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ASSESSMENT OF THEMATIC MAPPER BAND-TO-BAND REGISTRATION BY THE BLOCK CORRELATION METHOD

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INTRODUCTION

The configuration of the Thematic Mapper (TM) multispectral radiometer makes it especially susceptible to band-to-band misregistration. The non-cooled detectors of the visible and near-infrared spectral bands (TM bands 1-4) and the cooled detectors of the middle and thermal-infrared bands (TM bands 5-7) are located on physically separate focal planes in the sensor. In addition, there are several compensation devices in effect, such as the Scan Line Corrector (SLC), and the Attitude Displacement Sensor (Ref. 1). This creates the potential for inter-band misregistration, and could have serious consequences for the use of TM data in applications that rely on simultaneous observations. For example, Swain (Ref. 2) examined the effect of misregistration on classification accuracy of simulated TM data and showed that misregistration of 0.3 of a pixel (approx. 10 meters) could seriously degrade accuracy. The objective of the present study was to evaluate the magnitude of misregistration among the seven TM bands and to derive estimates of registration error that are sufficiently accurate for use in image correction.

There are several possible methods of quantifying band-to-band misregistration, some more subjective than others. A visual approach is to display black and white images on a video display screen at sufficient magnification (approx. 1x - 4x) and flicker between the two images of a band pair. For a quantitative assessment of the magnitude of misregistration, one can insert single pixel displacement in one band image of the pair, and for a given magnification, this results in a fractional pixel shift. For example, if the magnification is 4x, a single pixel displacement results in a 25%, or 0.25 pixel, shift. This can be repeated for increasing displacements until the misregistration appears negligible. The advantage of this method is its simplicity. Disadvantages are: 1) it is time consuming, and therefore only a few local areas can be examined for a given image, 2) it is highly subjective, depending on visual acuity and analyst judgement, 3) it allows only a limited set of subpixel shifts, determined by the size of the video display screen, and 4) it cannot be used with uncorrelated bands (e.g., a visible band and the near infrared band) because of contrast reversals that cannot be entirely eliminated in a consistent manner.

Another approach, and one that is partially visual and partially quantitative, is to subtract the two band images being compared. This essentially performs an edge enhancement, in which misregistration results in erroneous edges in the difference image. Obviously, this method performs best when the misregistrations show up as odd patterns or anomalies in the difference image that can be related to the imaging system characteristics or to software problems. For example, an early TM image of the Detroit area showed an approximate single pixel misregistration of several apparently randomly located blocks of 16 or 17 lines by about 128 samples. Investigation revealed that the problem had been caused by a bug in the line insertion step in the pre-processing software, and was apparently corrected during routine de-bugging procedures. Although the problem was identified in the flickering technique, image subtraction graphically displayed the effect over large areas. More quantitative techniques could easily miss the pattern so well displayed by image subtraction. On the other hand, quantitative assessment of the misregistration would be difficult with this technique.

A third approach would be to lay out subpixel sized targets of high contrast in an area of a known imminent satellite overpass, such as mirrors or white patches on a dark background. This procedure would allow estimation of misregistration of a major fraction of a pixel and has the advantage that the target is known to have no spectral ambiguities; therefore, the possibility of a bias related to the difference in wavelength between the two bands would not be a problem. However, early work by Evans (Ref. 3) showed that the precision of this method is limited to 1/2 to 1 pixel due to a combination of several factors: the error in location of the IFOV over the targets, effects of electronic filtering on the data, and narrow angle forward scattering in the atmosphere (the adjacency effect). Such sub-pixel targets require great care in placement, so only a few targets could be set out over a given TM scene; hence, neither useful patterns nor a statistically meaningful number of target points could be observed.

The approach taken in this paper, and one selected after trying the differencing and flicker methods mentioned above, was the block correlation method. This technique statistically correlates rectangular blocks of pixels from one band image against blocks centered on identical pixels from a second band image. The block pairs are shifted in pixel increments both vertically and horizontally with respect to each other and the correlation coefficient for each shift position is computed. The displacement corresponding to the maximum correlation is taken as the best estimate of registration error for each block pair.

