HAZE REMOVAL FOR HIGH RESOLUTION SATELLITE IMAGES

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ABSTRACT: Atmospheric scattering caused by haze usually generates path radiance and degrades the quality of remotely sensed images. Traditionally, Dark Object Subtraction (DOS) is a commonly used approach to reduce such disadvantage on images. Nevertheless, when the distribution of haze is not spatially homogeneous, DOS may no longer applicable. Haze Optimized Transformation (HOT) defines a Haze Vector that can be used to estimate the haze condition for each particular image pixel. Accordingly, a correspondent gray value correction for reducing the influence of path radiance can be obtained as well. However, for images with higher spatial resolution, the results of HOT algorithm become spatially unstable because the complicated ground objects are more observable. In this study, for suppressing the drawbacks caused by detailed ground objects, a filtering process is introduced to smooth the original output of HOT. Furthermore, in order to decide a reasonable window size for medium filter, a high frequency noise analysis in frequency domain is also included. After the proposed method is tested by using high resolution satellite images, the results show that the haze removed image by proposed method can have better visual quality and applicability.

1. INTRODUCTION

It is well known that the haze with constituents of water droplet, ice crystals and fog/smoke particles will affect the quality of image acquired by optical remote sensing sensors (Kaufman, 1989). Basically, atmospheric scattering contributed by haze such as Rayleigh scattering, Mie scattering and Nonselective scattering can generate excessive path radiance and increase the total radiance received by sensors (Schott, 1997). Dark Object Subtraction (DOS) is a commonly used approach to reduce such excessive path radiance (Chavez, 1989; Teillet and Fedosejevs, 1995). Basically, DOS uses some specific targets whose corresponding reflectance is almost zero as the “dark objects” (for example, clear water objects). As a result, the gray value of the pixels corresponding to these “dark objects” can be regarded as the contribution of path radiance. Then, by assuming that the distribution of haze is spatially homogeneous, the influence of haze can be reduced by subtracting the gray value of “dark objects” from original images. However, when the distribution of haze is not spatially homogeneous, DOS may have difficulties. Instead of using a specific target as a reference in DOS, Haze Optimized Transformation (HOT) (Zhang et al., 2002) defines a Clear Line in spectral feature space to describe the radiometric property of ground objects under the clear sky. By using Clear Line as a reference, a Haze Vector can be carried out to estimate the haze status for each pixel. Moreover, a correspondent gray value correction for reducing the drawbacks caused by excessive path radiance is then derived by the estimated haze status. In practice, using HOT to reduce the influence of haze on Landsat 7 ETM+ images has been tested and discussed in literature (Zhang and Guindon, 2003).

In this study, the HOT algorithm is tested by using high resolution satellite images acquired by FORMOSAT-2 and IKONOS satellites. In this case, because the complicated and detailed ground objects are more observable in these satellite images, the results of original HOT algorithm can be spatially unstable. Nevertheless, if a medium filter can be introduced to smooth the output of HOT in advance, the more reasonable results can be obtained.

2. METHODOLOGY

2.1 Haze Optimized Transformation (HOT)

In HOT, at first a Clear Line should be defined in “blue-red” spectral space (Zhang et al., 2002). Basically, Clear Line can be obtained by using the linear regression of the pixels without haze contamination. Then, in spectral space, the haze condition for a particular image pixel can be represented by its shortest distance to the Clear Line, i.e., the HOT of that pixel. It implies that a pixel is hazier if it is further away from Clear Line. Therefore, if the slope angle of Clear Line is Θ, the HOT image can obtained by Eq. (1).

$$HOT = B_1 \sin\Theta - B_3 \sin\Theta \quad (1)$$

where B_1 and B_3 are image pixel values in blue band and red band respectively.

The next is to estimate the gray value correction for each hazy pixel according to HOT values. In general, HOT value corresponding to the pixel without haze contamination represents a reference for the correction of haze. It means the pixel with this reference HOT value should not have any correction. On the other hand, if a pixel with a HOT value higher than this reference, some correction should be applied. In order to find the specific correction for each HOT value, a "dark target" subtraction scheme is proposed by Zhang (Zhang et al., 2002). At first, from the those pixels with zero HOT value, a minimum gray value $\boldsymbol{G}_{min0}$ can be found and regarded as the gray value of the "dark target of haze free pixels or pixels in clear sky areas". Then, for the pixels corresponding to any particular HOT value are collected and another minimum gray value $\boldsymbol{G}_{min}$(HOT) can be found and regarded as the gray value of the "dark target of that particular haze status". Noticed that the curve of $\boldsymbol{G}_{min}$(HOT) should be a monotonic increasing function because the radiance scattered by haze should be larger when the haze level is higher. Once the $\boldsymbol{G}_{min}$(HOT) for all HOT values are obtained, the gray value correction corresponding to any specific HOT value $\Delta\boldsymbol{G}$(HOT) can be obtained by Eq. (2).

