Destriping of Landsat MSS Images by Filtering Techniques

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ABSTRACT: The removal of striping noise encountered in the Landsat Multispectral Scanner (MSS) images can be generally done by using frequency filtering techniques. Frequency domain filtering has, however, several problems, such as storage limitation of data required for fast Fourier transforms, ringing artifacts appearing at high-intensity discontinuities, and edge effects between adjacent filtered data sets. One way for circumventing the above difficulties is to design a spatial filter to convolve with the images. Because it is known that the striping always appears at frequencies of 1/6, 1/3, and 1/2 cycles per line, it is possible to design a simple one-dimensional spatial filter to take advantage of this *a priori* knowledge to cope with the above problems. The desired filter is the type of finite impulse response which can be designed by a linear programming and Remez's exchange algorithm coupled with an adaptive technique. In addition, a four-step spatial filtering technique with an appropriate adaptive approach is also presented which may be particularly useful for geometrically rectified MSS images.

INTRODUCTION

THE STRIPING THAT OCCURS IN THE Landsat Multispectral Scanner (MSS) images generally results from a gain variation and/or offsets of multidetector sensors. It is known that there are six detectors installed in the scanner and that the striping in each spectral band results from the fact that five of the detectors have the same gain while the sixth has an offset in the gain during a single sweep (Moik, 1980). As a result of this miscalibration, every sixth line in the MSS images is visually darker than the other adjacent five lines. In particular, the effects produced by these striping patterns are more pronounced in bright homogeneous areas. The ocurrence of the horizontal striping patterns appears as a periodical noise and could significantly degrade image quality and image interpretation.

A simple cosmetic cleanup can be designed by replacing the values of the pixels in each striping line with the average of the gray levels obtained from the adjacent pixels above and below. However, the disadvantage of doing this is that it degrades the vertical resolution of that line to a certain extent (Billingsley, 1983). One way to improve this degradation is to design a spatial filter and convolve with the images. Because it is known that the striping always appears at frequencies of 1/6, 1/3, and 1/2 cycles per line, it is possible to design a spatial filter based on these desired frequency responses.

Over the past years several different methods have been proposed for destriping, e.g., histogram modification (Horn and Woodham, 1979), principal components analysis (Srinivasan, 1986), and filtering techniques (e.g., Cannon *et al.*, 1983; Srinivasan *et al.*, 1988; Pan, 1989). In this paper, we are interested in the filtering techniques which can be used in either the spatial or frequency domains.

In general, there are two approaches to filtering images. One is to transfer images from the spatial domain to the frequency domain after implementation of a Fourier transformation, then reject the striping-related spikes in the frequency domain, and, finally, transfer the resulting images back again to the spatial domain. Another alternative is to design a suitable spatial filter and convolve it with images directly in the spatial domain.

Despite the fact that the frequency filtering can eliminate the striping lines, it still suffers from several common problems such as a large amount of data storage needed for a fast Fourier transform, ringing artifacts resulting from high-intensity discontinuities, and edge effects between adjacent filtered data sets. In order to cope with the above problems, we use a one-dimensional spatial filter with specifications to reject striping-related frequencies. Then we apply an adaptive technique to reduce the ringing artifacts resulting from high intensity discontinuities in the image. The spatial filter designed in this approach is a finite impulse response (FIR) filter based on two techniques, a linear programming method and Remez's exchange algorithm. A relative performance is also studied. To further remove ringing artifacts, an adaptive technique is used with the filter. The idea is to adapt gray differences between the filtered pixels and their above and below neighbors. If the difference is greater than a prescribed threshold, the gray level of the corresponding pixel is updated; otherwise, the gray level remains unchanged. After all necessary gray levels are adjusted, a convolution is then applied to complete the destriping process.

