Image dehazing technique based on polarimetric spectral analysis

Pu Xia\textsuperscript{a,b,*}, Xuebin Liu\textsuperscript{a}

\textsuperscript{a} Key Laboratory of Spectral Imaging Technology, Xi'an Institute of Optics and Precision Mechanics, Chinese Academy of Sciences, Xi'an 710119, PR China
\textsuperscript{b} University of Chinese Academy of Sciences, Beijing 100049, PR China

\textbf{A R T I C L E   I N F O}

\textbf{Article history:}
Received 25 March 2016
Accepted 23 May 2016

\textbf{Keywords:}
Haze removal
Image correction
Atmospheric scattering
Polarization spectrometer
Spectral analysis

\textbf{A B S T R A C T}

Image took under hazy weather suffers from poor contrast and resolution, the haze particles will attenuate the light reflected by the targets and add unwanted scattering light. Based on the fact that the target reflection and scattering light have different polarimetric characteristics, light’s power to penetrate the haze particles is linked with wavelength, this paper combines the polarimetric dehazing technique with spectral analysis, firstly proposed the polarimetric spectral dehazing method. A polarimetric spectral imager is used to obtain data under a continuously changing weather circle, the dehazing result is analyzed under five different spectral channels of 451.4 nm, 551.2 nm, 650.9 nm, 750.7 nm and 850.5 nm. The results show that our method can effectively recover the haze degenerated image under visible and infrared channels, the restoration quality of detailed information of the near-field and the far-field targets are in varying degrees under different channels. The dehazing process can enhance the image contrast by 1.68–3.64 times under different wavelengths. Two correction factors, which regularity is given for particle use, are introduced to revise an image restoration result.

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1. Introduction

The worsening air pollution is causing serious haze problems in China\textsuperscript{[1,2]}, the air quality of nearly half of the days in 2015 in big Chinese cities like Beijing and Shanghai had failed to reach the standard. The high concentration of aerosol\textsuperscript{[3,4]}, which can attenuate the object radiance and add unwanted scattering light into the total intensity, has a serious effect on the resolution and contrast of the imaging quality. Ordinary imaging techniques can not function properly under hazy weather which can cause serious problem for information extraction and processing.

The image-dehazing techniques can be roughly categorized into two kinds: the method based on image enhancement, such as linear transformation\textsuperscript{[5]}, structure preserving\textsuperscript{[6]} and dark channel prior\textsuperscript{[7]}, the method based on physical model, such as polarimetric image-dehazing\textsuperscript{[8,9]}. The image enhancement methods, which focus on the haze-degraded image itself without considering the physical process of image degeneration, use computer vision techniques to enhance the image contrast, the loss of some detailed information is inevitable. The airlight scattered from the haze particles is partially polarized, meanwhile, the direct light reflected from the scene can be approximately considered as non-polarized light. The

\textsuperscript{*} Corresponding author at: Key Laboratory of Spectral Imaging Technology, Xi'an Institute of Optics and Precision Mechanics, Chinese Academy of Sciences, Xi'an 710119, PR China.
E-mail addresses: xiapu16@163.com (P. Xia), xb@opt.ac.cn (X. Liu).

http://dx.doi.org/10.1016/j.ijleo.2016.05.071
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polarimetric image-dehazing technique, which utilizes the polarimetric differences between the airlight and the direct light to extract the object radiance from the total intensity, can restore the detailed information of the image.

The research on polarimetric dehazing has mainly been focused on single-band’s visible image at present, based on our previous work [10,11], the image dehazing technique based on polarimetric spectral analyses, which has not been reported [9,12,13], is introduced. The object radiance’s ability to penetrate the haze particles has a huge difference under different spectral channels, it is of practical significance to combine the polarimetric dehazing method with spectral analysis. The polarimetric spectral imager used in this paper can obtain the two-dimensional spatial information, one-dimensional spectral information and polarimetric information simultaneously. This image restoration method utilizes the Stokes parameters and the Mueller matrix to extract polarimetric information from the scene and obtains the image restoration result through the correction of a series of bias factors. The image characteristic and the dehazing process of near-field and far-field scenes under different spectral channels are analyzed. This method realized multi-spectral image restoration based on polarimetric dehazing which makes it possible for the imaging spectrometer to work under hazy weather.