$$\Delta \boldsymbol{G}(\mathrm{HOT}) = \boldsymbol{G}_{min}(\mathrm{HOT}) - \boldsymbol{G}_{min0} \quad (2)$$

Once the gray value correction $\Delta\boldsymbol{G}$(HOT) is obtained, the correction process for removing the influence of haze with any specific HOT value can be performed by Eq. (3).

$$\boldsymbol{I}_{\mathrm{hr}} = \boldsymbol{I}_{\mathrm{source}} - \Delta \boldsymbol{G}(\mathrm{HOT}) \quad (3)$$

where $\boldsymbol{I}_{\mathrm{hr}}$ is the gray values of the pixels in haze removed image and $\boldsymbol{I}_{\mathrm{source}}$ is the gray values of the pixels in source image.

2.2 HOT for High Resolution Satellite Image

As mentioned previously, for high resolution satellite images, the complicated and detailed ground objects are more observable. It implies that obtained HOT image will reflect not only haze in atmosphere, but also the variation of ground objects. This problem can result in two drawbacks: (1) The function $\boldsymbol{G}_{min}$(HOT) may no longer a monotonic increasing function. This makes $\boldsymbol{G}_{min}$(HOT) do not follow the principle of haze scattering. (2) The HOT image may be affected by ground object and not directly relate to the haze variation.

2.3 Improvement for Monotonic Increasing Property

In order to ensure that $\boldsymbol{G}_{min}$(HOT) follow the behavior of monotonic increasing function, the generation of Gmin(HOT) is also modified as follows

$$\boldsymbol{G'}_{min}(\mathrm{HOT}) = \begin{cases} \boldsymbol{G}_{min}(\mathrm{HOT}), \\ \text{if } \boldsymbol{G}_{min}(\mathrm{HOT}) \geq \boldsymbol{G'}_{min}(\mathrm{HOT}-1) \\ \\ \boldsymbol{G'}_{min}(\mathrm{HOT}-1), \\ \text{if } \boldsymbol{G}_{min}(\mathrm{HOT}) < \boldsymbol{G'}_{min}(\mathrm{HOT}-1) \end{cases} \quad (4)$$

where $\boldsymbol{G'}_{min}$(HOT) is the modified minimum gray value for any specific HOT value. Accordingly, the modified version of gray value correction corresponding to any specific HOT value $\Delta\boldsymbol{G'}$(HOT) can be obtained by

$$\Delta \boldsymbol{G'}(\mathrm{HOT}) = \boldsymbol{G'}_{min}(\mathrm{HOT}) - \boldsymbol{G}_{min0} \quad (5)$$

2.4 Smooth HOT Image by Medium Filter

In general, for high resolution remote sensing images, the observable ground objects is increased with better image resolution, while the influence of haze generally remains unchanged. In other word, the more observable ground objects imply that the band to band correlation of image is decreased and the class distributions in image feature space are more distinguishable. This fact will cause that the HOT of those image pixels under same hazy condition differ a lot from each other. Therefore, if the original HOT image is directly used to correct the influence of haze, it is inevitable that the correction will affect by the detailed ground objects. In addition, it will also introduce high frequency noise in the haze removed image and not consist with the low spatial variation property of haze. Hence, in this study a medium filter is applied to HOT image in advance to decrease the influence of the detailed ground objects. However, the windows size of applied medium filter still has to be carefully selected. Filter with larger window size of course can more effectively suppress the noise caused by the ground objects, but the variation of haze certainly may also be smoothed out.

For choosing a suitable window size for filtering, a method based on high frequency noise analysis is proposed. At first, both the haze removed image and the source image are transformed to frequency domain by Fast Fourier Transform (FFT). Because the haze generally can only affect the image in low frequency part, the power spectrums of the two images in high frequency part theoretically should remain unchanged. However, if the smoothing window is used inappropriately, the power spectrums in high frequency part of the two images should not be the same and artificial noise will be created in the haze removed images. In this study, we assume that the wavelength of the haze variation is at least 4 times longer than image resolution. For example, if the source image is a FORMOSAT-2 multispectral image with 8 meter resolution, it is reasonable to assume that the significant spatial variation of haze should be always greater than 32 meters. Under this assumption, only the high frequency information under the upper half of the power spectrum is needed to be considered in the noise analysis. Therefore, according to the high frequency power differences between the source and haze removed images, their power RMSE can be used to measure the increased high frequency noise due to the problem of HOT image. Based on this point, we can use medium filters with various window sizes to generate a series of haze removed images. Then, if a medium filter with a suitable windows size is selected to filter the original HOT image, the high frequency power RMSE obtained from that specific haze removed images should be reasonably small.