This paper is organized as follows. We first examine previously used frequency filtering techniques with Landsat imagery and point out some potential relevant issues encountered in these approaches. We then present a spatial FIR filter to destrip the images. Two design methods for such an FIR filter are implemented and an adaptive method is also suggested to be incorporated into the destriping to reduce the ringing artifacts appearing at high-intensity discontinuities. Furthermore, a four-step spatial filtering technique is proposed to take care of the striping problems, which may be particularly useful for some geometrically rectified MSS images. Finally, a brief conclusion is included.

TWO-DIMENSIONAL POWER SPECTRUM ANALYSIS

In general, a signal can be represented by either a time function or a frequency function where the relationship is demonstrated by a Fourier transform. Which form is appropriate for representing a signal depends upon different applications. The techniques using the power spectrum of a signal in the frequency domain to identify the striping-related frequencies have been widely adopted and studied (Billingsley, 1983; Srinivasan *et al.*, 1988; Pan, 1989). More importantly, from a theoretical point of view periodic or almost periodic noises can be generally

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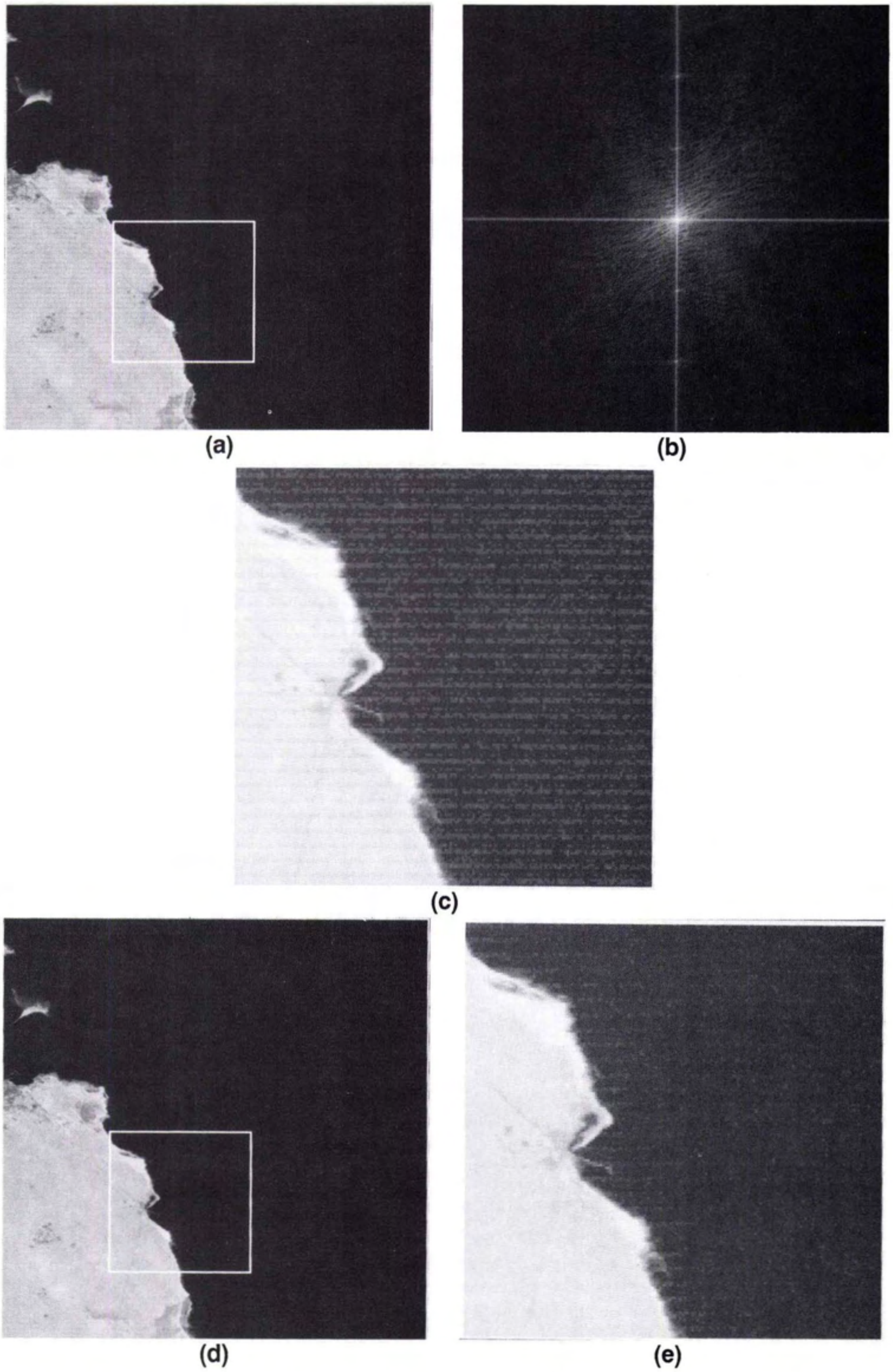
modeled by power spectra in terms of delta functions (Bendat and Piersol, 1971).

