A Simple Spatial Filtering Routine for the Cosmetic Removal of Scan-Line Noise from Landsat TM P-Tape Imagery

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ABSTRACT: A simple method for the cosmetic removal of scan-line noise from geometrically corrected Landsat Thematic Mapper data is presented. The method uses only standard spatial filters and arithmetic routines that are already present on most image processing systems. Examples are provided, and the possible effects upon image signal are discussed.

INTRODUCTION

SCAN-LINE NOISE can be considerably distracting and obstructive in the manual interpretation of remotely sensed imagery. This paper presents a simple spatial filtering routine that can cosmetically remove most perceptible scan-line noise from Landsat Thematic Mapper (TM) P-tape imagery with very little perceptible effect upon image signal. P-tape data are the standard geometrically rectified product for Landsat TM. The removal of scan-line noise from P-tape imagery has been a problem primarily because the noise that is originally attributable to individual detectors becomes smeared across neighboring output image lines during the rectification process.

CAUSES OF SCAN-LINE NOISE IN TM DATA

The causes of Landsat TM scan-line noise have been described in detail elsewhere (e.g., Engel *et al.*, 1983; Fischel, 1984; Barker, 1985; Fusco *et al.*, 1985, 1986; Kieffer *et al.*, 1985; Metzler and Malila, 1985; Murphy *et al.*, 1985; Doherty and Oriol-Pibernat, 1986). Broadly grouped, they include (1) relative gain and/or offset differences among the 16 detectors within a band (causing "striping") and (2) relative gain and/or offset variations between neighboring forward (west to east) and reverse (east to west) scans of all 16 detectors (causing "banding"). The latter are primarily attributable to an imperfect response of the detectors to changing scene content and the fact that recent viewing history is a function of scan direction. For example, detector output values tend to be depressed after prolonged periods of saturation such that scans away from bright targets (clouds, snow, sand) can be significantly darker than the interleaved scans toward bright targets.

PREVIOUS METHODS OF NOISE REMOVAL

Several methods of adjusting data to suppress scan-line noise from a band image have been described previously. However, most are not applicable after data resampling, are not sensitive to local variations in noise, are computationally demanding, and/or require specialized programs that are not generally available on most image processing systems.

Prior to resampling for geometric rectification, a simple first-order adjustment can sometimes be made by equalizing the means and variances of the data from each detector. This method assumes that, for a sufficiently large scene, each detector is exposed to an equivalent radiance distribution that differs in the data only as a linear function of calibration gain and offset. Unfortunately, linearity can be a poor assumption, especially if many scene pixels are saturated. A similar method consists of equalization of the histograms for the data from each detector. This procedure can work well and largely accounts for nonlinearities, but again it is only applicable prior to data resampling and is thus not applicable to Landsat TM P-tape data. Variations of these methods have been described by Goetz *et al.* (1975), Horn and Woodham (1979), Murphy (1981), Narendra (1982), and Poros and Peterson (1985).

For some scenes, suppression of scan-line noise may be possible by use of forward and reverse principal component (PC) transformations. If, after the forward transformation, the noise is largely isolated from signal among the PCs, then it will be largely removed by setting the noisy PCs to a constant value prior to the reverse transformation back to wavebands. Note that some scan-line noise (especially banding) is likely to be correlated among wavebands and will not necessarily be relegated to the last few PCs. Drawbacks to this method are its computational requirements and, more critically, the strong possibility that signal and scan-line noise will not be well-separated among the PCs.

Scan-line noise removal can also be attempted by filtering the data in the frequency domain after implementation of a Fourier transformation (e.g., Rindfleisch *et al.*, 1971; Moik, 1980; Peli and Verly, 1983). Although this approach can work quite well, there are at least two drawbacks. First, Fourier transformations are computationally demanding and must be made both forward (to the frequency domain) and backward (to the spatial domain). Second, identification of noise in the frequency domain is highly subjective and can be difficult, requiring iterative trials. Srinivasan *et al.* (1988) describe a method that attempts to automate the identification of noise and potentially overcomes some of the difficulties.