One of the earliest implementations of the method was the system developed at the Laboratory for Applications of Remote Sensing (LARS), Purdue University, West LaFayette, Indiana. The LARS procedure was developed for spatial registration of multi-spectral, multi-temporal digital imagery (Ref. 4). Historically, the registration software now resident on Ames Research Center's CDC 7600 computer was developed by the Center for Advanced Computation (CAC) of the University of Illinois at Urbana-Champaign for implementation on Ames' ILLIAC IV computer. The program was part of an interactive software system for remote sensing called EDITOR, developed in a joint project by NASA, USGS, CAC, and LARS (Ref. 5). Foreseeing the eventual demise of the ILLIAC IV, Ames personnel implemented the program on the CDC 7600, and eventually incorporated a Fast Fourier Transform (Ref. 4) to speed up the correlation computations.

METHOD

The image selected for the investigation was the Arkansas TM scene of August 22, 1982,in "P" (geometrically correct) format. EDITOR software was modified for a SEL 32/77 minicomputer at Ames to pre-process the data before input to the block correlation program. A systematic array of 17 blocks (square arrays of pixels) along-scan and 20 across-scan were selected and, with scene border deletions , this resulted in an array of 297 blocks that effectively covered the entire TM image. The primary blocks (64 pixels by 64 pixels) were selected from the TM band chosen to remain fixed in position, and the secondary blocks (32 pixels by 32 pixels) were selected from the TM band chosen to vary in position over the primary block. Each set of blocks, primary and secondary, was centered on the same TM pixel and the correlation coefficient was computed for every possible position of the secondary block within the primary block. The displacement (shift) of the center of the secondary block relative to that of the primary block corresponding to the maximum correlation was considered to be the best estimate of misregistration for the block pair. Subpixel accuracy was attempted by performing a bi-quadratic interpolation on the eight pixels surrounding the maximum correlation pixel, and fractional shift values for along-scan and across-scan directions were recorded. Mathematical formulas and algorithms for block correlation will not be discussed in this paper. The paper by Anuta (Ref. 4) is an excellent exposition of the Fast Fourier Transform approach to block correlation and includes the relevant formulas.

Edge enhancement was performed on the TM image in order to improve the estimation of shifts, especially in areas where correlation of unprocessed imagery was impossible, due to radiometric light-dark reversals between bands. Two operators were tried--one was the gradient operator implemented in the original version of the EDITOR correlation program:

$$|\text{grad } F(i,j)| = |F(i-1,j)-F(i,j)| + |F(i,j+1)-F(i,j)| + |F(j-1,i)-F(i,j)| + |F(i+1,j)-F(i,j)|$$

for the pixel at line i and sample j, with radiometric value F(i,j). The other was the well-known Sobel operator (Ref. 6):

$$|\text{grad } F(i,j)| = |F(i-1,j+1)+2F(i,j+1)+F(i+1,j+1)-F(i-1,j-1) -2F(i,j-1)-F(i+1,j-1)| + |F(i+1,j-1)+2F(i+1,j) +F(i+1,j+1)-F(i-1,j-1)-2F(i-1,j)-F(i-1,j+1)|$$

Results are presented in this paper for the EDITOR gradient operator, since it was the method that was operational in the block correlation program at the start of the project, and subsequent testing showed no improvement of shift estimates for selected band combinations using the Sobel operator.

Post-processing of the shift data was performed on an HP-3000 mini-computer using the MINITAB statistical package (Ref. 7). Editing of the data consisted of deleting blocks (i.e., shift values corresponding to blocks) that had low correlation values. This procedure tended to eliminate blocks having obviously high positive or negative shifts. However, not all outliers were eliminated, therefore a further step was to discard exceptionally high shift values by keeping only those shifts within a specified threshold. This approach was somewhat subjective, and its consequences will be discussed in the following section.