For example, Figures 1a and 1b show a striped MSS image and its power spectrum. The dark area in Figure 1a is water and the bright area is land. Figure 1c also shows a three-time enlarged portion of the block in Figure 1a. The spikes in the central vertical axis of the power spectrum in Figure 1b indicate that the horizontal periodic nature of the striping occurs at frequencies 1/6, 1/3, and 1/2 cycles per line.

An easy way to remove these spikes is to design a two-di-



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

FIG. 1. (a) A multispectral scanner (MSS) image with striping. (b) The associated power spectrum. (c) A detail from the block in (a) after three-time enlargement. (d) The filtered image based on the power spectrum analysis. (e) The three-time enlarged and linear stretched part from the block in (d). Apparently, most of stripings have been removed, but the ringing artifacts appeared along land-water boundary.

mensional Gaussian notch filter in the frequency domain (u, v), which is defined by (Pan, 1989)

$$H(u, v) = 1 - e^{r^2/2\sigma^2} \quad (1)$$

where $r = \sqrt{(u - u')^2 + (v - v')^2}$, (u', v') is the frequency of the spike to be removed, and σ is the standard deviation of the Gaussian distribution. A problem which often arises from destriping in this way is that, when we destrip an image by setting amplitudes at these frequencies to zero, some desired and useful information at the same striping frequencies is also unfortunately removed from the original image, and in the mean time certain ringing artifacts may occur as well.

As an example, the image in Figure 1d was processed by the frequency filtering described above and Figure 1e is a three-time enlarged and linear stretched portion of the block in Figure 1d. Apparently, the striping pattern was reduced. Unfortunately, some ringing artifacts appeared along the water-land boundary which resulted from the high discontinuity of intensity in the image. The occurrence of these ringing artifacts could be treated as artificial light and dark patterns which could also affect edge detection for post-processing.

Because the input image data applied to a discrete Fourier transform is assumed to be periodic, the effect of intensity discontinuity on four edges could also produce some ringing phenomena, called "edge effect." In order to reduce edge effect, it is useful to implement a window (such as Hamming window) function to smooth the data at the edges or expand the data by linear extrapolation to a larger size before using a discrete Fourier transform; then, truncate the padded data after filtering is done. However, these approaches will also create some mosaicking problems where two adjacent filtered spatial data sets may not be continuous at their joint edges.

A method which has been studied recently to alleviate this problem is to design a spatial filter to generate desired frequency responses and convolve this filter with the image. In what follows, we describe how to design such a spatial filter.

ONE-DIMENSIONAL SPATIAL FILTERING

With this phenomenon the striping usually appears in a horizontal direction. This enables us to deal with two-dimensional filtering problems by considering one-dimensional filters. A spatial filter was proposed and designed which satisfied the desired frequency specifications, i.e., a filter which can generate the same frequency responses as those defined in frequency filtering. We employed an FIR filter because it could be designed to possess a linear phase and is also easily implemented. FIR filter design will be our main focus in this paper.