2. Atmospheric scattering model and polarimetric dehazing method

The total intensity of the light \( I \) received by the imager under hazy weather can be divided into two parts: the part generated by the reflection of targets which is the direct light reflected from the scene \( D \), the part generated by the scattering of the atmosphere which is the airlight scattered from haze particles \( A \). Under hazy weather, the scattering of aerosol will add unwanted airlight into the total intensity of light and the absorption of aerosol will attenuate the reflection of the scene. The energy imager receives will be the object radiance \( L \) when there is no aerosol between the imager and the scene. The direct light reflected from the scene \( D \) is non-polarized light which decreases with the observation distance, meanwhile, the airlight scattered from the haze particles \( A \) is partially polarized which increases with the observation distance. Based on the difference of \( D \) and \( A \), the image restoration can be realized by separating the airlight from the total intensity and compensating the attenuation of the direct light. In Schechner’s theory [14], the object radiance \( L \) after the image restoration is

\[
L = \frac{I^1 + I^\| - (I^1 - I^\|)/p}{1 - (I^1 - I^\|)/pA_\infty}
\]

where \( I^1 \) is the image taken when the orientation of the polarizer is perpendicular to the plane of incidence, \( I^\| \) is the image taken when the orientation of the polarizer is parallel with the plane of incidence, \( A_\infty \) is the airlight from an object at an infinite distance such as the sky region, \( p \) is the degree of polarization. The total intensity of the light received by the polarimetric imager under hazy weather changes with the orientation angle of the polarizer \( \alpha \), when the orientation of the polarizer is parallel with the plane of incidence \((\alpha = \theta^\|)\), the intensity of the airlight scattered from haze particles \( A^\| \) is the smallest which represents the best state of the original image, when the orientation of the polarizer is perpendicular to the plane of incidence \((\alpha = \theta^\perp)\), the intensity of the airlight scattered from haze particles \( A^\perp \) is the largest which represents the worst state of the original image.

Based on the Stokes parameters and the Mueller matrix, the dehazing algorithm extract the polarimetric information through four linear polarimetric images with fixed orientation of 0°, 45°, 90° and 135° which means no manual operation or subjective evaluation is needed during the hole image restoration process. The Stokes parameters are

\[
\begin{aligned}
S_0 &= I(0) + I(90) \\
S_1 &= I(0) - I(90) \\
S_2 &= I(45) - I(135)
\end{aligned}
\]

where \( S_0 \) represents the total intensity of the image, \( S_1 \) and \( S_2 \) represent the linear polarimetric characteristic of the image. The angle of polarization perpendicular to the plane of incidence is \( \theta^\perp = \frac{1}{2} \arctan \frac{S_2}{S_1} \), the angle of polarization parallel with the plane of incidence is \( \theta^\| = \theta^\perp + \frac{\pi}{2} \). Base on the Mueller matrix, the total intensity of the image on the angle of polarization \( \alpha \) is

\[
I(\alpha) = \frac{1}{2} (S_0 + S_1 \cos 2\alpha + S_2 \cos 2\alpha)
\]

The algorithm acquires \( I^1 \) and \( I^\| \) by substituting \( \theta^\perp \) and \( \theta^\| \) into Eq. (3).

