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短文 Short Note

A Destriping and Enhancing Technique for EROS Remote Sensing Imagery

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ABSTRACT

A novel technique is presented for destriping and enhancing Earth Resources Observation Systems (EROS) remote sensing imagery. In this paper, we develop a destriping algorithm based on the method of one-dimensional Discrete Fourier Transform (*DFT*). The basic spatial frequency composition of the degradation is determined by a simple one-dimensional accumulation in the frequency domain. After destriping, based on Laplacian and Gaussian filtering, a modified image enhancement approach is proposed to reduce the noise and to enhance the quality of the restored image for further applications. Experimental results demonstrate that the proposed method can effectively destripe and enhance the EROS remote sensing imagery.

Keywords: remote sensing imagery, destriping, discrete Fourier transform, one-dimensional accumulation

針對 EROS 遙測影像的一種去除條紋雜訊與影像增強方法

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摘　要

我們提出一種新穎的方法來消除 EROS 影像中的條紋雜訊，同時也對於影像品質提出增強的方法。為了達到有效解決而實際運用時速度要快的要求下，針對 EROS 影像的特性，我們利用一維離散傅立葉轉換(*DFT*)去轉換 EROS 影像，在轉換後的頻率域中去統計出條紋雜訊明顯的基頻，去掉這些基頻以降低條紋雜訊對影像的干擾。在影像去除條紋雜訊後，我們以一個 Laplacian 高頻銳化及 Gaussian 低頻平滑的改良型 Unsharping 濾波器，來增強影像品質。實驗結果證明了上述的技術的確能夠提昇 EROS 的影像品質，以利後續的判讀作業。

關鍵字：遙測影像、去除條紋雜訊、離散傅立葉轉換、一維空間累積計算

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I. INTRODUCTION

The world commercial services for space high-resolution imagery market faced fast growth during the last few years. Several attempts were made by different companies to provide services of high-resolution satellite images. Space Imaging Inc. had successfully launched IKONOS-2 with 1.0 meter resolution on September 24, 1999 [1]. The EROS (Earth Resources Observation System) program conducted by ImageSat International N.V. intends to operate a constellation of 8 commercial imaging satellites in LEO (Low Earth Orbit). The first satellite, EROS-A1, was successfully launched by a Russian START-1 launcher on December 5, 2000, and is presently successfully operating with 1.8 meter to 1.0-meter resolution [2]. EarthWatch Inc. successfully launched its QuickBird satellite with 0.6 meter resolution on the Boeing Delta II launch vehicle on October 18, 2001 [3].

However, uncalibrated sensors that introduce horizontal or vertical stripes across the image data sets occasionally degrade satellite data. The striping problems resulted on Landsat Multi-Spectral Scanner (MSS) and Thematic Mapper (TM) images and other satellite images had been discussed and there are several schemes for removing the stripes and compensating the resulting visual degradation in the data [4-16]. Regarding these methods, they are often obtained only through much operation interaction and trial and error or by using information not normally available to the normal users. Radiometric equalization techniques have been applied primarily to remove nonperiodic striping in image data [7]. In these techniques, a simple gain and bias model is developed for all detectors and then used for compensation. The nonlinearity in sensor variations is not considered by this method. The Karhunen-Loeve transformation or the principal components analysis has been used to remove noisy scan lines from TM images [9]. After the principal components are obtained, the noisy higher order components are simply set to zero and an inverse transformation is performed. However, it involves an enormous amount of computation to compute statistics and eigenvectors. In the histogram modification method [5, 6], the histogram of the noisy data is made to match a histogram of suitable reference data. This suitable reference histogram can be the global histogram of the image, from some other compatible images, or from one of the detectors considered as the reference with histogram data from other detectors matched to it. These techniques are easily implemented but can involve trial and error and inconsistent results. Although so many techniques have been proposed, they are used for multispectal imagery, the destriping technique for EROS satellite data with only one single band has not been discussed and presented yet. Some commercial software packages, such as ENVI [17] and ERDAS [18], have provided their own destriping functions for general users. However, they are only suitable for removing periodic and low-frequency stripes. Although the stripes appeared in EROS imagery are also periodic, they are high-frequency and noisy. Since the striping problem of EROS is more complicated than the other satellites mentioned above, current proposed techniques are

