomposition theory to fuse different results. As can be seen from the previous design of scale parameters, two different ways are designed, one is based on getting as much detail as possible, another is based on removing haze as much as possible and making the color fidelity. Both of them have their own advantages and application purposes. If the results of the two different ways

are fused, the purpose of removing haze and keeping details and colors will be achieved. This is also a highlight of the MSMHC algorithm.

The key technology of multi-scale fusion of wavelet transform is the determination of fusion rules. In the proposed MSMHC algorithm, pixel level fusion rules are used. Firstly, the two images are processed by multi-scale wavelet transform; then the coefficients sub-images of each corresponding decomposition scale are fused; finally, the inverse wavelet transform is performed. The fusion rules of wavelet decomposition at different scales are as follows. The low-frequency coefficient sub-images are processed by average weight method, and the high-frequency coefficients are processed according to the principle of taking large and giving up small. Let $I_1(x, y)$ and $I_2(x, y)$ represent two remote sensing images processed by different methods, and $F(x, y)$ represents the fused images, then the mathematical model of weighted fusion is as follows.

$$F(x, y) = w_1 \cdot I_1(x, y) + w_2 \cdot I_2(x, y) \tag{16}$$

Here w_1 and w_2 represent the fusion weight values of $I_1(x, y)$ and $I_2(x, y)$, respectively, i.e. the weight coefficients, and $w_1 + w_2 = 1$. If $w_1 = w_2 = 0.5$, it is an average weight, namely, their weight values are equal. The redundant information in the source image can be filtered well by using the strategy of weighted coefficients. For source images with little difference, good results can be achieved. Because the objects processed in two different ways are the same remote sensing image, the differences between them are very small. So the fusion results in this way will better than other ways.

For sub-images of high-frequency coefficients on each decomposition scale, they adopt the principle of large value to complete image fusion processing. And the mathematical model of fusion operation is shown in equation (17).

$$F(x, y) = \begin{cases} I_1(x, y); & I_1(x, y) \geq I_2(x, y) \\ I_2(x, y); & I_1(x, y) < I_2(x, y) \end{cases} \tag{17}$$

Because this method ignores the information of another source image, the fusion effect is usually not ideal when the difference between them is large. The MSMHC algorithm fuses information according to the results of two different processing schemes, so they can achieve good results both in the fusion of low-frequency coefficient sub-images and in the fusion of high-frequency coefficient sub-images. On the contrary, if other fusion rules are used, such as local gradient method, variance method and contrast method, they not only unable to obtain the satisfactory results, but also for homogeneous area of the surface target, it is very easy to generate error information.

(9) Output the processed results. According to the auxiliary information, if the initial input image is a gray image, it needs to be converted into a gray image and then to be output; if it is a color image, the corresponding results will be output directly.

IV. EXPERIMENTAL RESULTS AND ANALYSIS

A. EVALUATION INDEXES FOR QUANTITATIVE ANALYSIS

There are two ways to evaluate image processing results: subjective evaluation and objective evaluation. In addition to subjective evaluation, there are also some objective evaluation indexes. Subjective evaluation mainly relies on visual effects to judge, so the subjective wishes and experience of individuals are the dominant factors. Objective index evaluation is to judge the quality of processing results by some evaluation indexes, such as brightness, contrast, standard deviation, average value and information entropy. The standard deviation (SD) reflects the brightness and contrast of the image. The information entropy (IE) includes the average condition of the amount of information in the image. The peak signal-to-noise ratio (PSNR) reflects the degree of error between the processed image and the original image. The structural similarity (SSIM) is an index to measure the similarity between two images. Image contrast (IC) reflects the clarity of the image. Therefore, this paper will adopt SD, IE, PSNR, SSIM and IC parameters to analyze and evaluate the experimental results.

The parameter SD reflects the discrete state of pixel gray value relative to the gray mean of the whole image. Essentially, SD reflects the discrete degree of image details and is a direct measure of contrast within a certain range. When SD value is larger, the contrast in a given area is also greater, and the dynamic range of the gray value is larger, which shows that the more detailed information the image reflects, the more gradient level the image has, the better the visual effect of the image is. Equation (18) is used to calculate the standard deviation of an image.

$$SD = \sqrt{\frac{1}{M \times N} \sum_{x=1}^{M} \sum_{y=1}^{N} [I(x, y) - \mu]^2} \tag{18}$$

$$\mu = \frac{1}{M \times N} \sum_{x=1}^{M} \sum_{y=1}^{N} I(x, y) \tag{19}$$

In above equations, $I(x, y)$ denotes the gray value of pixel (x, y), $M \times N$ is the size of the image, μ is mean of the gray value of the image. For color images, the components of R, G and B color channels can be calculated separately, and then they carry out summation and average operation. You can also convert color images into gray images and then calculate the standard deviation. The results obtained by the two methods are not very different. In this paper, the second method is used for quantitative analysis.

The IE index reflects the average amount of information in an image, and it is a very important index to evaluate the image quality. The definition of IE is given by

$$IE = -\sum_{i=0}^{L-1} P(i) \log P(i) \tag{20}$$

Here $P(i)$ denotes the probability of occurrence of the i^{th} gray level, and L is the number of the gray level of the image.

For color images, it can also be converted to gray images first and then calculated. According to the theory of entropy, if the information entropy of an image is larger, it shows that the more information the image contains, the more abundant the detailed information in the image is.

The PSNR index is usually used to evaluate the quality of a processed image as compared with the original image. It is often defined simply by mean square error (MSE). Assume that $I(i,j)$ is the processed image, $G(i,j)$ is the original image, and their sizes are $M \times N$, the mathematical model of MSE is given as follows.

$$MSE = \frac{1}{M \cdot N} \sum_{i=0}^{M-1} \sum_{j=0}^{N-1} [I(i,j) - G(i,j)]^2 \tag{21}$$

The definition of PSNR is given in equation (22).

$$PSNR = 10 \cdot \log_{10} \left(\frac{MAX_I^2}{MSE} \right) \tag{22}$$

Here MAX_I represents the maximum gray level in an image $I(i,j)$. If the value of each pixel is expressed in 8 bits, the value of MAX_I is 255. The higher the PSNR value is, the smaller the distortion of the processed image is.