3. EXPERIMENTAL RESULT AND DISSCUTION

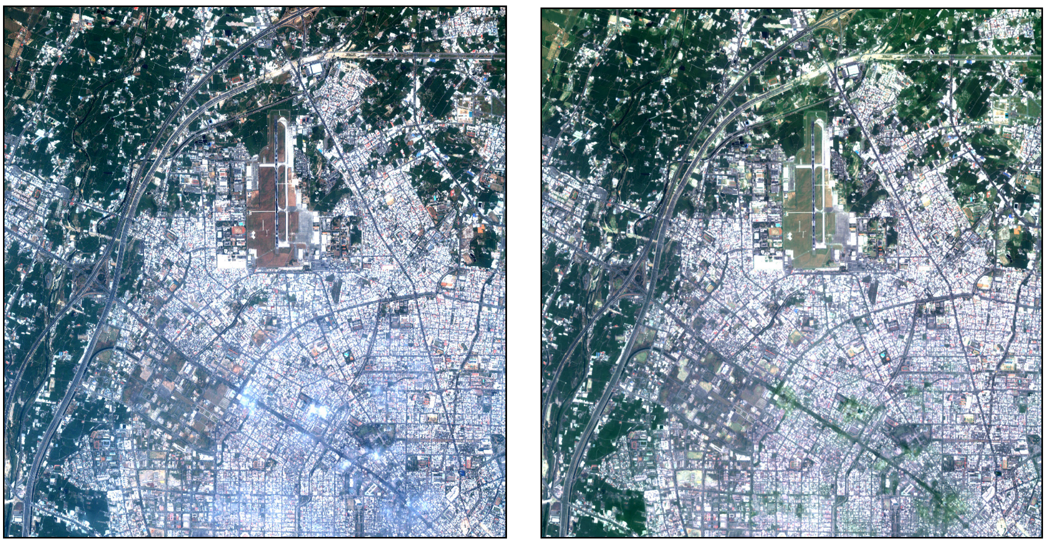
In this study, a FORMOSAT-2 image and an IKONOS image are used as test images. Figure 1 shows the original FORMOSAT-2 image and its haze removed image. The ground coverage for this test FORMOSAT-2 is 10x40 km. Figure 2 shows the original IKONOS image and its haze removed image. The ground coverage for this test IKONOS images is and 6.3x6.7 km. It is clear that all the original images are partially affected by haze and tends to be brighter than the unaffected areas. Although the haze removed images can be carried out according to proposed method, it is important that the optimal windows sizes of the smoothing filters for the two test images should not be the same because their resolutions are different. Normally the image with higher resolution requires larger window size of smoothing filter because there are more detailed objects need to be suppressed.

As shown in figure 3, the enlarged version of original image and haze removed images with different window sizes, it is clear that the haze removed image by HOT image without any filtering contains lots of pepper and salt noise. However, if a medium filter with larger window size is applied to smooth the HOT image, the pepper and salt noise can be significantly reduced. Another point worth to mention is that the IKONOS image usually needs a filter with larger window size for smoothing the HOT image because its higher spatial resolution.

In figure 4 shows the HOT images without any smoothing and smoothed with a medium filter by 9x9 window size. Theoretically, a higher value in HOT image means that the corresponding pixel is more affected by haze. Nevertheless, it can be observed that in figure 4(a), the HOT image without any filtering, the structure of ground object can still be seen clearly and the spatial distribution of HOT values is very noisy. In fact, this HOT image is unable to represent the corresponding influence of real haze. Compared to figure 4(b), the HOT image smoothed with a medium filter, in this case the HOT values are more related to the haze variation observed on the source image.

(a) (b)

Figure 1. The original FORMOSAT-2 satellite image and its haze removed images. (a) Original FORMOSAT-2 image. (b) Haze removed FORMOSAT-2 image with 9x9 window size.



(a) (b)

Figure 2. The original IKONOS satellite image and its haze removed images. (a) Original IKONOS image. (b) Haze removed IKONOS image with 17x17 window size.