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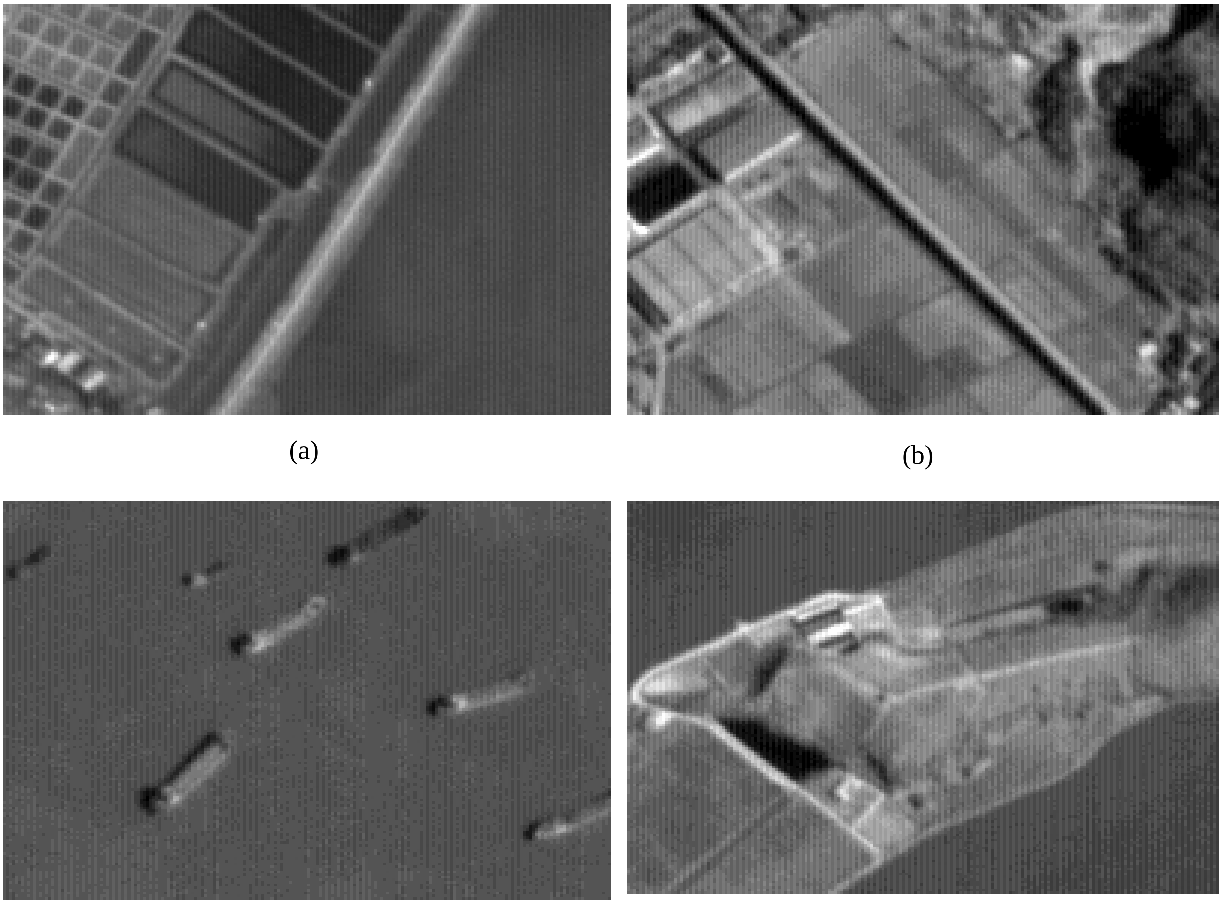
not applicable to the EROS satellite data. Therefore, it is essential to develop a technique for destriping EROS imagery resulted by imperfect calibrated detectors.

As mentioned previously, uncalibrated sensors that introduce horizontal or vertical stripes across the image data sets occasionally degrade satellite data. Since those horizontal or vertical stripes in the spatial domain are periodic noises, they will result in symmetric peak values in the frequency domain. As such, for the case of vertical stripes, they will appear in the 2-D power spectrum showing peak components on the horizontal axis (due to vertical stripes) and other peak components as well. Attempts have been made to zero the problematic peak components in the power spectrum and then inversely transform the data to remove the noise. However, this method involves careful selection of problematic components by the operator. Moreover, in the presence of other noise in the image, these components are often obscured and difficult to detect. In the imaging process of the EROS satellite, vertical and periodic stripes with a certain spatial frequency are formed across the image data sets as shown in Fig.1. To highlight the striping effect, the image has been enlarged by 150 times.



(a) (b)

(c) (d)

Fig. 1. Four sample EROS images with stripes.

In this paper, we develop a novel destriping algorithm based on the method of one-dimensional Discrete Fourier Transform (*DFT*). The basic spatial frequency composition of the degradation is determined by a simple one-dimensional accumulation in the frequency domain. As such, the frequency component of stripes can be detected and removed by setting its value to zero. After the inverse *DFT*, the uncontaminated original image is restored. After destriping, based on Laplacian and Gaussian filtering, an image enhancement method is proposed to reduce the noise and enhance the quality of the restored image for further applications. Experimental results for destriping EROS remote sensing imagery are demonstrated in this paper to show the robustness of proposed approaches.

The remaining of this article is organized as follows. Sec. II describes the proposed destriping method used in this work. The experimental results are demonstrated and the destriping performance achieved by our method is evaluated in Sec. III, prior to conclusions in Sec. IV.