Structural similarity is an objective evaluation index for image quality by comparing the structural information of two images and judging the distortion of them. Its maximum value is one. The definition of SSIM can be described by equation (23).

$$SSIM(X,Y) = l(X,Y)^{\alpha} \cdot c(X,Y)^{\beta} \cdot s(X,Y)^{\gamma} \tag{23}$$

Here $l(X,Y)$, $c(X,Y)$ and $s(X,Y)$ represent brightness, contrast and structure respectively, in which structure is the main factor. Their values are calculated by equation (24).

$$\begin{cases} l(X,Y) = \dfrac{2\mu_X\mu_Y + c_1}{\mu_X^2 + \mu_Y^2 + c_1} \\ c(X,Y) = \dfrac{2\sigma_X\sigma_Y + c_2}{\sigma_X^2 + \sigma_Y^2 + c_2} \\ s(X,Y) = \dfrac{\sigma_{XY} + c_3}{\sigma_X\sigma_Y + c_3} \\ \sigma_{XY} = \dfrac{1}{N-1} \sum_{i=}^{N} (X_i - \mu_X)(Y_i - \mu_Y) \end{cases} \tag{24}$$

Here X and Y represent the reference image and the image to be measured, respectively. The mean, variance and covariance of images X and Y are μ_X, μ_Y, σ_X^2, σ_Y^2 and σ_{XY}, respectively. N denotes the number of pixels in the whole image. c_1, c_2 and c_3 are very small normal numbers. The purpose is to avoid instability when the denominator in the variance is zero. α, β and γ denote the weight of each component. When $\alpha = \beta = \gamma = 1$, $c_3 = c_2/2$, and equation (23) can be rewritten into equation (25).

$$SSIM(X,Y) = \frac{(2\mu_X\mu_Y + c_1)(2\sigma_{XY} + c_2)}{(\mu_X^2 + \mu_Y^2 + c_1)(\sigma_X^2 + \sigma_Y^2 + c_2)} \tag{25}$$

Image contrast is a parameter to describe the clarity of an image. It is defined as the ratio of black to white, i.e. the gradient level from black to white. The larger the contrast value is, the more the gradient is, the richer the color is, and the higher the clarity is. The mathematical model of image contrast definition is as follows.

$$IC = \sum_{\delta} [\delta(i,j)]^2 P_{\delta}(i,j) \tag{26}$$

Here i and j denote the gray values of adjacent pixels, respectively. $\delta(i,j) = |i - j|$ denotes the gray difference between adjacent pixels. $P_{\delta}(i,j)$ is the probability of the pixels with the gray difference of δ between adjacent pixels.

B. COMPARISON EXPERIMENTS OF DIFFERENT SCALE PARAMETER VALUES

When the scale parameter σ in center-surrounded Gaussian function $G(x,y)$ takes different values, it will directly affect the effect of Retinex algorithm to remove haze. In these experiments, different results of haze removal were obtained by setting different scale parameter values and were shown in Figs. 4-6. The original haze remote sensing image is shown in Fig. 4(a), and the coverage scene of the image is mainly urban area. Figs. 4(b)-(j) is the processing results of different scale parameter values, respectively. It can be seen in Fig. 4, for the SSR algorithm, different values of scale parameters have a greater impact on the results of haze removal. With the increase of scale parameter value, the effect of haze removal increases gradually, but when the value reaches a certain value, the effect of image enhancement and haze removal is almost unchanged. Obviously, when the scale parameter value is less than 64, the effect of removing haze is not ideal; when the scale parameter value is greater than 512, the effect of haze removal is rarely changed.

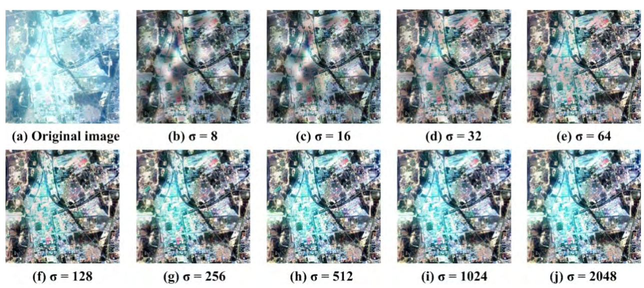


FIGURE 4. Results obtained from different scale parameter values in SSR method.

Similarly, the same results are obtained through quantitative index analysis, as shown in Fig. 5 and Fig. 6. The SD obtained by SSR algorithm with different scale parameter values is shown in Fig. 5. The abscissa represents the different values of scale parameters, where 0 denotes the original image and the ordinate represents the SD values of the obtained images. It can be seen in Fig. 5 that the SD of the original image is the lowest, only 47.53, showing that the quality of the image is the worst, reflecting the least detail information. After image processing by SSR algorithm, the image quality is obviously improved. When $\sigma = 8$ and $\sigma = 16$, the SD value of the image is 57.5, and with

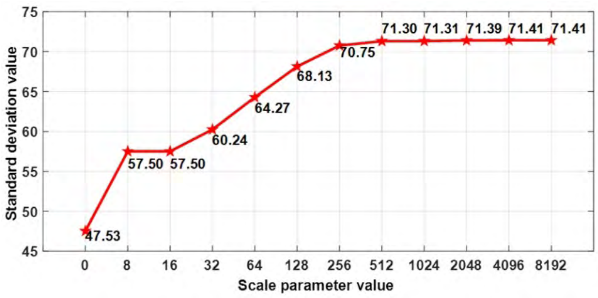


FIGURE 5. SD of image obtained by SSR method with different scale parameter values.