One of the commonly used methods to design an FIR filter is to cast an FIR filter design problem as a Chebyshev approximation problem so that the well-known Parks-McClellan algorithm (McClellan *et al.*, 1973) can be applied to finding an optimum set of filter impulse responses to meet the desired specifications. More precisely, let $H_o(u)$ be the desired function of frequencey in the range of interest $[B_p, B_s]$ and $2N + 1$ be the desired filter length. Assume that $\underline{h} = [h(-N), h(-N+1), \ldots, h(0), \ldots, h(N-1), h(N)]$ is the impulse responses of the designed filter and $H_{\underline{h}}(u)$ is its corresponding frequency response which is defined by

$$H_{\underline{h}}(u) = \sum_{n=-N}^{N} h(n)\cos(nu). \quad (2)$$

Let $r(\underline{h}, u)$ be the error function to measure the difference defined by $|H_{\underline{h}}(u) - H_o(u)|$ and the Chebyshev norm or $r(\underline{h})$ be defined by

$$\|r(\underline{h})\| = \max_{u\in[B_p, B_s]} |r(\underline{h}, u)|. \quad (3)$$

As a consequence, the design problem is reduced to finding an optimum set of coefficients $\{h^*(n)\}_{n=-N}^{N}$ which minimizes the Chebyshev norm of the error $\|r(\underline{h})\|$ between the desired frequency response $H_o(u)$ and its approximation $H_{\underline{h}}(u)$, *viz.*, the set of $\{h^*(n)\}_{n=-N}^{N}$ is a solution to the following minimization problem:

$$\text{MInimize}_{\underline{h}} \ \|r(\underline{h})\|. \quad (4)$$

The optimum filter determined by the set of $\{h^*(n)\}_{n=-N}^{N}$ is one which satisfies our needs.

An alternative for designing an FIR filter is based on a linear programming (Lewin and Telljohann, 1984; Pan and Domingue, 1990). Although this method need not generate an optimal filter, the advantage of linear programming over the Chebyshev approximation is its easy implementation. The problem formulation of using linear programming can be described as follows:

$$\text{Minimize}_{\underline{h}} \ R(\underline{h}) \quad (5)$$

where

$$R(\underline{h}) = -|2h(0)| + \sum_{n=-N}^{N} |h(n)|e^{qn}, \quad (6)$$

h is defined as above and q is a positive constant. Before using the simplex method to minimize $R(h)$, each $|h(n)|$ must be represented by two non-negative variables, so that the objective function can be modified to be a linear function of these variables. This minimization is subject to the constraint, $|H_h(u) - H_o(u)| \leq W(u)$, where the error tolerance function $W(u)$ is chosen to be a very small value compared to $H_o(u)$.

In spite of minimizing different objective functions, these two methods can generate very close filter coefficients $\underline{h}$. The difference is that the Remez exchange algorithm produces equal-ripple oscillations between two specified frequencies and it occasionally generates negative frequency responses in the stop band; whereas the linear programming method uses an objective function and constraints composed of the spatial and frequency responses simultaneously so that the oscillation between two specified frequencies is reduced.

A major drawback in the FIR filter design is the need of a large number of the impulse responses to adequately approximate sharp-cutoff filters, which results in tremendous computing time required for convolution with images. Nevertheless, we may still use a filter with smaller length to reduce computing time at the expense of accuracy for approximation.

Figure 2a shows the profile of the central vertical axis of the power spectrum in Figure 1b, in which the spikes indicate that the horizontal periodic nature of the striping has fundamental frequencies at 1/6, 1/3, and 1/2 cycles per line. Figure 2b shows the desired frequency response and the frequency responses generated by the Remez exchange algorithm and the linear programming. The desired frequency response is based on a smoothed notch filter which sets the response to zero at those three striping-related frequencies.