II. METHODS

A. The destriping approach

The Discrete Fourier Transform (*DFT*) is used to decompose an image into its sine and cosine components [19]. *DFT* can be used in a wide range of applications, such as image analysis, image filtering, image reconstruction and image compression. In the Fourier domain image, each point represents a particular frequency component contained in the spatial domain image. In this paper, we use it to detect the specific stripe frequencies in EROS images in which stripes are appeared in a periodic form. In the frequency domain, the distance of the point to the center can be explained as follows: the maximum frequency, $f_{\max}$, which can be represented in the spatial domain as one pixel wide stripes. The maximum frequency can be given by

$$f_{\max} = \frac{1}{1\ pixel} \tag{1}$$

in which a pixel is the minimum sampling point in the image. Thus, the points in the Fourier image are halfway between the center and the edge of the image, i.e. the represented frequency is half of the maximum and represented by

$$f = \frac{1}{2\ pixel} = \frac{f_{\max}}{2} \tag{2}$$

The approach used to detect the stripe frequency is to accumulate the one-dimensional *DFT*s calculated from each row. Suppose that the size of the image $f(x,y)$ is $M \times N$. The *DFT*s are calculated row-by-row from the top to the bottom of the image. The results are accumulated into one accumulated vector, $F_A(u)$. This accumulation process can be represented by

$$F_y(u) = \frac{1}{M}\sum_{x=0}^{M-1} f(x,y)e^{-j2\pi ux/M} \tag{3}$$

where $y = 0, 1, 2, \ldots, N-1$ and

$$F_A(u) = \frac{1}{N}\sum_{y=0}^{N-1} F_y(u) \tag{4}$$

in which $u = 0, 1, 2, \ldots, M-1$. The accumulated power spectrum, $P_A(u)$, can be given by

$$P_A(u) = |F_A(u)|^2 \tag{5}$$

In the accumulated power spectrum, the frequency components of non-periodic signals are neutralized to small values; on the other hand, the frequency components of the periodic signals are accumulated to peak values. Therefore, except for the highest peak value resulted by the zero frequency, the second highest peak value can be detected if there exist vertical stripes with a fixed frequency spread around the whole image. Suppose that, in $P_A(u)$, the detected stripe frequency is u_n, then, the stripe noise can be removed by setting its frequency value, $F_y(u_n)$, in the *DFT* of each row to zero. The destriped image, $\hat{f}(x,y)$, can be restored by the inverse *DFT* operation as

$$\hat{f}(x,y) = \sum_{u=0}^{M-1} F_y(u) e^{j2\pi ux/M} \tag{6}$$

in which $y = 0, 1, 2, \ldots, N$ and $F_y(u) = 0$ for $u = u_n$.

B. The enhancing approach

Although the image contaminated by stripes can be restored by Eq. (6) and a satisfied result can be achieved, the image quality may not be good enough for further applications if there exist other noises in the original image. This case occurs in EROS imagery. Therefore, for removing noise and image enhancement, we propose an image enhancement approach as shown in Fig. 2 by excluding the destriping block.

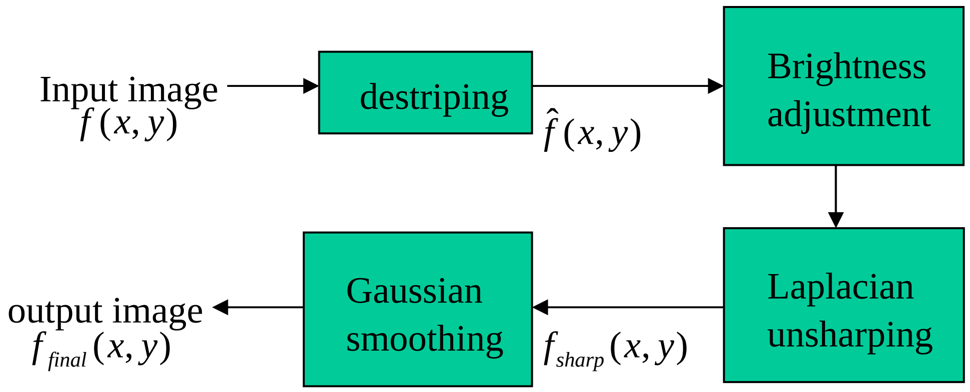


Fig. 2. Proposed destriping and image enhancement approach.

The image enhancement approach starts from a procedure of brightness adjustment to adjust the intensity value of each pixel in the image. For remote sensing imagery, the overall image brightness is darker than those of normal images. To visualize the image details, the usual way is to increase the overall brightness level of the whole image. However, the brightness is always overexposed after adjustment and the bright details are lost. To solve this problem, the procedure of brightness adjustment is proposed to automatically adjust the intensity value of each pixel and preserve the details in the bright and the dark end of the histogram. The first step is to calculate the mean intensity value of the destriped image. The second step is to compute the offset value that is to be added into each pixel value. The offset value is obtained by subtracting the mean intensity value from a certain value (110). The purpose of this addition is to shift the distribution of all pixel values to the center (gray value=128) of the histogram. Therefore, the details in the bright and the dark end of the histogram are manifested.