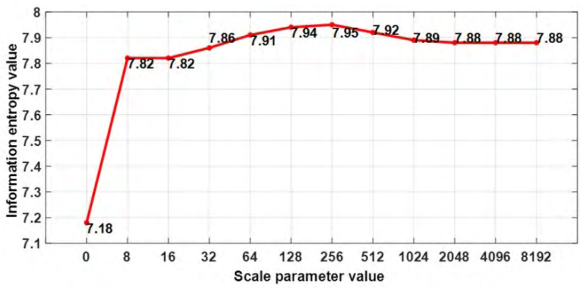


FIGURE 6. IE of image obtained by SSR method with different scale parameter values.

the increase of scale parameter values, the SD values also increases. But when $\sigma > 512$, the SD values are almost unchanged, maintaining a stable constant value. Fig. 6 shows the variation rule of IE values with different scale parameter values, which reflects the same rule as Fig. 5. When the scale value is small, the processing effect is not very good and the original haze image has the lowest value. When the scale value increases, the IE value of the image also increases, but to a certain extent, its value does not increase anymore and keeps a constant value. Above experiments show that SSR algorithm has a limit value in image processing, and when the limit is reached, the scale parameters will no longer affect the image processing effect. That is to say, the ability of SSR algorithm to remove image haze is limited. In this experiment, the influence of different scale parameter values on removing haze from remote sensing images provides a very useful help and is theoretical basis for MSR algorithm to select the number of scale parameters. In MSMHC algorithm, the theoretical basis for setting two different ways of scale parameters is also derived from these experimental results.

C. COMPARISON OF MSR ALGORITHMS WITH DIFFERENT PARAMETER NUMBERS

Different scale values have a certain impact on the processing effect of SSR algorithm. Similarly, for MSR algorithm, the number of scale parameters has a greater impact on it. In general, the number of scales in the MSR algorithm is usually set to three, and their range is often set to [20, 200]. In this experiment, three scale values are 20, 80 and 180, respectively. We have set up three schemes, and their scale number is three, six and nine, marked as MSR3, MSR6 and MSR9, respectively. The scale parameter settings for MSR6 and MSR9 were shown in Table 1 and Table 2. The experimental data and results were shown in Fig. 7. Two remote sensing images from different types were shown in Fig. 7(A) and Fig. 7(B), respectively. Both of them came from the QuickBird satellite. It is the original image shown in Fig.7(a). The experimental results shown in Figs 7(b)-(d) were obtained by the MSR3, MSR6 and MSR9 methods, respectively. It can be seen in fig. 7, with the increase of the number of scale parameters, the haze removal effect of MSR theory is better.

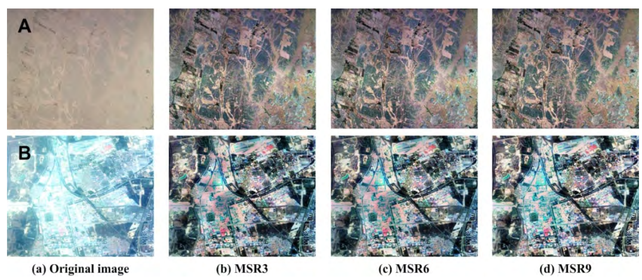


FIGURE 7. Results of MSR algorithm with different scale numbers.

The following is a further analysis of their performance from quantitative indexes. The comparison indexes include SD and IE, and their concrete values are shown in Table 3. It can be seen in Table 3 that no matter which method in MSR theory is used to process haze images, the SD and IE values of the images processed by them are significantly improved. For example, the SD and IE values of the original image of Fig. 7(A) are 18.23 and 6.21, respectively; but after processing by MSR6, their values become 40.66 and 7.38, respectively. This shows that the quality and visual effect of the images are improved obviously, as shown in Fig. 7. For Fig. 7(A), the SD and IE of the three methods are similar, but the visual effect of the third method (i.e. MSR9) is the best. Similarly, in Fig. 7(B), not only can these three methods effectively remove haze from remote sensing images, but also their SD and IE values are almost the same, but the value of MSR9 is slightly larger. However, their visual effects are different, and the best is MSR9. The coverage area of the image in Fig. 7(A) is country, and the largest SD is MSR6, which is slightly larger than MSR3 and MSR9, but

TABLE 3. SD and IE of MSR algorithm with different scale numbers.

Scheme	SD	IE	Scheme	SD	IE
Fig. 7(A)	18.23	6.21	Fig. 7(B)	47.53	7.18
MSR3	40.61	7.38	MSR3	65.20	7.93
MSR6	40.66	7.38	MSR6	64.91	7.92
MSR9	40.42	7.39	MSR9	68.75	7.96

its visual effect is not as good as MSR9. The area covered by image in Fig. 7(B) is town, whether SD or IE, MSR9 is the largest and the best visual effect. Through the analysis of a large number of experiments on removing haze from remote sensing images, the results and rules reflected are similar to the above situation. Therefore, MSMHC algorithm et up two different processing schemes. If the area covered by remote sensing image is mainly country or other natural environment, MSR9 is used for processing, which is the second solution. If the remote sensing image area is mainly cities or towns, in order to better retain the rich details and information, and effectively remove haze, MSR6 and MSR9 methods are used to process respectively, and then their processing results are fused, which is the first solution.

It can be seen in Fig. 5 and Table 3 that the SSR algorithm can get larger SD by setting larger scale parameter values, and the SD value may be larger than that obtained by MSR algorithm. Compared with MSR algorithm, MSMHC algorithm has been improved in processing effect and detail information abundance, which will be discussed in detail in next section. In addition, in Fig. 6 and Table 3, it can be seen that after the image is processed by the MSR algorithm, the IE values of the image will approach or exceed the maximum value of 7.95 processed by the SSR algorithm. It can be known in Fig. 4 and Fig. 7 that the haze removal ability of the SSR algorithm is worse than that of the MSR algorithm.