Filtering in the spatial domain can be more straightforward and preferable if feasible and effective. One simple spatial filtering method for removal of scan-line noise is to use an along-line convolution high-pass filter. This filter is calculated for each pixel by subtracting the mean of a window (e.g., 101 samples by 1 line, centered at the pixel) from the pixel value. A constant (e.g., 128) is then added to keep all resultant values within the quantization range (e.g., 0 to 255). This filter displays only departures from local average within-line brightnesses. Although it successfully removes most scan-line noise, such a filter is typically unacceptable because it also removes most low-frequency signal (Goetz *et al.*, 1975; Gillespie, 1980).

Soha *et al.* (1976) and Algazi and Ford (1981) presented methods that adjusted entire lines such that the sequence of their mean values was low-pass filtered. This too can remove most scan-line noise but usually cannot be applied after image rectification. Also, it is not sensitive to along-line changes in banding, such as those found in some TM data.

Nathan (1966) and Rindfleisch *et al.* (1971), in enhancing vidicon-based digital camera system images of Mars, presented

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methods that adjusted each pixel by an amount equal to the difference between the local mean of that pixel's line and the local mean of several neighboring lines. Neighboring lines were weighted in direct relation to their proximity, and the number of neighboring lines used was determined subjectively. By using local means, the filters were sensitive to along-line noise variations.

METHOD AND CONCEPT

The method presented in this paper is similar to those of Nathan (1966) and Rindfleisch *et al.* (1971), but it is designed to take into account the cyclic characteristics of the Landsat TM scan-line noise. Each pixel adjustment is based upon a comparison of the local mean of that pixel's line to an unweighted local mean of those closest neighboring lines that approximately cover one full maximum across-line noise period (a forward-backward scan pair).

The routine consists of four simple steps that can be implemented with existing programs on most image processing systems. These steps are:

(1) Apply a 101-sample by 1-line low-pass (mean) filter:

$$F1_{ij} = \frac{1}{101} \sum_{k=j-50}^{j+50} F0_{ik}$$

i = line, j = sample; F0 = original image, F1 = image of along-line local means

(2) Apply a 33-line by 1-sample high-pass filter (central pixel value minus filter-window mean) to the output from step 1:

$$F2_{ij} = F1_{ij} - \frac{1}{33} \sum_{k=i-16}^{i+16} F1_{kj}$$

F2 = noise image with artifacts

(3) Apply a 31-sample by 1-line low-pass (mean) filter to the output from step 2:

$$F3_{ij} = \frac{1}{31} \sum_{k=j-15}^{j+15} F2_{ik}$$

F3 = final noise image

(4) Subtract the noise image produced in steps 1, 2, and 3 from the original image:

$$F4_{ij} = F0_{ij} - F3_{ij}$$

F4 = cleaned image

A constant (e.g., 128) is normally added in steps 2 and 4 to keep pixel values within the quantization range (e.g., 0 to 255) throughout the procedure.

The general concept is to subtract the scan-line noise after it has been isolated by a combination of filters that largely eliminate image signal. Scan-line noise is mostly of low spatial frequencies along TM P-tape image lines and is typically cyclic and of higher spatial frequencies across the lines. The 101-sample, 1-line low-pass filter largely isolates low-frequency signal plus scan-line noise from high-frequency signal. The 33-line, 1-sample high-pass filter then largely separates the relatively high frequency and cyclic scan-line noise from the low-frequency signal. The 31-sample, 1-line low-pass filter is applied to suppress artifacts introduced by the high-pass filter (discussed below). The noise is thus approximately isolated and can then be subtracted from the original image.

EXAMPLES

Figure 1 shows 512 by 512 pixels of a band-5/band-4 ratio image from Landsat TM scene 50262-07373 of northeastern Sudan. Forward/reverse scan banding is distractingly prominent in parts of this scene that are otherwise fairly uniform in brightness (Figure 1A). The filtering routine largely isolates the banding noise (Figure 1B, see caption note), and subtraction of the noise from the original scene results in a much improved image (Figure 1C). Figures 1D to 1F show 4x enlargements of equivalent parts of Figures 1A to 1C, respectively.