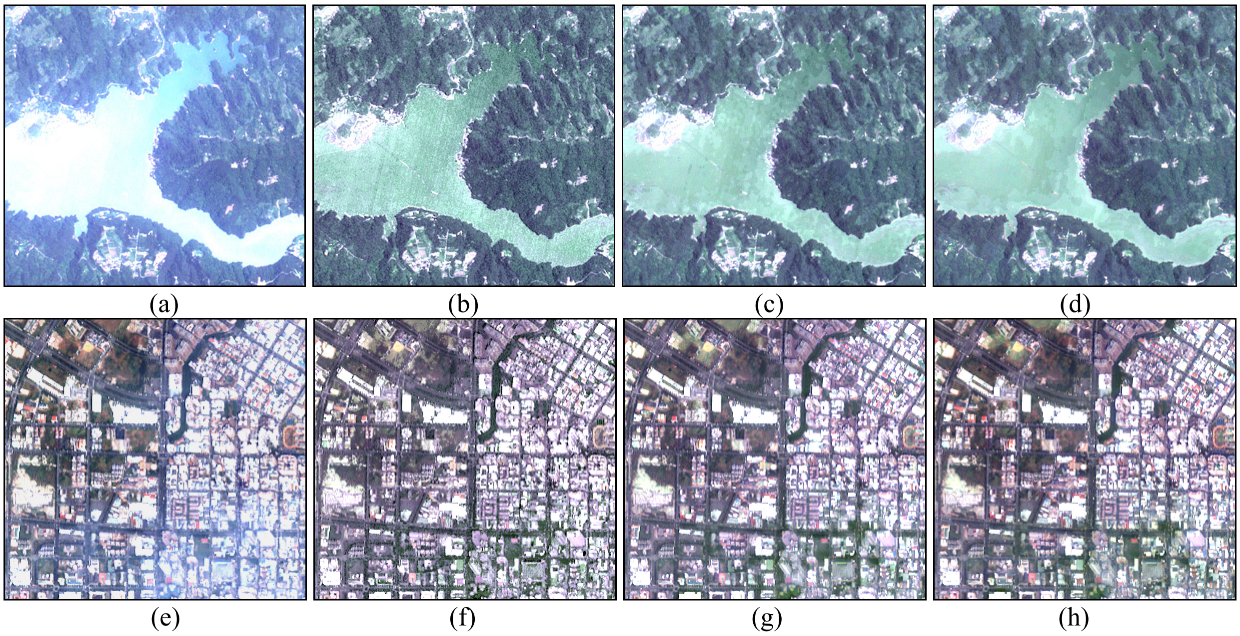


Figure 3. The enlarged version of original images and haze removed images with different window sizes. (a) Original FORMOSAT-2 image. (b) Haze removed FORMOSAT-2 image by HOT image without any filtering. (c) Haze removed FORMOSAT-2 image by HOT image smoothed with a 5x5 medium filter. (d) Haze removed FORMOSAT-2 image by HOT image smoothed with a 9x9 medium filter. (e) Original IKONOS image. (f) Haze removed IKONOS image by HOT image without any filtering. (g) Haze removed IKONOS image by HOT image smoothed with a 9x9 medium filter. (h) Haze removed IKONOS image by HOT image smoothed with a 17x17 medium filter.