D. COMPARISON BETWEEN MSMHC ALGORITHM AND MSR ALGORITHM

In previous section, it is pointed out that the SD values of the image obtained by the MSR algorithm are lower than that of the SSR algorithm with large scale parameter values. In MSMHC algorithm, the histogram equalization method is used to remedy the deficiency of MSR algorithm. In order to highlight the advantages of MSMHC algorithm, this part separately discusses the difference between MSMHC algorithm and MSR algorithm.

In the experiments, the MSR9 algorithm is chosen to compare with the MSMHC algorithm, and experimental results are shown in Fig. 8. The experiment images include natural environment type and town type. The area covered by the image is the city or town in Fig. 8(A) and Fig. 8(C); the scene captured in Fig. 8(B) and Fig. 8(D) is natural environments. Fig. 8(A) is an outdoor photo image, and it is used as a standard of image processing in [8]. Other three images (Figs. 8(B)-(D)) are from the remote sensing satellite QuickBird. Fig. 8(a) shows the original haze images, which will be used for haze removal experiments. The test results are shown in Fig. 8(b) and Fig. 8(c), and they are obtained by MSR9 and MSMHC algorithm, respectively. It can be seen in Fig. 8, both MSR9 and MSMHC algorithm can effectively remove haze in the image, and have achieved good experimental results. As a whole, an image processed by MSR9 algorithm is dark, but the image processed by MSMHC algorithm is moderate brightness, and has more obvious contrast, richer details and better effect of removing haze. The parameter values of SD and IE are compared, and the concrete results are shown in Table 4.

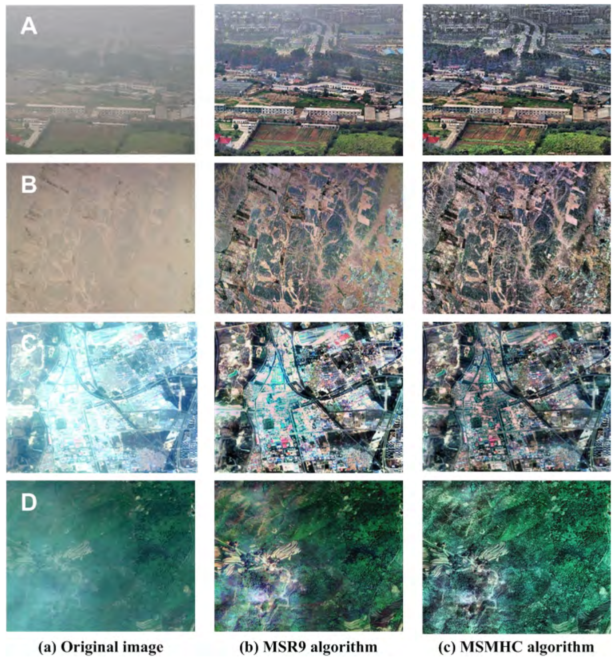


FIGURE 8. Results of MSR9 algorithm and MSMHC algorithm.

It can be seen in Table 4 that the SD value of haze remote sensing images is significantly increased after they are processed by MSR9 or MSMCHC algorithm. As shows that two methods not only can remove haze effectively, but also keep the detail information well, so as to improve the image quality. In addition to Fig. 8(C), the SD values of other image processed by MSMHC method are much higher than that of MSR9 algorithm. From the viewpoint of information entropy, we can get the same conclusion that except for Fig. 8(C), the IE values of other images processed by MSMHC algorithm are higher than that of MSR9 algorithm. This indicates that the processing effect of MSMHC algorithm is better than that of MSR9 algorithm. For Fig. 8(C), although the

TABLE 4. SD and IE of MSR algorithm and MSMHC algorithm.

Parameter	Method	Fig. 8(A)	Fig. 8(B)	Fig. 8(C)	Fig. 8(D)
SD	Original image	22.00	18.23	47.53	42.34
	MSR9	42.65	40.42	68.75	47.00
	MSMHC	55.46	53.76	56.89	53.97
IE	Original image	6.42	6.21	7.18	7.39
	MSR9	7.45	7.39	7.96	7.46
	MSMHC	7.76	7.74	7.80	7.68

parameter values obtained by MSR9 algorithm are higher than those obtained by MSMHC algorithm, its visual effect is not as good as that of MSMHC algorithm, especially the removal of haze, as shown in Fig. 8. Since a large number of buildings are contained in Fig. 8(C) and they have strong contrast reflection characteristics, which leads to the details obtained by MSR9 algorithm are slightly richer than those of by MSMHC algorithm. But from the visual view, it is very obvious that the ability of haze removal of MSR9 algorithm is not as good as that of MSMHC algorithm. Therefore, on the whole, the performance and scope application of MSMHC algorithm is better than that of MSR9 algorithm, which can achieve a good compromise in removing haze and maintaining details.