Figure 2 shows 512 by 512 pixels of band 5 from Landsat TM scene 50100-17382 of southeastern California. The striping is due to inconsistencies among the 16 band-5 detectors, with the output of one detector being particularly bright relative to the others (Figure 2A). The filtering routine largely isolates the striping noise (Figure 2B, see caption note), and subtraction of the noise from the original scene again results in a much improved image (Figure 2C). Figures 2D to 2F show 4x enlargements of equivalent parts of Figures 2A to 2C, respectively.

EFFECT UPON SIGNAL

Although Figures 1 and 2 show that the filtering routine can work quite well, two potential problems exist that the user should be aware of. The first problem is that any signal that has structure very similar to that of the noise (i.e., signal structures that are extensively elongated parallel to the scan lines) can be reduced in constrast by the routine. Fortunately, this is usually not a serious problem because (1) precise alignments of this type are rare or absent in most scenes, and (2) minor or even moderate loss of contrast will typically not be noticeable or a hindrance to image interpretation because the human perceptual system tends to emphasize edges in a picture but is fairly insensitive to the amount of change in intensity across the edges (Huang, 1965; Cornsweet, 1970).

The second problem is the possibility that contrast reductions can be erroneously extrapolated along-line. For example, areas of fairly uniform brightness can acquire false patterns that are the inverse of high-contrast patterns in areas located along-line nearby. This results from the fact that the line-to-line intensity adjustments are based upon low-pass, along-line data smoothings.

While both of these potential problems are undesirable, their effects are commonly imperceptible or minor in scenes of natural terrain. However, extrapolated contrast-reduction artifacts can be quite troublesome in scenes of high-contrast signal having uniform regions with sharp boundaries (e.g., agricultural fields or terrain that includes lakes). Modifications of the method using some form of "variable threshold zonal filtering" (Nathan, 1966; Schwartz and Soha, 1977) could reduce the generation of such artifacts but would significantly complicate the routine.

For some scenes, the generation of these artifacts can be largely avoided by use of masking and pixel-substitution procedures applied both before and after the filtering routine. The general concept is to temporarily remove the extreme high contrasts in the signal so that less signal variance becomes erroneously incorporated into the noise image produced in steps 1, 2, and 3. For example, if water pixels are very dark compared to nearly all land pixels, then an approximate land-only image can be created by masking-out all pixels that are darker than some determined threshold. These masked-out water pixels are then replaced by a uniform value more typical of land (e.g., the mean or modal land pixel value) or, preferably, by land pixels from along-line nearby. The full filtering routine is then applied. Finally, the original water pixels are returned to the image. (The details of each step in this procedure are scene-dependent and can vary among image processing systems but typically involve only standard, existing, simple-arithmetic programs.) Of course, as described, scan-line noise is not removed from the water pixels in this procedure (final contrast stretches commonly render them uniformly black anyway). However, if needed, the procedure could be similarly applied to water-only pixels and the two results could then be merged.

CHOICE OF FILTER SIZES

The possibility of extrapolated contrast reductions (artifacts) discussed above suggests that a shorter step-1 low-pass, along-