Tables 1 and 2 show the filter coefficients derived by the Remez exchange algorithm and linear programming, respectively, on the basis of a one-dimensional spatial filter of length 31. Note that only half of them are listed here because it is symmetric with respect to the first (central) coefficient $h^*(0)$. The sum of all the filter weights $\{h^*(n)\}_{n=-15}^{15}$ is generally normalized to one for avoiding gray level shifting. In this example, the sum of all the filter weights is nearly the same in both methods. However, the degradation of the magnitudes of the filter coefficients obtained by the linear programming from the center of the filter to the edges is faster than that be the Remez exchange

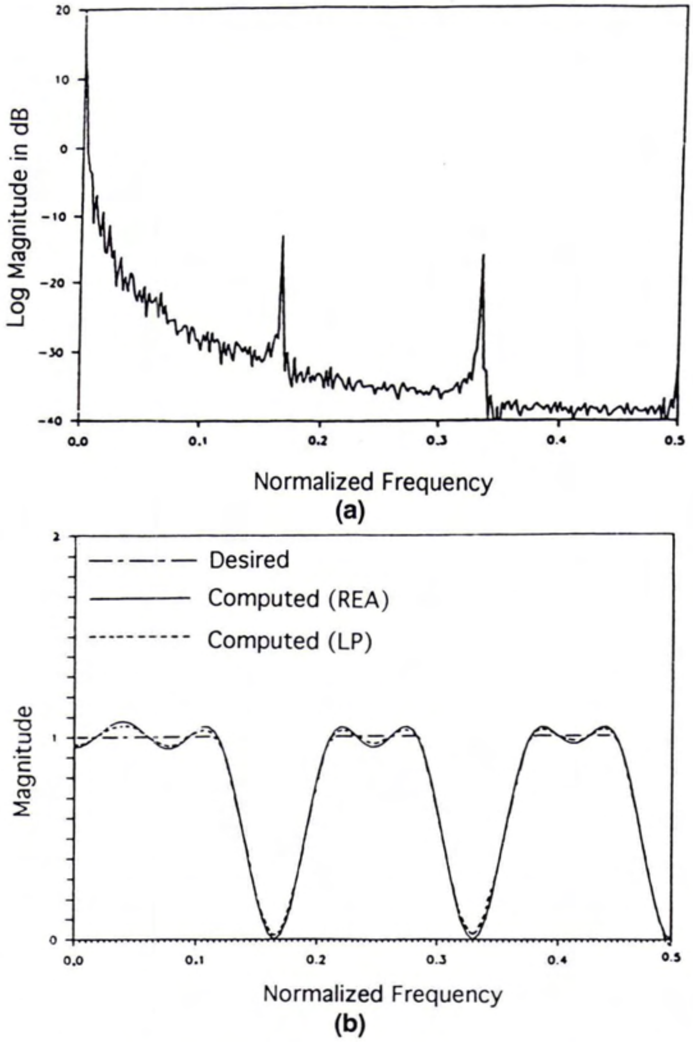


FIG. 2. (a) The central vertical axis of the power spectrum shown in Figure 1b. (b) The desired and computed frequency responses. REA is Remez exchange algorithm and LP is linear programming.

TABLE 1. THE SPATIAL FILTER COEFFICIENTS DERIVED FROM REMEZ EXCHANGE ALGORITHM.

$h(n)$	Coefficients
$n=0$	0.74549794
1	0.05204472
2	0.04865874
3	0.04936339
4	0.04138442
5	0.04322706
6	−0.19874610
7	0.03775158
8	0.03383373
9	0.02873908
10	0.01869504
11	0.01835599
12	−0.09142277
13	0.01161429
14	0.00858602
15	0.00471893

TABLE 2. THE SPATIAL FILTER COEFFICIENTS DERIVED FROM LINEAR PROGRAMMING.

$h(n)$	Coefficients
$n=0$	0.75137070
1	0.05102997
2	0.05124710
3	0.04902745
4	0.04626700
5	0.04450182
6	−0.19915300
7	0.03708376
8	0.03137173
9	0.02737051
10	0.02304267
11	0.01711373
12	−0.09744902
13	0.00843744
14	0.00623821
15	0.00268549

algorithm. The results show that the frequency response generated by the linear programming did a better job of removing the noise than that by the Remez exchange algorithm.