After the procedure of brightness adjustment, the image is processed by applying a Laplacian unsharp filter [19] followed by a Gaussian smoothing filter [19]. The operation of a general Laplacian unsharp filter is shown in Fig. 2 represented by a Laplacian unsharping block. The unsharp filter is a simple sharpening operator that derives its name from the fact that it enhances edges (and other high frequency components in an image) via a procedure that subtracts an unsharp, or smoothed, version of an image from the original image. The unsharp filtering technique is commonly used in the photographic and printing industries for crispening edges. A common way of implementing the unsharp mask is using the negative Laplacian operator to extract the highpass information directly. This filter can be represented by

$$f_{sharp}(x,y) = \hat{f}(x,y) + \hat{f}_{-Laplacian}(x,y) \quad (7)$$

in which $\hat{f}(x,y)$ stands for the destriped image, $\hat{f}_{-Laplacian}(x,y)$ is the resulted image of $\hat{f}(x,y)$ processed by a Laplacian unsharp filter, and $f_{sharp}(x,y)$ is the sharpened image of $\hat{f}(x,y)$. Unlike the general unsharp filters needed to specify the size of the filter masks, in this work, we fix the filter size to 3×3 for the purpose of automatic processing. The 3×3 unsharp filter used is shown in Fig. 4 (a).

After the operation of the Laplacian unsharp filter, to remove unwanted noise pixels, the image is processed by a Gaussian smoothing filter. The Gaussian smoothing operator is a two-dimensional (2-D) convolution operator for noise reduction of an image corrupted by the Gaussian noise. In 2-D space, an isotropic (i.e. circularly symmetric) Gaussian has the form:

$$G(x,y) = \frac{1}{2\pi\sigma^2} e^{-\frac{x^2+y^2}{2\sigma^2}} \quad (8)$$

in which σ is the standard deviation of the distribution. The effect of Gaussian smoothing is to blur an image, in a similar fashion to the mean filter. The degree of smoothing is determined by the standard deviation of the Gaussian. Since the Gaussian filter here is used for noise reduction, the selected standard deviation should be small. In theory, the Gaussian distribution is non-zero everywhere, which would require an infinitely large convolution kernel. But in practice, it is effectively zero more than about three standard deviations from the mean, and so we can truncate the kernel at this point.

For practical applications, the final resulted image, $f_{final}(x,y)$, processed by Gaussian smoothing operator can be given by

$$f_{final}(x,y)=\frac{\sum_{s=-a}^{a}\sum_{t=-b}^{b}G(s,t)\,f_{sharp}(x+s,y+t)}{\sum_{s=-a}^{a}\sum_{t=-b}^{b}G(s,t)} \quad (9)$$

in which $G(s,t)$ stands for a convolution mask of Gaussian smoothing operator with a size $(2a+1)\times(2b+1)$. In this work, a 3x3 Gaussian smoothing operator is used and shown in Fig. 4 (b) in which $a=b=1$.

In this work, the new destriping algorithm presented is based on the Fourier domain power spectrum of the image to be processed. It is fast and requires no operator intervention. The frequency domain composition of the striping can be determined from an accumulation of the one-dimensional power spectrum of the image. As such, the frequency component of stripes can be removed by setting its value to zero. After the inverse *DFT*, the uncontaminated original image is restored. Following the detriping process, based on Laplacian and Gaussian filtering, an image enhancement method is proposed to reduce the noise and enhance the quality of the restored image for further applications. At first, a method of automatic pixel intensity adjustment is used to manifest the image details in the bright and dark side of the histogram. Then, a modified Laplacian unsharp filter is used to reduce the noise and enhance the quality of the restored image. After the processing of the Laplacian unsharp filter, the image is further smoothed by a Gaussian smoothing filter to remove the unwanted noise pixels. A detailed flowchart of the whole process is shown in Fig. 2. Experimental results for destriping EROS remote sensing imagery are shown in next section to demonstrate the robustness of proposed approaches.

To evaluate the process results, a signal-to-noise-ratio (*SNR*) criterion is adopted in this work. To estimate the noise component from the EROS data, we use a "shift difference" approach. This approach assumes that each pixel contains both signal and noise and, in doing so, adjacent pixels contain the same signal, but a different noise. The "shift difference" is performed on the data by differencing adjacent pixels to the right and above of each pixel and averaging the results to obtain the "noise" value to assign to the pixel being processed. The SNR criterion is defined by

$$SNR=\frac{A[f(x,y)^2]}{A[n(x,y)^2]} \quad (10)$$

where $A[\bullet]$ is the average operator. Since the optimal noise estimation is derived from the shift-difference statistics of a homogeneous area rather than the entire image, therefore, $A[n(x,y)^2]$ is the average noise energy of a selected homogeneous area and $A[f(x,y)^2]$ is the average energy of the entire image.