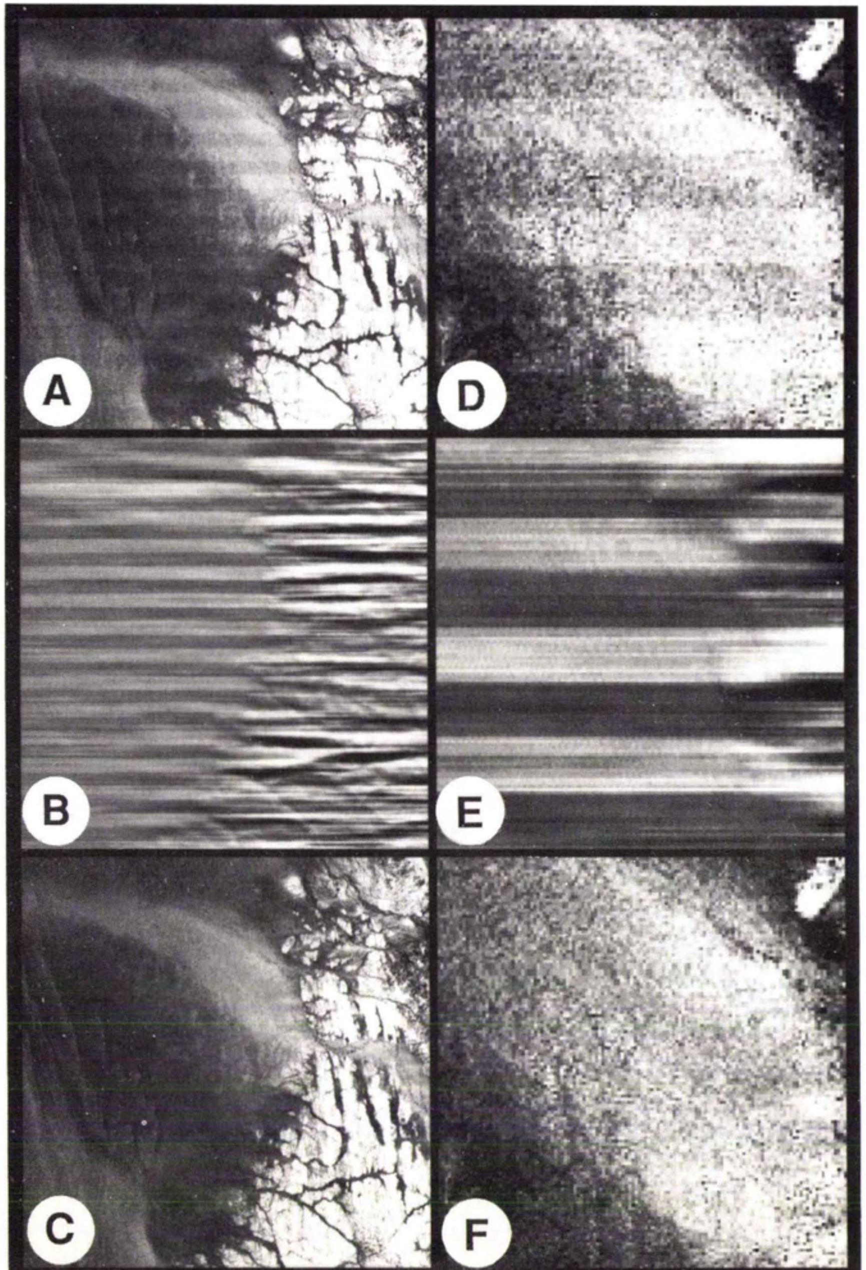

FIG. 1. Forward/reverse scan noise (banding) in TM band-4/band-5 ratio image, northeastern Sudan. (A) Original. (B) Noise after filtering steps 1 and 2 (exaggerated contrast). Note the presence of diagonal artifacts yet to be suppressed by filtering step 3. (C) Cleaned image after noise subtraction in step 4. (D,E,F) 4x enlargements of upper-central parts of A,B,C, respectively.