After the filter coefficients $\{h^*(n)\}_{n=-15}^{15}$ are generated, it can be implemented as a vertical window function which place its center at the input pixel $p(i,j)$ to do convolution: i.e.,

$$p'(i, j) = \sum_{n=-15}^{15} p(i, j + n)h^*(n) \qquad (7)$$

where $p'(i,j)$ is the filtered pixel.

Figure 3a shows the filtered image after we apply the linear programming designed spatial filter, and Figure 3b is an enlarged and linear stretched portion extracted from the filtered image to demonstrate the existence of the ringing artifacts along the water-land boundary. The designed filter basically performs the same processing as does the frequency filtering. Therefore, in order to further remove these ringing phenomina, an adaptive technique is suggested and described in the following section.

ADAPTIVE ONE-DIMENSIONAL SPATIAL FILTERING

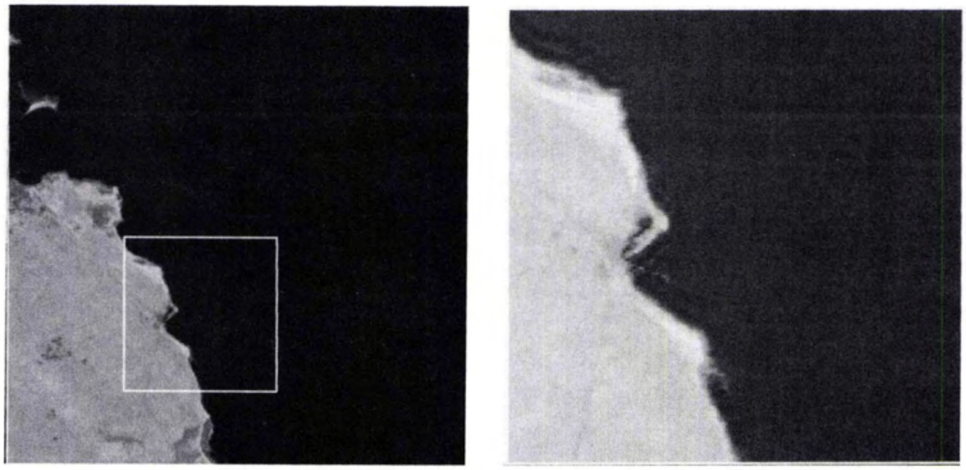
To eliminate the ringing artifacts across the boundary with high-intensity contrast, an adaptive approach is proposed for the cosmetic removal of these artifacts.

The idea is that, when a window $\{h^*(n)\}_{n=-N}^{N}$ is moving across each pixel $p(i,j)$ with $p(i,j)$ corresponding to $h^*(0)$, we compute the differences of gray levels between each pixel $p(i,j + m)$ and $p(i,j)$, using $-N \le m \le N$, $m \ne 0$. If the difference is greater than a prescribed threshold, the $p(i,j + m)$ is replaced by $p(i,j)$ in Equation 7. Some other complicated techniques were also proposed to achieve similar improvements, for example, the variable threshold zonal filtering proposed by Schwartz and Soha (1977).

Figure 4a shows the filtered image after the adaptive technique is applied to the original image (Figure 1a), and Figure 4b is an enlarged portion of it. The threshold used in this example is 15. It can be seen clearly that the ringing artifacts have been suppressed.