III. EXPERIMENTAL RESULTS

It was mentioned earlier that specific components dominate the frequency power spectrum if periodic background noise is presented in an image. By observing the EROS imagery, the stripes contaminate the images in every other pixel in the vertical direction. Four examples of the EROS images are shown in Fig. 1. Therefore, for every row of the image, in the power spectrum of one-dimensional *DFT*, the stripe frequency has achieved the maximum frequency given by Eq. (1). This can be shown in Fig. 3.

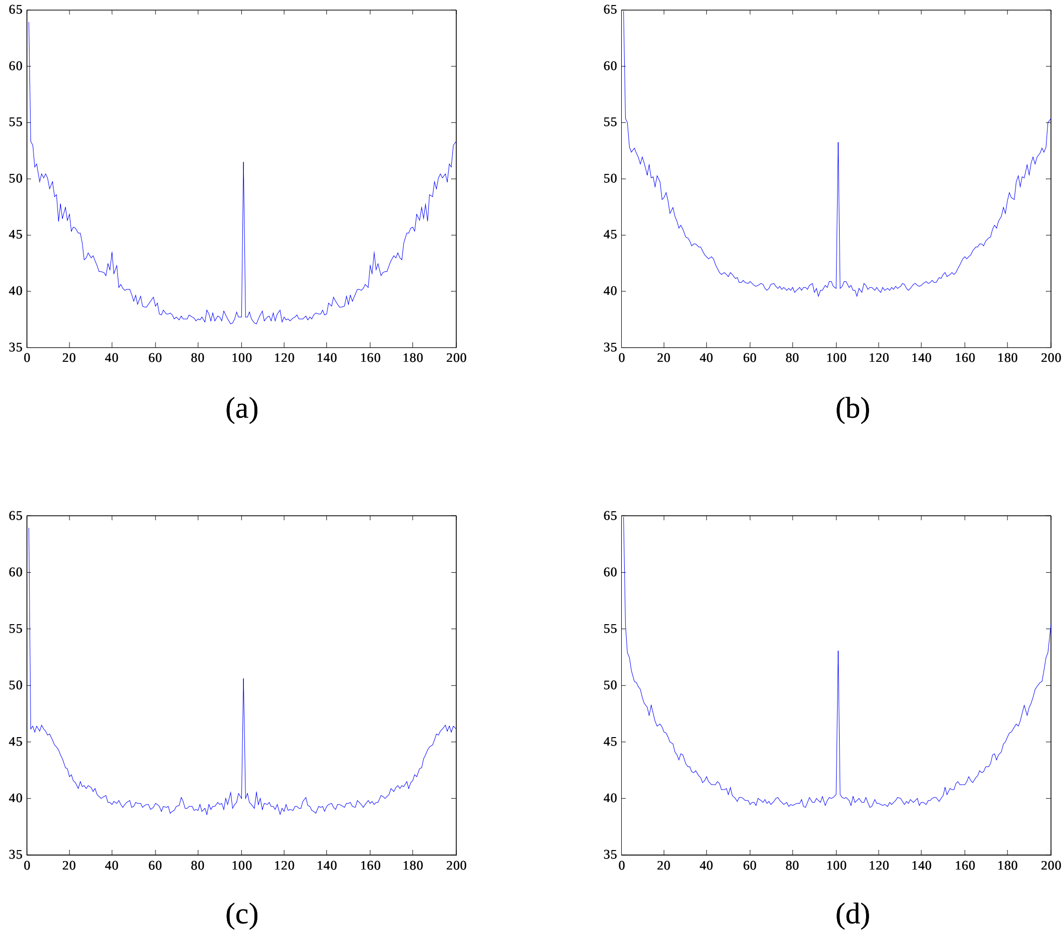


Fig. 3. Corresponding one-dimensional accumulated power spectrums of the 4 images in Fig. 1.

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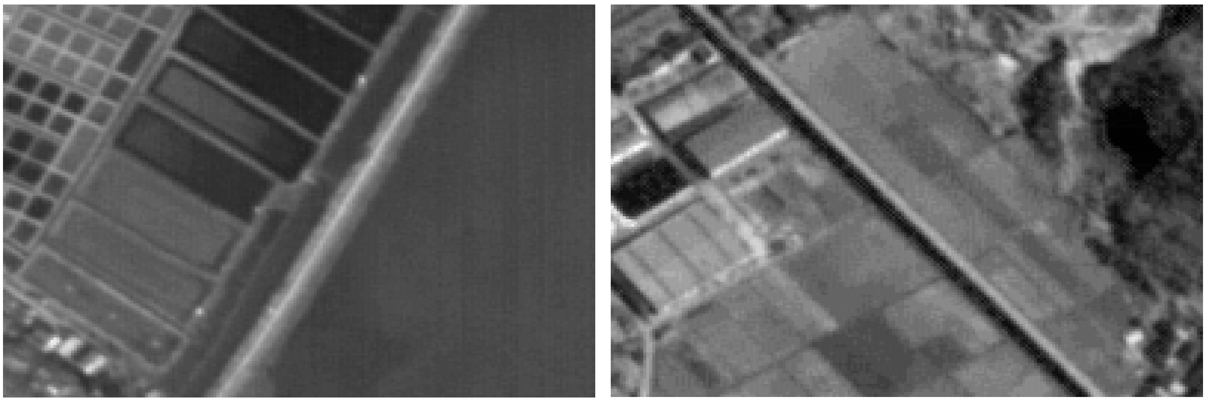
0	-1	0
-1	4	-1
0	-1	0