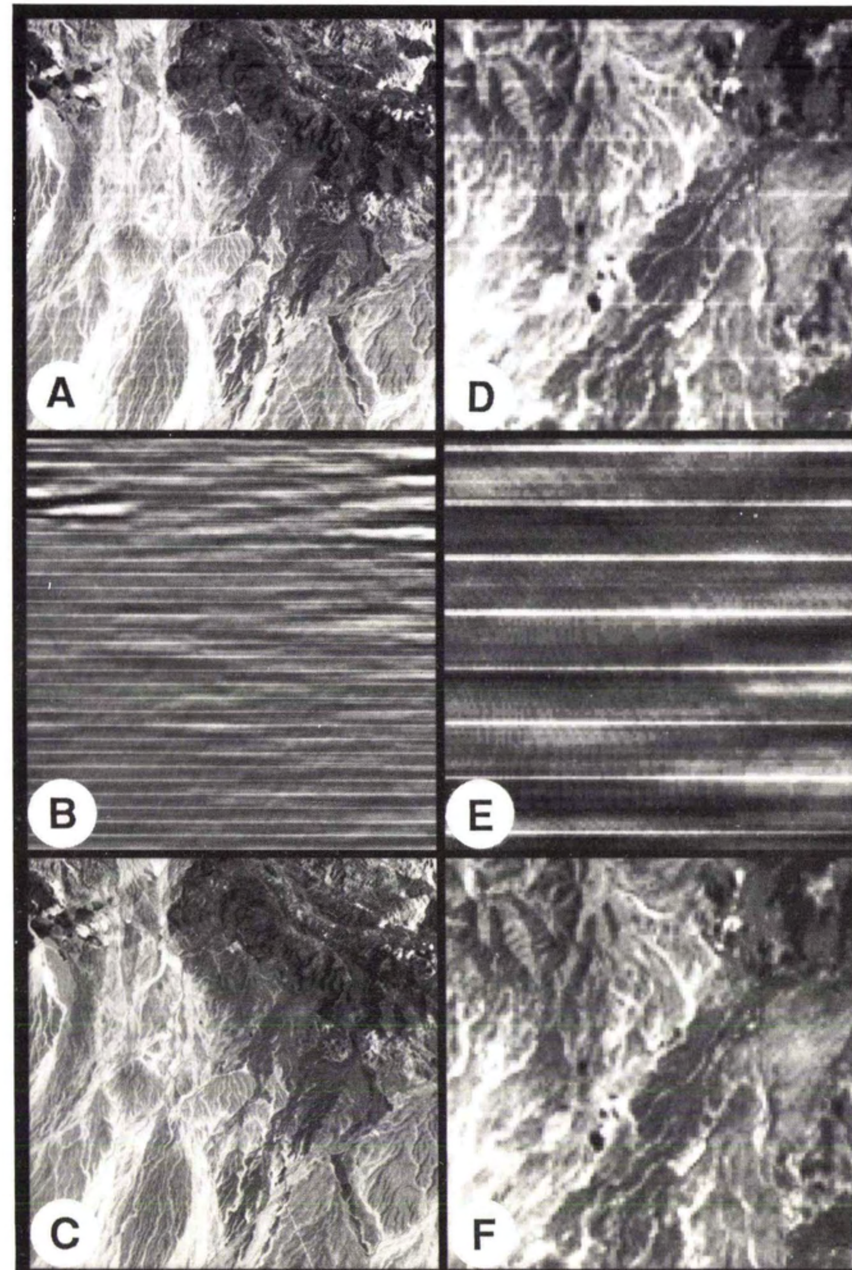

FIG. 2. Detector-specific scan noise (striping) in TM band-5 image, southeastern California. (A) Original. (B) Noise after filtering steps 1 and 2 (exaggerated contrast). (C) Cleaned image after noise subtraction in step 4. (D,E,F) 4x enlargements of near-central parts of A,B,C, respectively. Note in E the presence of along-line high-frequency artifacts created by filtering step 2, thus necessitating filtering step 3.

line filter could be desirable. To see why it is not desirable, consider again the purpose of this filter. It must be sufficiently large to separate the low-frequency signal and scan-line noise from the high-frequency signal. If it is too short, this will not happen. Consequently, more signal will pass through the step-1 filter and ultimately be inappropriately removed. The 101-sample filter size was selected as a good balance between minimizing signal removal and minimizing artifact generation, while eliminating virtually all perceptible scan-line noise. The ideal low-pass filter length for any given scene may vary somewhat with scene content.

The 33-line height of the high-pass filter is largely invariable because it is determined by the periodicity of the scan-line noise. Forward/reverse banding has a periodicity equal to twice the number of lines that represent one scan. Each scan is made by 16 detectors. However, in the generation of P-tape data, pixel spacing is decreased from 30m to 28.5m in an array that is almost, but not quite, aligned with the original scan lines (Beyer *et al.*, 1983). The output from the 16 detectors is therefore spread over approximately ($16 \times 30 / 28.5 =$) 16.85 lines. Twice 16.85 equals 33.7. Thus, 33 lines are used to define the local average to which variations are normalized by the filtering procedure (33 is the odd integer nearest to 33.7).