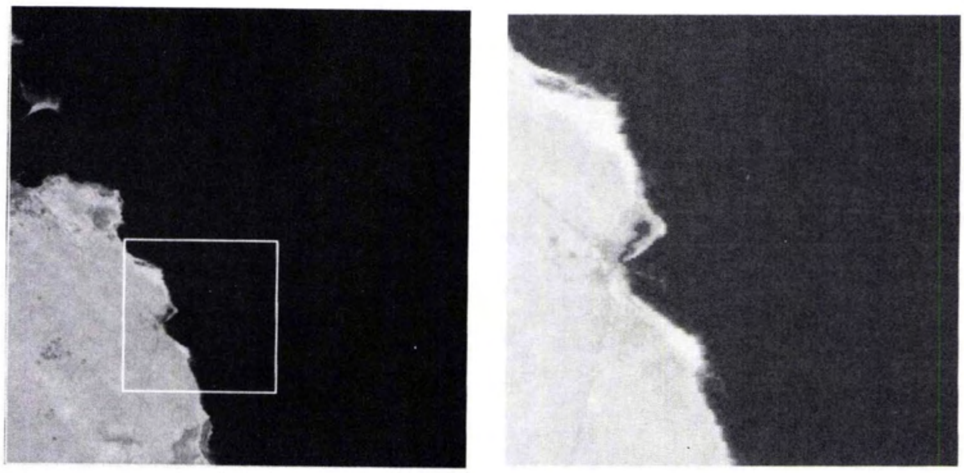
A FOUR-STEP SPATIAL FILTERING

It is often the case that the striping is not exactly horizontal after a geometric correction due to the influence of the filter and other residual errors. There could be no spikes appearing in the power spectrum as that for banding (swathing) problem in Landsat Thematic Mapper (TM) P-tape images. To resolve this



(a) (b)

FIG. 3. (a) The filtered image using the one-dimensional spatial filter designed from the linear programming. (b) The three-time enlarged and linear stretched part from the block in (a).



(a) (b)

FIG. 4. (a) The filtered image using the one-dimensional adaptive filter. (b) The three-time enlarged and linear stretched part from the block in (a). Compared with Figure 3b, the ringing artifacts along land-water boundary have been significantly reduced.

problem, Crippen (1989) proposed a simple spatial filtering routine for the cosmetic removal of banding noise. His simple routine can be modified to destriping MSS images for our purpose here.

- Step 1 : Apply a 1-line by 51-sample low-pass filter to the original image $p(i,j)$, where i and j indicate the ith line and jth sample, respectively,

$$q(i, j) = \frac{1}{51} \sum_{j=-25}^{j=25} p(i, j) \tag{8}$$

- Step 2 : Apply a 13-line by 1-sample high-pass filter to $q(i,j)$,

$$r(i, j) = q(i, j) - \frac{1}{13} \sum_{i=-6}^{i=6} q(i, j). \tag{9}$$

- Step 3 : Apply a 1-line by 31-sample low-pass filter to $r(i,j)$,

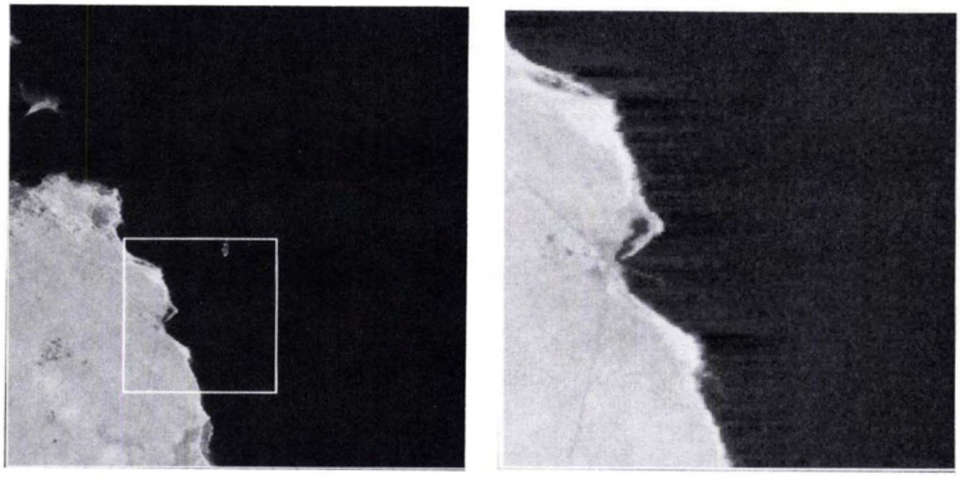
$$s(i, j) = \frac{1}{31} \sum_{j=-15}^{j=15} r(i, j). \tag{10}$$