(a)

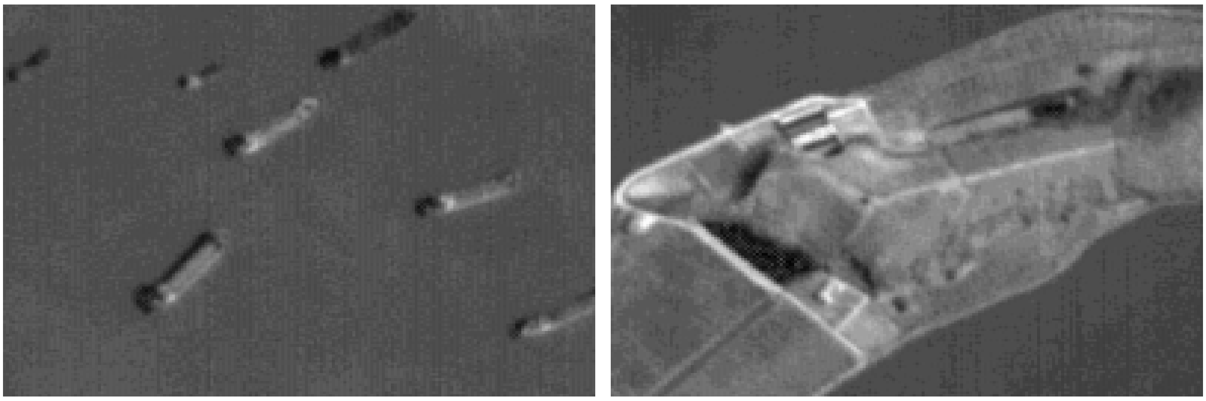
1/16	1/8	1/16
1/8	1/4	1/8
1/16	1/8	1/16

(b)

Fig. 4. Two 3×3 filter masks used in this work. (a) The Laplacian unsharp mask, (b) The Gaussian smoothing mask.



(a) (b)