If forward/reverse banding is not a problem, then a 17-line high-pass filter can be used to suppress only the striping due to differences within the set of individual detectors (represented by 16.85 lines). The 33-line filter will work for both banding and striping, but the 17-line filter is preferred for striping without banding because it is more likely to cleanly extract the across-line high-frequency noise from the low-frequency signal that is retained by the preceding 101-sample low-pass filter. (With decreasing window size, high-pass filters exclude a broader range of low spatial frequencies.)

The 31-sample length of the second low-pass filter (step 3) was found to be adequate to effectively suppress the artifacts created by the preceding high-pass filter (step 2). The high-pass filter creates high-frequency along-line variations even though it is applied after the 101-sample, along-line low-pass filter (see Figures 1E and 2E). Most of these variations are quantitatively minor, but they can be visually significant when they trend across several lines. They are particularly troublesome when they create linear structures (commonly conjugate) oriented oblique to the data lines (Gillespie, 1979, 1980). Such structures are evident in the lower-right quadrant of Figure 1B. Fortunately, this second low-pass filter is not sufficiently long to greatly increase any erroneously extrapolated contrast-reduction effects (discussed above). In some images, artifacts created in step 2 may be minor enough to warrant the omission of step 3.

Interestingly, all three of these uniformly-weighted high-pass and low-pass filters can be programmed so that their computational speed is fast and nearly-independent of their size. This is because the summation statistic used for each successive pixel can be simply calculated as a one-pixel modification of its predecessor (Nathan, 1966; Seidman, 1972; Gillespie, 1980). In any case, because they are one-dimensional, the filters used here are not computationally demanding.

DISCUSSION AND OVERVIEW

Scan-line noise is far more annoying than numerical noise measures (e.g., signal-to-noise ratios) may indicate. This is because scan-line noise is highly geometrically structured, and the human visual system is far more sensitive to structured noise than to random, grainy, "salt and pepper" noise (Roberts, 1962; Schreiber, 1967; Hamerly, 1983). It is particularly sensitive to parallel straight lines oriented vertically or horizontally (Huang and Mitchell, 1977).

Scan-line noise is particularly noticeable in areas that are otherwise uniform (Figures 1A and 2A). This observation is consistent with other studies that have shown grey-level errors to be most noticeable in scenes of low spatial complexity (e.g., Huang, 1965; Zwick and Brothers, 1975).

The removal of scan-line noise from Landsat TM P-tape data has been problematic due to the facts that (1) the noise is smeared across image lines by resampling during image rectification, (2) the P-tape data lines are not precisely parallel to the original detector lines, and (3) some scan-line noise varies in magnitude along scan-lines. The method presented in this paper is successful for many scenes because it makes adjustments on a pixel-by-pixel (rather than a line-by-line) basis, while taking into account the spatial orientation and cyclic characteristics of the noise. The method is easily implemented because it uses only off-the-shelf, general purpose processing routines that are already present on most image processing systems.

Artifacts can be created by the method, particularly in areas where signal contrast is great. However, as discussed, additional steps can be taken to greatly reduce them (even perceptually eliminate them) in many cases. The method may also not work well where the signal has spatial properties very similar to those of the noise. This is unfortunate because noise most highly masks such signal (Harmon and Julesz, 1973); however, it is generally not important because strong spatial similarities between signal and scan-line noise are rare.

Finally, it must be emphasized that the method provides a cosmetic fix that owes part of its success to the characteristics of the human visual perception system. It is not likely to provide a highly consistent radiometric fix, and it may create problems when applied to band data that will subsequently be used in sensitive numerical procedures such as band ratioing. However, it can be applied successfully after band ratioing, as was demonstrated, and it may provide statistical advantages for some objectives. For example, it may increase uniformity within spectral classes, leading to improved image classification accuracies.

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