- Step 4 : Substract $s(i,j)$ from the original image $p(i,j)$, and get the filtered image $t(i,j)$,

$$t(i, j) = p(i,j) - s(i, j). \tag{11}$$

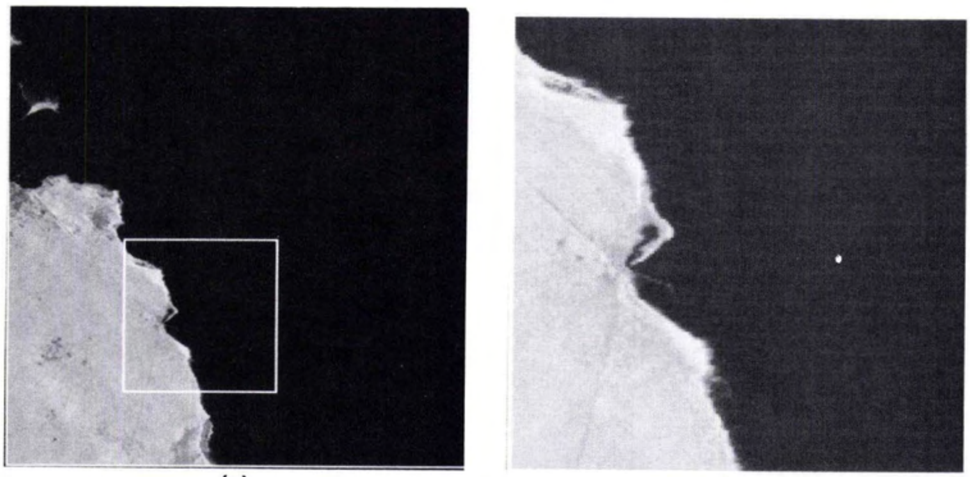
The size of the filter (1 to 51) in Step 1 was ultimately dependent upon the homogeneity of images. The size of the filter (13 by 1) used in Step 2 was associated with the number of detectors in the scanning system. It was determined by taking twice the number of detectors plus one. Figure 5a shows the image after the above four-step filtering technique was applied. Figure 5b is an enlarged and linear stretched portion of Figure 5a. As is shown, the striping noises have been reduced; however, ringing artifacts along the boundary emerged. The same problems also existed when Crippen's (1989) algorithm was applied to some TM images with high-intensity contrasts between different subjects.

In order to suppress these ringing artifacts, a similar adaptive approach used earlier was incorporated into Steps 1 and 3 of



(a) (b)

FIG. 5. (a) The filtered image using the four-step spatial filter. (b) The three-time enlarged and linear stretched part from the block in (a).



(a) (b)

FIG. 6. (a) The filtered image using the adaptive four-step spatial filter. (b) The three-time enlarged and linear stretched part from the block in (a). Compared with Figure 5b, the ringing artifacts along land-water boundary have been significantly reduced.

the four-step spatial filtering. If the difference in Steps 1 and 3 between the pixel centered in the window and a neighbor is greater than a predetermined threshold, this neighbor will not be included in the summation. The threshold used in this example was 15. The estimate of this threshold is empirically desired and data dependent. Figure 6a shows an image obtained by using the adaptive four-step spatial filtering technique, and Figure 6b is an enlarged and linear stretched portion. Once again, the adaptive approach significantly reduced the ringing artifacts.

CONCLUSIONS

Because the striping in MSS images can be regarded as a periodic noise and also identified in the power spectrum, it is possible to design an FIR filter in the spatial domain which performs the same processing as does a notch filter in the frequency domain. The desired spatial filter can be designed by either a linear programming or Remez's exchange algorithm. In order to further remove ringing artifacts from destriping, an adaptive method is also proposed.

In addition, a four-step spatial filtering technique incorporated with a similar adaptive method was tested. This technique requires only simple low- and high-pass filters, and can be useful if the striping noise is not a pure horizontal periodic signal. The tradeoff of using an adaptive approach is the increase of computational time, but the improvement in the results is demonstrable.

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