The direct light reflected from the scene is almost completely attenuated when the observation distance is close to infinity which means there is only airlight component left. The total intensity of the image \( I \) at an infinite observation distance may be considered as the airlight from an object at an infinite distance \( A_\infty \). The degree of polarization of the airlight can be obtained by \( p = (I^1 - I^\|)/(I^1 + I^\|) \). It should be noted that the estimation of \( p \) and \( A_\infty \) is based on the hypothesis that the extinction coefficient \( e^{-\beta z} \) of the sky region in the image is zero, under normal circumstances, aerosol of large radius like the water vapor particles will absorb the radiance and generate secondary radiance as light sources which means completely
elimination of atmospheric scattering will lead to deep and dark sky region [8,14]. In order to correct the estimation error, a bias factor and a correction factor is introduced to revise \( p \) and \( A_\infty \)

\[
p_c = p \times \varepsilon_1
\]

\[
A_{\infty c} = A_\infty \times \varepsilon_2
\]

where \( p_c \) and \( A_{\infty c} \) are the corrected degree of polarization of the aircat and the intensity of the aircat from an object at an infinite distance. The promotion of image restoration quality and the inhibition of noise can be done by slightly enlarging the value of \( p \) and \( A_\infty \). In order to make sure that \( p_c \) is within a reasonable range \((0 < p_c < 1)\), the value of \( \varepsilon_1 \) should be \( 1 < \varepsilon_1 < 1/p \), meanwhile, the value of \( \varepsilon_2 \) should make sure that \( A_{\infty c} < S_0 \).

3. Instruments and experiment environment

The polarimetric spectral imager used in experiments can work on 380–1000 nm spectral range, has 1.5 nm spectral resolution and 970 pixel's vertical physical resolution. 0’’s, 45’’s, 90’’s and 135’’s linear polarimetric images of 413 different spectral channels can be obtained in one push-scanning. The comparison experiment of the polarimetric dehazing results under different spectral channels has high requirement for stability. The PTU-D48E electronic controlled PTZ made by the American company FLIR is used in the experiments to stabilize the test platform. All the original data is gathered under same integration time, aperture and sensitivity of the detector.

The polarimetric spectrum data was collected on building 2 of Xi’an Institute of Optics and Precision Mechanics, geographical coordinates was 108 51’56”N, 34 10’24”E. In order to evaluate the concentration of haze to study its influence on image quality, Air Quality Index (AQI) which contains PM2.5’s evaluation parameter is introduced. The high demands of urban heating in January 2016 required mass amount of fossil fuel combustion which aggravated the air pollution, the AQI was in long-term stability of over 200. The urban area of Xi’an experienced heavy snowfall in January 21 and 22 which greatly improved the air quality, the AQI on January 23 was 73. Due to the heavy pollution, the air quality continued to deteriorate after the snow, the AQI on January 30 was back to over 200. The polarimetric spectrum data was collected twice a day during that period to find the best data for the dehazing experiment. The data collected in 10:54 am on January 29 was selected for the experiment for the moderate concentration of haze and the significant changes of the image degradation level with the observation distance. The GPS data was collected during the experiment to measure the distance of different targets from the observation point which is helpful in judging the influence of haze and comparing the image restoration results. Based on the GPS data, the distance of the parking lot in the near-field scene was 107 m, the distance of the two tall buildings under construction in the far-field scene were 493 m.

4. Original data and dehazing results

The test of the dehazing method is based on 451.4 nm, 551.2 nm, 650.9 nm, 750.7 nm and 850.5 nm data. The evaluation of the method is given by subjective comparison between the 0’’s, 45’’s, 90’’s, 135’’s original images and the dehazed images and objective analyzation of histograms and horizontal line plots.

4.1. Experiment under 451.4 nm

0’’s, 45’’s, 90’’s and 135’’s original images under 451.4 nm are shown in Fig. 1(a–d). The original images are greatly attenuated by the haze, the clarity of the parking lot in the near-field scene is greatly affected and the two tall buildings under construction in the far-field scene are almost submerged into the background. The bias factor \( \varepsilon_1 \) is set to 2.1, the correction factor \( \varepsilon_2 \) is set to 1.1, the dehazing result is shown in Fig. 1 (e). The clarity of the parking lot is enhanced and it is much easier to identify the two tall buildings in the far-field scene. The vertical resolution of the image is 970, the horizontal line plot shown in Fig. 1(f) is based on row number 128 which completely passes through the two tall buildings and makes no contact with other targets. The result of the horizontal line plot shows that the contrast of the left and the right buildings are increased by 1.82 and 1.68 times.