E. COMPARISON BETWEEN MSMHC ALGORITHM AND OTHER METHODS

In order to verify the advantages of the proposed MSMHC algorithm, a series of experiments were carried out with the typical dark channel prior (DCP) method, histogram equalization (HE) method, homomorphic filtering (HF) method, brightness preserving dynamic fuzzy histogram equalization (BPDFHE) algorithm, SSR algorithm and MSSR3 algorithm. The experimental images and results were shown in Fig. 9 and Fig. 10, respectively. The original haze images are shown in Fig. 9. Here Fig. 9(B) and Fig. 9(F) are gray images, and the rest are color images. The images shown in Fig. 9(A), Fig. 9(C) and Fig. 9(L) were the outdoor photo images, which were obtained by an ordinary camera, and others were remote sensing images. Figs. 9(I)-(K) were acquired by unmanned aerial vehicles (UAV), and other remote sensing images were from the QuickBird satellite. The experimental data contain different types of haze remote sensing images, and the differences between them are also quite large. According to the scene content covered by remote sensing images, they are divided into two categories: urban architecture (cities and towns) images (like Figs. 9(A)-(C), (G), (I), (J)) and natural environment images (like Figs. 9(D)-(F), (H), (K), (L)). One hundred sets of image data were carried out the comparative experiments, but because of the limited space, only experimental results of several typical types of images were given here, which were shown in Fig. 10. In these experiments, the scale value of SSR algorithm was set to 64; the number of scales of MSR algorithm was three, called MSR3 algorithm and three different scales were set to 20, 80 and 180, respectively. Figs. 10(A)-(L) represent different original haze images and they are corresponding to images of Figs. 9(A)-(L). Experimental results obtained by DCP, SSR, MSR3, HE, HF, BPDFHE and MSMHC algorithms are shown in Figs.10(a)-(g) respectively. To avoid uncertain interpretation and understanding, the processed results of Fig. 10 (A) are represented by Figs. 10(A.a)-(A.g); the results of Fig. 10(B) are described by Figs. 10 (B.a)-(B.g); the processing results of other images Figs. 10 (C)-(L) are expressed in the same way.

FIGURE 9. **Original haze images for test experiments.**

Fig. 10(A) is an outdoor image containing scenes such as buildings and agricultural land. It is known in Fig. 10(A) that the best effect of haze removal is Fig. 10(A.g), which was obtained by MSMHC algorithm. The results processed by DCP method are darker, which is shown in Fig. 10(A.a). The effect of other methods to remove haze is not ideal.

Fig. 10(B) covers artificial buildings, while Fig. 10(F) covers natural environment areas. Both of them are gray images, but contain different scenes. For Fig. 10(B) of town image, these methods can remove haze well. But the effect shown in Figs. 10(B.b)-(B.d) and Fig. 10(B.g) is better than other, especially detail and contrast. They are obtained by SSR, MSR3, HE and MSMHC methods, respectively. In Fig. 10(F), the effect obtained by MSR3, HE and MSMHC methods is good, which is shown in Fig. 10(F.c), Fig. 10(F.d) and Fig. 10(F.g), respectively. The effect of other methods to remove haze is general.

Fig.10(C) and Fig. 10(L) are outdoor photo images, where in Fig. 10(C) there is mainly urban area and Fig. 10(L) is natural environment area. For Fig. 10(C), the effect of HE, BPDFHE and MSMHC algorithms is better than other methods, which is shown in Fig. 10(C.d), Fig. 10(C.f) and Fig. 10(C.g), respectively. For Fig. 10(L), the MSMHC algorithm achieves the best results, as shown in Fig. 10 (L.g). And the next are the SSR, MSR3 and HE algorithms.

Figs. 10 (D), (E), (H) and (K) are remote sensing images of natural environment areas. For Fig. 10(D), Fig. 10(D.d) and Fig. 10(D.g) obtained by HE and MSMCHC algorithm are good for haze removal. But the color distortion of HE algorithm is large. The effect of other methods to remove haze is not ideal. For Fig. 10(E), the best result is the MSMHC algorithm (shown in Fig.10 (E.g)). Then it is SSR algorithm and MSR3 algorithm, and they also can get better results which are shown in Fig.10 (E.b) and Fig.10 (E.c). The result of HE algorithm is a little too bright, which is shown in Fig. 10(E.d). The image details obtained by the other three methods (i.e. DCP, HF and BPDFHE) are not clear. In Fig. 10(H) and Fig. 10(K), the distortion of HE algorithm is the most serious, which is shown in Fig.10(H.d) and Fig.10(K.d).

The MSMHC algorithm is the best method to remove haze, and the corresponding processing results are shown