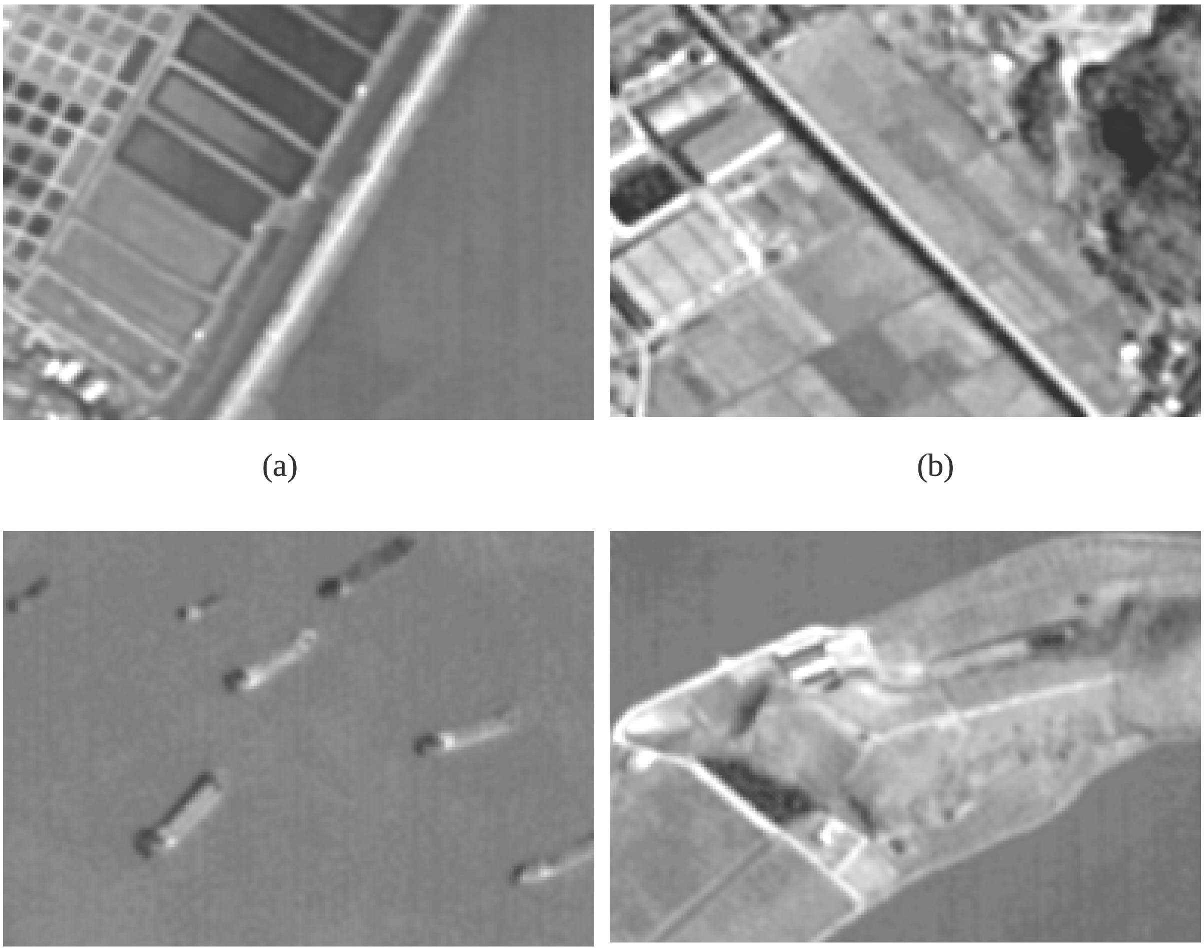


(c) (d)

Fig. 5. Corresponding destriped version of the 4 images in Fig.1 processed by using the proposed approach.

The destriping procedure can be achieved by setting the maximum frequency value to zero in the frequency domain. The restored image can be obtained by the inverse one-dimensional DFT row-by-row from the top to the bottom of the image as shown in Eq. (6). However, to reduce the computation cost, instead of computing *DFT* directly, Fast Fourier Transform (*FFT*) [19] is commonly used. *FFT* can be used to reduce the computation time from $O(M^2)$ to $O(M\log_2 M)$. The destriped image of Fig. 1 is shown in Fig. 5.

Fig. 5 shows that the stripe effect is greatly removed by this destriping procedure. After the application of the destriping procedure, the image enhancement approach is applied to the image. The resulted image by the proposed destriping and image enhancement approach of Fig. 2 is shown in Fig. 6.