4.2. Experiment under 551.2 nm

0’’s, 45’’s, 90’’s and 135’’s original images under 551.2 nm are shown in Fig. 2(a–d), the clarity of the parking lot in the near-field scene is slightly bettered and the two tall buildings in the far-field scene are barely visible compared with 451.4 nm, but the overall effect is far from ideal. The bias factor \( \varepsilon_1 \) is set to 1.9, the correction factor \( \varepsilon_2 \) is set to 1.5, the dehazing result is shown in Fig. 2 (e). The horizontal line plot under the same parameter is shown in Fig. 2(f), the result shows that the contrast of the left and the right buildings are increased by 3.14 and 2.13 times, the 551.2 nm dehazing result is better.
4.3. Experiment under 650.9 nm

0°, 45°, 90° and 135°'s original images under 650.9 nm are shown in Fig. 3(a–d), the haze has smaller effect on 650.9 nm image compared with 451.4 nm and 551.2 nm, the contour of the two tall buildings in the far-field scene are visible, but there is still much room for improvement. The bias factor $\varepsilon_1$ is set to 2.1, the correction factor $\varepsilon_2$ is set to 1.8, the dehazing result is shown in Fig. 3(e), the result of the image restoration especially the two tall buildings in the far-field scene is better compared with 451.4 nm and 551.2 nm, but the dehazing process has aggravated the noise in the sky region. The horizontal line plot under the same parameter is shown in Fig. 3(f), the result shows that the contrast of the left and the right buildings are increased by 2.75 and 2.05 times.

4.4. Experiment under 750.7 nm

0°, 45°, 90° and 135°'s original images under 750.7 nm are shown in Figs. 4(a–d), the object radiance under 750.7 nm has better power to penetrate the haze particles, but the noise is aggravated. The bias factor $\varepsilon_1$ is set to 1.6, the correction factor $\varepsilon_2$ is set to 2.1, the dehazing result is shown in Fig. 4(e), targets in the near-field scene like the trees and the parking lot have better clarity and richer detailed information, but the clarity of the two tall buildings in the far-field scene are not much enhanced compared with 650.9 nm due to the noise. The horizontal line plot under the same parameter is shown in Fig. 4(f), the result shows that the contrast of the left and the right buildings are increased by 3.64 and 2.43 times.

4.5. Experiment under 850.5 nm

0°, 45°, 90° and 135°'s original images under 850.5 nm are shown in Figs. 5(a–d), the effect of haze on the object radiance under 850.5 nm is smaller, but the problem of noise is more serious. The bias factor $\varepsilon_1$ is set to 1.4, the correction factor $\varepsilon_2$ is set to 2.5, the dehazing result is shown in Fig. 5(e), the trees in near-field scene have more detailed information. The horizontal line plot under the same parameter is shown in Fig. 5(f), the result shows that the contrast of the left and the right buildings are increased by 2.51 and 2 times.
Fig. 2. (a–d) Original polarimetric images of \(0^\circ, 45^\circ, 90^\circ, 135^\circ\) under 551.2 nm; (e) dehazed image; (f) horizontal line plot.

Fig. 3. (a–d) Original polarimetric images of \(0^\circ, 45^\circ, 90^\circ, 135^\circ\) under 650.9 nm; (e) dehazed image; (f) horizontal line plot.
Fig. 4. (a–d) Original polarimetric images of $0^\circ, 45^\circ, 90^\circ, 135^\circ$ under 750.7 nm; (e) dehazed image; (f) horizontal line plot.