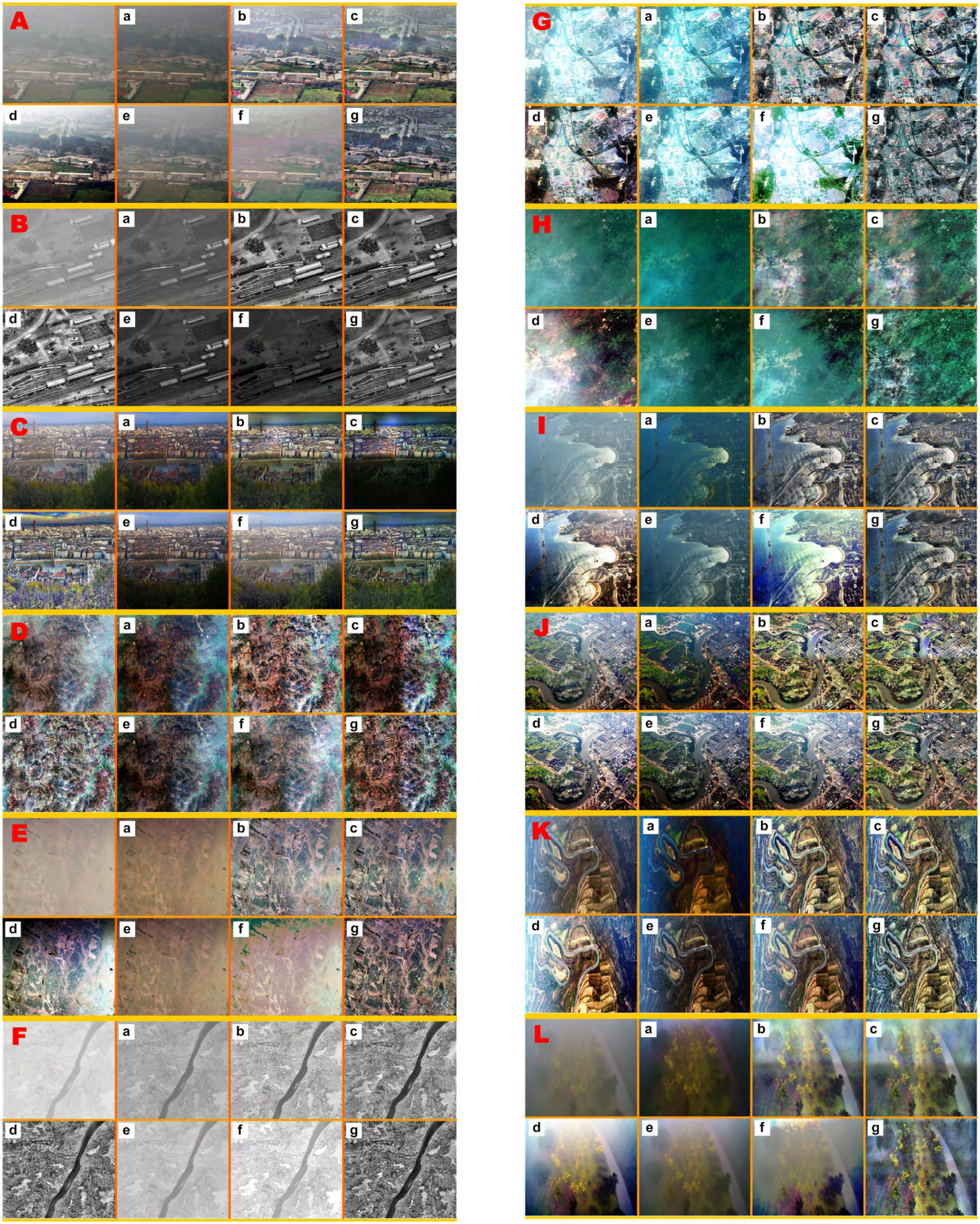


FIGURE 10. Experimental results of different methods for different images. A-L denotes different original images shown in Fig. 9, and a-g represents results obtained by DCP, SSR, MSR3, HE, HF, BPDFHE and MSMHC algorithms, respectively.

in Fig. 10(H.g) and Fig. 10(K.g). This shows that MSMHC algorithm can not only effectively remove haze from remote sensing images, but also can obtain good details and clarity. The processed results of other algorithms for Fig. 10 (H) are not satisfactory. In Fig. 10(K), the results obtained by DCP and HF algorithms are somewhat dark, while the effects of haze removal by SSR, MSR3 and BPDFHE can be achieved.

In Fig. 10(G), Fig. 10(I) and Fig. 10(J), the ground scenes they cover are mainly urban areas, but also include some greening facilities. For Fig. 10 (G), using the DCP, HF and BPDFHE algorithms to remove haze, the effect of haze removal is not desirable. Other four methods have good haze removal effect, and the best is still MSMHC algorithm. It not only removes haze well, but also obtains good geometric details and clarity, and the distortion degree is relatively small. In Fig. 10(I), there are large areas of ocean and buildings. Except DCP and HF methods, other methods can basically effectively remove haze. But the results obtained by HE and BPDFHE algorithms are brighter, as shown in Fig. 10 (I.d) and Fig. 10 (I.f). The following SSR, MSR3 and MSMHC algorithms treat ocean waves as geometric details of objects. In Fig. 10 (J), there are rivers, lakes, roads, buildings and natural landscapes. The better methods to remove haze are SSR, MSR3 and MSMHC, among which MSMHC is the best and the clearest.

Through above comparative experiments and results analysis, the following conclusions can be drawn.

(1) For outdoor photo images, DCP and BPDFHE algorithms can effectively remove haze in a certain range. The image processed by DCP is darker, while BPDFHE can keep the brightness of the image better, so the resulting image is brighter. BPDFHE algorithm can get the best results for outdoor photo images including the sky, especially the perspective part of the sky region. Both HE and MSMHC algorithms can obtain good experimental results, but the HE algorithm has obvious color distortion, and it is very difficult for them to deal with the sky part.

(2) For gray remote sensing images, DCP, HF and BPDFHE algorithms have poor ability to remove haze. However, HE and MSMCHC algorithms can effectively remove haze and obtain good clarity and detail information.

(3) For color remote sensing images, MSMHC algorithm achieves good results except for images containing ocean areas. The distortion of HE algorithm is obvious. At this time, DCP, HF and BPDFHE algorithms cannot remove haze well, which indicates that their ability to remove haze from remote sensing images is not strong. The ability of SSR and MSR3 to remove haze is also very limited. MSMHC algorithm can remove haze effectively in general.

(4) MSMHC algorithm can effectively remove haze except for outdoor images of sky and remote sensing images of ocean area. The experimental results obtained by this method have good clarity, less distortion and rich details.

(5) In terms of haze removal ability, MSR3 algorithm is superior to SSR algorithm, and the image details obtained by MSR3 algorithm are more abundant. For outdoor images, the SSR algorithm is better and brighter than the MSR3 algorithm.

The experimental results of the above-mentioned methods are compared and analyzed with visual or subjective judgment, which is shown in Fig. 10. Next the performance of these methods will be compared and analyzed quantitatively with some parameters, such as SD, IE, PSNR, SSIM and IC. The statistical analysis results of these parameter values are shown in from Fig.11 to Fig.15.

The statistics of SD values are shown in Fig. 11. It is known in Fig. 11 that the SD value of HE method is relatively large for all processed images. This shows that the HE method can adjust the gray range and make the image clearer. Previously, it has been analyzed that HE method can usually effectively remove haze from images, especially gray images, but for color images, its distortion is serious. For images with more detailed information, the SD values are relatively small for HE method, as shown in Figs. 10 (C), (D) and (G). Except for gray images, the SD values obtained by BPDFHE algorithm are relatively high, which shows that it can maintain the brightness of the image better, but it is not suitable for gray image processing. Similarly, for the MSMHC algorithm, the SD values obtained are also relatively large, indicating that it can effectively remove haze.