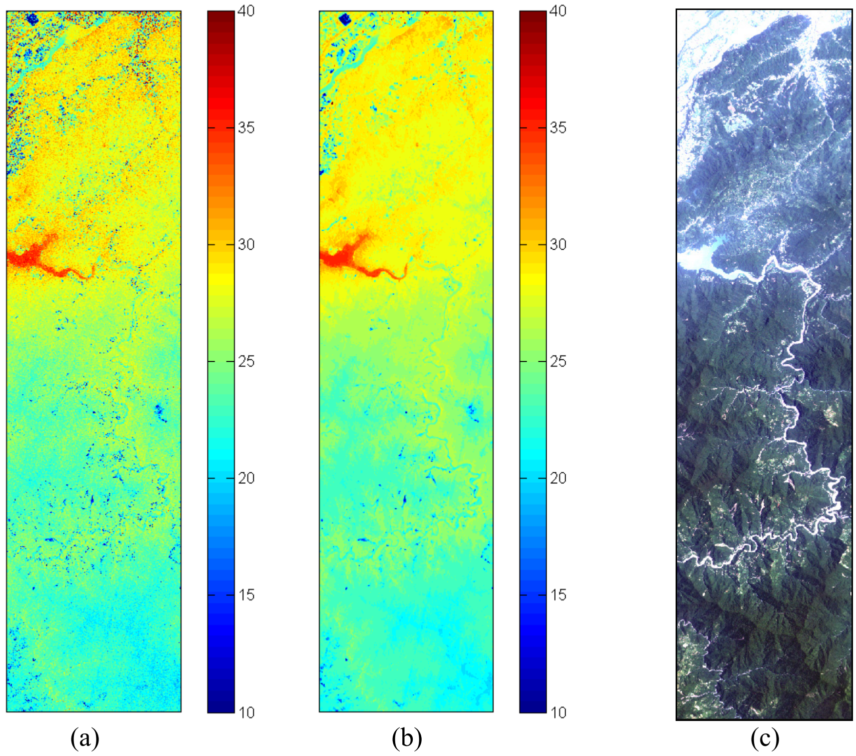
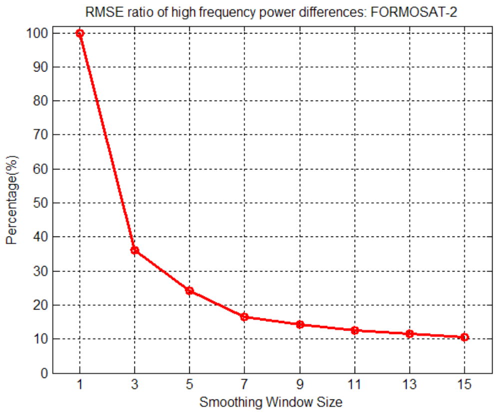


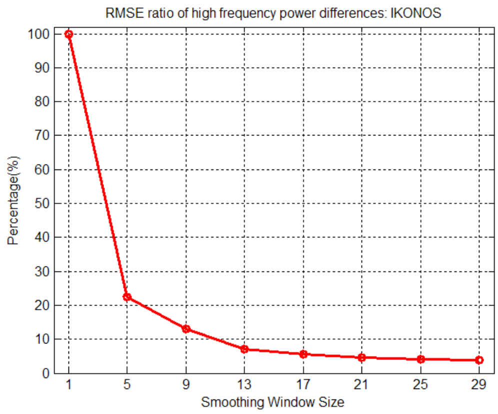
Figure 4. The comparison of two HOT images generated by different approaches. (a) HOT image without any filtering. (b) HOT image smoothed with a medium filter with 9x9 window size. (c) Original FORMOSAT-2 image for comparison.

If the high frequency power RMSE obtained from the haze removed image by HOT image without any smoothing and smoothed with a nxn medium filter are indicated as $\boldsymbol{P}_{rmse}(1)$ and $\boldsymbol{P}_{rmse}(\mathrm{n})$ respectively, then high frequency RMSE ratio $\boldsymbol{R}_{rmse}(\mathrm{n})$ for haze removed image by HOT image smoothed with a nxn medium filter can be defined as

$$R_{rmse}(n) = P_{rmse}(n) / P_{rmse}(1) \qquad (6)$$



(a)



(b)

Figure 5. High frequency RMSE ratio $R_{rmse}(n)$ in percentage with HOT image smoothed by medium filter with various windows sizes. (a) The case for FORMOSATE-2 image. (b) The case for IKONOS image.

In figure 5, the high frequency RMSE ratios $R_{rmse}(n)$ in percentage for different source images are illustrated. It can be found that the $R_{rmse}(n)$ is decreased to about 15% of maximum RMSE if a 9x9 medium filter is used for the case of FORMOSAT-2 image. Similarly, for the case of IKONOS image, the $R_{rmse}(n)$ is decreased to lower than 10% of maximum RMSE if a 17x17 medium filter is used. Therefore, by using high frequency RMSE ratio $R_{rmse}(n)$, a suitable window size for filtering can be determined when the improvement in RMSE is insignificant with larger window size. For example, in the test images used in this study, the suggested window sizes of medium filters for FORMOSAT-2 and IKONOS images may be 9x9 and 17x17 respectively. In addition, a further smoothing is not suggested because the larger window size may over smooth the haze behavior in HOT image.

4. CONCLUSION

In this study, according to the HOT algorithm to remove the influence of haze in remote sensing image, a medium filter is used to smooth the HOT image and improve the quality of haze removed image. Moreover, by using high frequency RMSE ratio $R_{rmse}(n)$, a suitable window size of medium filter can be selected to suppress the noise created by detailed ground objects. In addition, two haze affected source images acquired by FORMOSAT-2 and IKONOS satellites are used to evaluate the performances of proposed method. The experimental results show that if the HOT images are smoothed with suggested sizes of medium filters in advance, the influence of haze in the source images can be removed with comparable lower high frequency noise.

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