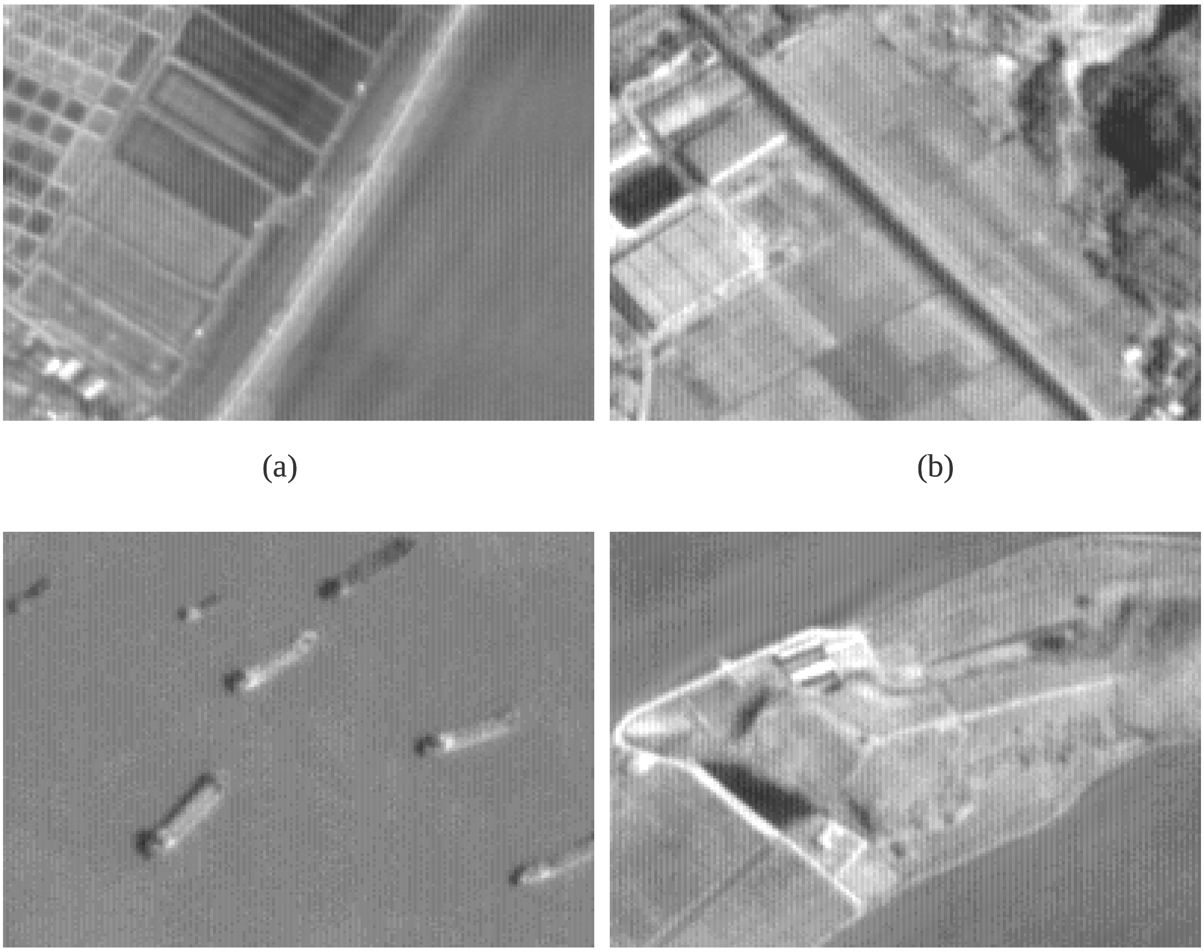


(a) (b)

(c) (d)

Fig. 6. Details preserving and noise removal for the 4 images in Fig. 4 using proposed method in Fig. 2 for image enhancement.

In Fig. 6, most of the noises in Fig. 5 have been removed from the image. Since the Laplacian unsharp filter is used, image details are still preserved after the noises had been removed. Also, we have applied the proposed approach to several EROS imageries contaminated by vertical stripes and promising results have been obtained. For comparison purposes, the destriping result processed by using ERDAS for Fig. 1 is shown in Fig. 7.



(a) (b) (c) (d)

Fig. 7. Corresponding destriped version of the 4 images in Fig. 1 processed by using ERDAS.

Since ENVI and ERDAS refer to the same techniques [11,13] for destriping the contaminated satellite data, we use ERDAS as an example to compare with our approaches. When destriping the data, ERDAS calculates the mean of every n-th line and normalizes each line to its respective mean. This type of striping is often seen in Landsat MSS data (every 6th line) and less commonly, in Landsat TM data (every 16th line). Comparing Fig. 6 to Fig. 7, the destriped image by using ERDAS can not achieve better results than our proposed approach. The main reason is that ERDAS or ENVI can solve only pure periodic striping problems, but not the striping problems appeared in EROS imagery. Meanwhile, the techniques used in ERDAS or ENVI cannot remove the stripes contaminating the images in every other pixel in the vertical direction in EROS imagery. Therefore, experimental results have demonstrated that our proposed approach is suitable to solve the vertical striping problem occurred in the EROS imagery. Furthermore the corresponding *SNR* values for Figs. 5, 6 and 7 are shown in Table 1 for comparing the performance of the propose approach with the method in ERDAS and ENVI. As shown in Table 1, the four test images in Fig. 6 are having the highest SNR values. That is, the proposed approach for destriping and image enhancement has achieved the best performance.

Table 1. The *SNR* values for the four test images in Figs. 5, 6 and 7.

SNR values for four test images				
Image	**(a)**	**(b)**	**(c)**	**(d)**
Fig. 5	**1139:1**	**1182:1**	**976:1**	**1534:1**
Fig. 6	**1346:1**	**1381:1**	**1195:1**	**1726:1**
Fig. 7	**874:1**	**795:1**	**789:1**	**966:1**

IV. CONCLUSIONS

To destripe Earth Resources Observation Systems (EROS) remote sensing imagery resulted by imperfect calibrated detectors, we propose here the use of a simple one-dimensional accumulation of the power spectrum in the frequency domain. The processing steps are as follows.

(A1)For each striped EROS image, the Discrete Fourier Transform (DFT) of each row is calculated. The results are accumulated into one accumulated vector by Eq. (3).

(A2)The stripe frequency achieved the maximum frequency can be detected from Eq. (5). Then, the strip noise can be removed by setting its frequency value in the power spectrum of each row to zero.

(A3)The destriped image can be restored by Eq. (6).

(A4)To manifest the image details in the bright and dark side of the histogram, a method of automatic pixel intensity adjustment is used.

(A5)For removing noise and image enhancement, we apply a modified Laplacian unsharp filter followed by a Gaussian smoothing filter to the destriped image.

We have found that the above algorithm works well on the EROS imagery contaminated by vertical stripes and unwanted noises. The method is easily implemented and computationally simple and requires no trial and error to yield a promising result. Before using the EROS imagery for further applications, this is an important preprocessing step for not only removing all the noises, but also preserving the original information simultaneously. Though this paper addresses only a remote sensing example of striping, we believe that this method can be equally applicable to several other applications in which striping or other periodic noise poses a problem. Although we have obtained promising results in several EROS images, the more advanced destriping techniques and a larger EROS dataset will be conducted and tested in our future research.

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