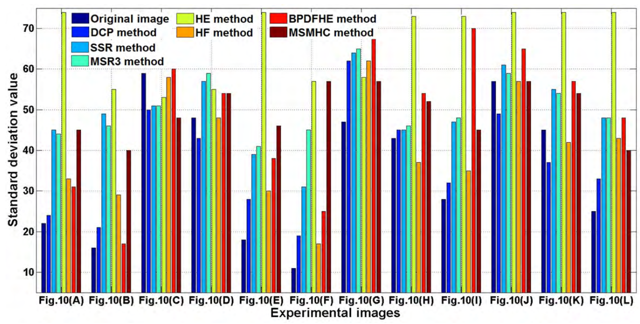


FIGURE 11. Statistical and comparative graphs of SD values.

Fig. 12 shows IE statistics for different images. From the viewpoint of information entropy, these methods can obtain high amount of information, indicating that they can remove haze. However, for gray images, the IE values of DCP, HF and BPDFHE algorithms are relatively low, which indicates

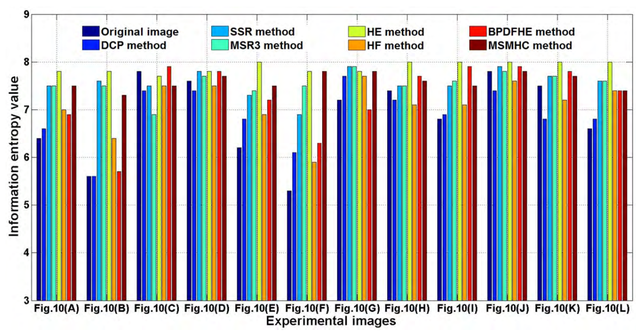


FIGURE 12. Statistical and comparative graphs of IE values.

that their processing ability is not strong for dealing with haze in gray images.

Fig. 13 shows the PSNR values of the experimental images. Because the physical meaning of PSNR is the error obtained by comparing with the original image, the value of PSNR of the original image is infinite. The infinite value is replaced by zero in Fig. 13. If the amount of haze removed from the image is smaller, the smaller the difference between the processed image and the original image is, and the larger the PSNR value is; On the contrary, if the image haze is removed completely, the larger the difference between the processed image and the original image is, the smaller the PSNR value is. It can be seen in Fig. 13, the PSNR value of the image processed by BPDFHE algorithm is the largest in any experiment. It shows that BPDFHE algorithm can effectively maintain better brightness, but its ability of haze removal is poor, because the processed image is the closest to the original image. In addition, the value of HF algorithm is relatively large, and the value obtained by other algorithms is not much different.

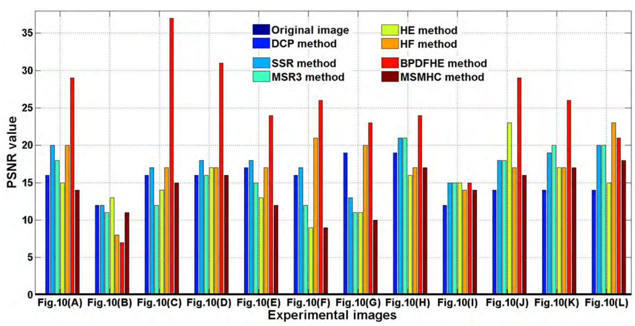


FIGURE 13. Statistical and comparative graphs of PSNR values.

The statistics of SSIM values are shown in Fig. 14. SSIM is an important index to evaluate the structural similarity between two images, i.e. the processed image and the original image. Therefore, the SSIM value of the original image itself is the largest, equal to one. Because the original image contains haze, the smaller the haze removal is, the more similar it is to the original image, and the larger the SSIM value is, i.e., the closer to one. It can be seen in Fig. 14 that the SSIM values obtained using the DCP, HF and BPDFHE algorithms are generally relatively large. This shows that the processed images are closer to the original images, indicating that their ability to remove haze is poor. In Fig. 14, there is a remarkable feature that the SSIM value obtained by MSMHC algorithm is the smallest. The results show that the image processed by MSMHC algorithm is quite different from the original image. The difference is that the haze is removed and the contrast and clarity are improved. For gray images, HE and MSMHC algorithms achieve similar results of SSIM values.

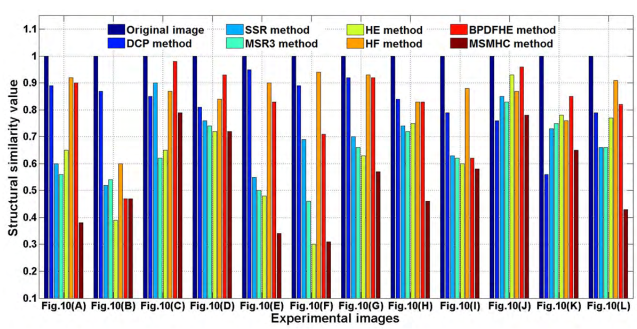


FIGURE 14. Statistical and comparative graphs of SSIM values.

Fig.15 shows the IC values of different images. The typical characteristic of haze image is that the whole image appears gray-white, the contrast of the image decreases, and the details of the image are blurred. Therefore, as can be seen in Fig. 15 that the IC values of the original haze image are very low. It is very obvious that the highest value of IC is HE and MSMCHC algorithm. For gray images and outdoor photos, the IC value of HE algorithm is higher, which shows that it can remove haze well, but for remote sensing images, its ability to remove haze is obviously inferior to MSMHC algorithm. At the same time, it can be also seen in Fig. 15 that the IC values obtained by DCP and HF algorithms are relatively low, which shows that although they can remove haze in the image, but the clarity of the obtained image is not high and the details are not very clear.

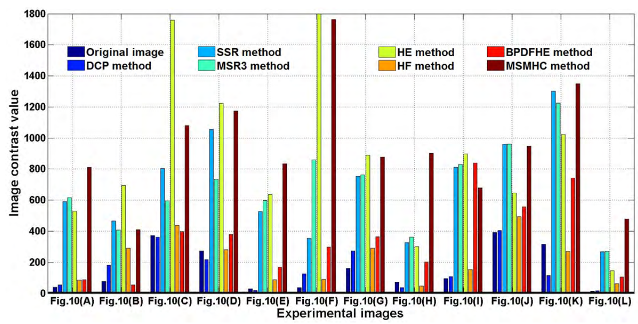


FIGURE 15. Statistical and comparative graphs of IC values.