Fig. 5. (a–d) Original polarimetric images of $0^\circ, 45^\circ, 90^\circ, 135^\circ$ under 850.5 nm; (e) dehazed image; (f) horizontal line plot.
5. Data analysis

5.1. Analysis of the bias factor and the correction factor

The optimal values for the bias factor $\varepsilon_1$ and the correction factor $\varepsilon_2$ used in the dehazing algorithm are shown in Fig. 6. The results show that the value of $\varepsilon_1$ and $\varepsilon_2$ have certain regularities: the value of $\varepsilon_1$ is around 2 under visible channels and around 1.5 under infrared channels; the value of $\varepsilon_2$ grows with wavelength in a stable slope, these regularities are good references for new imaging conditions. In practice, parameters like AQI, airflow, wind velocity and so on need to be taken into consideration to get the optimal value for $\varepsilon_1$ or $\varepsilon_2$.

5.2. Analysis of contrast of the targets in far-field scene

In order to evaluate the dehazing results of the far-field targets, the gray value of target and background of the left building under construction in the original images are analyzed. The regularity is obvious, the contrast of the target increases with wavelength, the difference of gray value is the smallest under 451.4 nm which is 23.9%, the difference of gray value is the largest under 850.5 nm which is 42.0%.

The same target is used to analyze the contrast of the dehazed images. The regularity is the same, the contrast of the dehazed images increases with wavelength, the difference of gray value is the smallest under 451.4 nm which is 37.1%, the difference of gray value is the largest under 850.5 nm which is 64.4%.

The contrast of images under different wavelengths have tremendous increases after the dehazing process which means the method is applicable to 451.4 nm–850.5 nm spectral channels. Spectral band has a huge influence on both the original and the dehazed images, the longer wavelength the better contrast, the statistics of the image contrast under different wavelengths is shown in Fig. 7.
5.3. Analysis of resolution of the targets in near-field scene

In order to evaluate the dehazing result of the near-field targets, an area of 160 × 140 which starts from row number 570 and column number 210 is separated from the image, the smoothness of its histogram is obtained by comparing the dynamic range of gray values and maximum pixel numbers. From 551.2 nm to 850.5 nm, the dynamic range of histogram of the dehazed images are increasing with wavelength which is shown in Fig. 8(a), the maximum pixel numbers are decreasing with wavelength which is shown in Fig. 8(b). The histograms are smoother after the dehazing process which means the dehazed images have more detailed information, but the images under 451.4 nm fail to comply with the above law due to blurry. A conclusion can be made that: the dehazing process can make a great enhancement for the targets in the near-field scene, for images with certain clarity, the longer wavelength the better.

6. Conclusions

(1) A new dehazing method based on subdivision of spectral channels is proposed, the dehazing results under 451.4 nm–850.5 nm are analyzed by comparison of histograms and horizontal line plots.

(2) Conclusions are made from the data analysis: our dehazing method can effectively enhance the image quality of both the far-field and the near-field scenes; wavelength has a huge impact on the image contrast of the far-field targets, the longer the better, the dehazed image under 850.5 nm has the greatest contrast; the resolution of the near-field targets is also highly related with wavelength, the longer the higher, dehazed image under higher spectral channel has richer detailed information.

(3) Wavelength also has a huge impact on the quality of the original images, the longer wavelength the better contrast, light under higher spectral channel has better ability to penetrate the haze particles.

(4) The optimum value for the bias factor $\varepsilon_1$ and the correction factor $\varepsilon_2$ are related with wavelength, the value of $\varepsilon_1$ is higher under visible channels than near-infrared channels, the value of $\varepsilon_2$ grows with wavelength, the regularities can be used to predict $\varepsilon_1$ and $\varepsilon_2$ in practice.

The method introduced in this paper makes a breakthrough by expending the polarimetric dehazing technique from single-channel’s visible image to 451.4 nm–850.5 nm spectral channels’ visible and near infrared images, an analysis of regularity of the dehazing process is made to test the method. Our method puts forward a new way to guarantee the use of imaging spectrometer under hazy weather, pushes forward the development of polarimetric spectral imaging technology and provides new ideas for image dehazing.

Acknowledgements

This work was supported by the National High Technology Research and Development Program of China under Grant 20137031071B and the National Natural Science Foundation of China under Grant 61275149.

References