To further explain the performance and effects of different algorithms, two typical remote sensing images were selected for comparison and analysis, which were Fig. 10(G) and Fig. 10(H). And all parameter values were shown in Table 5 and Table 6. The imaging scene of Fig. 10(G) is a town area, and the scene of Fig. 10(H) is a natural environment area. From Table 5 and Table 6, it is known that the IC and IE values of MSMHC algorithm are relatively large, the SSIM, SD and PSNR values are relatively small, which shows that this algorithm can not only effectively remove haze, but also have good details and clarity. The parameter values of HE algorithm are similar to those of MSMHC algorithm, but when it processes color images, the degree of color distortion is relatively large, as shown in Fig. 10(G.d) and Fig. 10(H.d). At the same time, it can be seen that the IC values of DCP and HF algorithms are relatively small, which indicates that the two methods cannot obtain a clearer

TABLE 5. Evaluation index values of Fig. 10(G).

	SD	IE	PSRN	SSIM	IC
Original image Fig. 10(G)	48	7.2	∞	1	162
DCP method Fig. 10(G.a)	62	7.7	19	0.92	274
SSR method Fig. 10(G.b)	64	7.9	13	0.70	754
MSR3 method Fig. 10(G.c)	65	7.9	11	0.66	763
HE method Fig. 10(G.d)	58	7.8	11	0.63	891
HF method Fig. 10(G.e)	62	7.7	20	0.93	291
BPDFHE method Fig. 10(G.f)	69	7.0	23	0.92	364
MSMHC method Fig. 10(G.g)	57	7.8	10	0.57	877

TABLE 6. Evaluation index values of Fig. 10(H).

	SD	IE	PSRN	SSIM	IC
Original image Fig. 10(H)	43	7.4	∞	1	73
DCP method Fig. 10(H.a)	45	7.2	19	0.84	38
SSR method Fig. 10(H.b)	45	7.5	21	0.74	326
MSR3 method Fig. 10(H.c)	46	7.5	21	0.72	361
HE method Fig. 10(H.d)	74	8.0	16	0.75	301
HF method Fig. 10(H.e)	37	7.1	17	0.83	46
BPDFHE method Fig. 10(H.f)	54	7.7	24	0.83	203
MSMHC method Fig. 10(H.g)	51	7.6	17	0.46	903

image or a higher contrast image after processing the haze remote sensing image. For Fig. 10(G) and Fig. 10(H), the values of various parameters obtained by SSR and MSR3 algorithms are almost the same, indicating that their ability to remove haze is similar. From the parameter values, the ability of BPDFHE algorithm to remove haze is in the middle. Its main advantage is that it can maintain a good brightness, but it cannot remove the haze in the image very well.

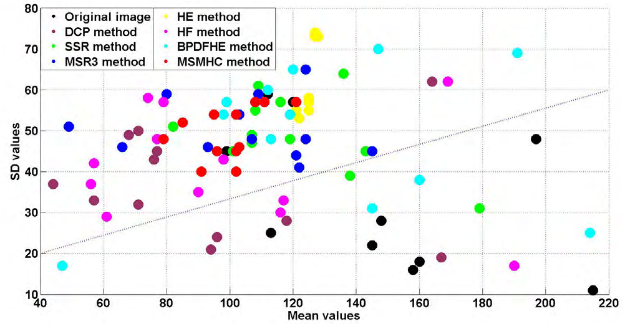


FIGURE 16. The scatter diagram of mean and SD.

The performance of different algorithms is evaluated and analyzed from the point of view of single image or single parameter. Next, we will analyze the statistical characteristics of each image from the perspective of joint mean and standard deviation. The experimental results are shown in Fig. 16, which describes the scatter diagram of the mean and SD values of all experimental images. It can be seen in Fig. 16 that the average values of the original images are relatively large, while the SD values are relatively small. The reason is that when the image is affected by haze, the average gray intensity increases, but the details become blurred. The images processed by MSR3, HE and MSMHC have scattered points above the straight line. This shows that they can get a larger SD value, i.e. more details information, and can effectively remove haze from different haze images. The scatter points obtained by the other four methods (DCP, SSR, HF and BPDFHE) are both above and below the straight line. This shows that these methods cannot achieve good results for all images, and their general adaptability is relatively poor. The SSR and BPDFHE algorithms get larger mean value of the image, which is closer to the original image. It shows that they can maintain better brightness, but their ability to remove haze is weak. The scatter points of the HE and MSMCHC algorithms are concentrated, which shows that they can achieve better results for different images and have wider applicability. The previous analysis shows that the biggest disadvantage of HE algorithm is that the color of the image is distorted greatly.

V. CONCLUSION

The existence of haze seriously affects the quality of optical remote sensing images. The problem of haze removal in optical remote sensing images is deeply studied in this paper, especially the difference between remote sensing images and outdoor photo images, and the characteristics and application scope of existing image haze removal algorithms. Based on the content of remote sensing image, a new algorithm for removing haze is proposed, namely MSMHC algorithm. The new algorithm is based on remote sensing image content, multi-scale model and histogram characteristic. After a lot of validation experiments, MSMHC algorithm can achieve good results. It shows that MSMHC algorithm can not only effectively remove haze from remote sensing image, reduce haze interference, improve image quality and utilization value, but also has rich detail information. The MSMHC algorithm is indeed a feasible and effective method for remote sensing image haze removal. It is not the best algorithm for MSMHC algorithm to process these images containing large areas of the sky or ocean. Cloud removal in remote sensing images is not discussed in this paper, so the next step is to combine cloud and haze removal.

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