RESULTS

Table 1 displays the fundamental results of the block correlation analysis for selected TM band combinations. The table shows the results of editing the shift data by discarding all shift values having corresponding correlations less than 0.6. In order to show that this editing procedure is not unreasonable, band pairs 3 versus 5 and 6 versus 7 were subjected to further editing. These pairs were selected because they showed the largest outliers in Table 1. Band pair 3 versus 5 was edited by discarding blocks that had shifts outside the range -3 to 3 pixels or had correlations < 0.6. Similarly, band pair 6 versus 7 was edited by discarding blocks that had shifts outside the range -10 to 10 or had correlations < 0.3. Table 2 displays the results, showing that the mean shift values are quite robust to the editing procedure (discarding shifts based on correlation thresholds and shift values). By restricting the shift values for band 3 versus band 5, only two outliers were discarded and the mean shifts were affected only slightly; for band 6 versus band 7, the mean shifts shifts remained fairly stable, even though the sample size increased from 4 to 96 and the maximum absolute shift increased to 10. Table 3 displays mean shifts versus correlation threshold for band 3 versus 5, and indicates that the threshold for correlation of 0.6 in Table 1 is not unreasonable: for no restriction on either correlation or maximum shift, the mean shift estimates are reasonably close to those for correlation greater than 0.6. This illustrates again the robustness of the estimates of average shift.

In order to quantify somewhat the interpolation error involved in the use of a bi-quadratic fit to the correlations for obtaining subpixel shift estimates, band 3 was correlated against itself. All 297 blocks locked on with maximum correlation 1.0 at integral values of zero shift in each direction, as was to be expected. However, after interpolation, the average shifts were found to be 0.0006 and 0.0012 with standard deviations of 0.009 and 0.04 in the across-scan and along-scan directions, respectively. This indicates that interpolation error can safely be neglected.

The sign associated with the shift values in the tables indicates the relative direction of misregistration. A plus sign in the along-scan direction indicates a right shift, and a plus sign in the across-scan direction indicates a downward shift in the secondary band with respect to the primary band. Similarly, negative shifts would be to the left and upwards. In the tables, the primary band is always written first. For example, in Table 1, for bands 6 versus 7, with band 6 stationary, band 7 is to the left and upwards. The tables also show the number of blocks remaining after editing, the standard deviations, minima and maxima of the shifts, and a nominal 95% confidence interval around the mean shift based on the assumption of approximate normality of the shift distributions (after editing).

Table 1 shows that the target specification for TM band-to-band registration of 0.2 pixels is easily achieved for those band combinations within the same focal plane (bands 1 versus 3 and 3 versus 4 in the non-cooled focal plane, and bands 5 versus 7 in the cooled focal plane), with the exception of bands 6 versus 7. Band 6 presents special problems, which will be discussed below. Although the shift for band 3 versus band 4 was within the 0.2 pixel specification, the standard deviations of across-scan and along-scan shifts were higher than the 1-3 and 5-7 band pairs, and far fewer blocks were retained after editing (44 out of 297). The relatively poor performance for bands 3 and 4 is apparently the result of natural low correlation between a visible and a

Table 1

Descriptive statistics for band-to-band misregistration for selected Thematic Mapper band combinations (Arkansas scene - August 22, 1982). The first band listed in each set is the primary band for the correlations, and all correlation blocks having the correlation coefficient <.6 were discarded. (Unit of misregistration [shift] is in pixels.)

TM Bands	Shift Direction	Number of Blocks	Mean Shift	S.D.	Min Shift	Max Shift	95% Conf. Int. for Mean Shift
3 vs 1	Across-scan	256	-.04	.06	-.2	.2	(-.05,-.03)
	Along-scan	256	-.03	.06	-.4	.1	(-.04,-.02)
3 vs 4	Across-scan	44	-.03	.33	-1.0	1.1	(-.13,.07)
	Along-scan	44	.10	.38	-.4	1.9	(-.02,.22)
3 vs 5	Across-scan	217	.22	.73	-9.3	3.3	(.12,.32)
	Along-scan	217	.49	.41	-2.7	4.0	(.44,.54)
3 vs 7	Across-scan	264	.16	.20	-.4	2.2	(.14,.18)
	Along-scan	264	.49	.18	-.4	1.1	(.47,.51)
7 vs 5	Across-scan	280	.06	.09	-.5	.6	(.05,.07)
	Along-scan	280	-.01	.07	-.4	.3	(-.02,.0)
6 vs 7	Across-scan	4	-3.50	1.04	-4.7	-2.2	(-5.2,-1.8)
	Along-scan	4	-3.20	2.31	-4.9	.2	(-6.9,.48)

Table 2

Results of alternative editing for Band 3 vs Band 5 and Band 6 vs Band 7. (Unit of shift is in pixels.)

Restrictions: (3 versus 5) Correlations >.6, |shift|<3

(6 versus 7) Correlations >.3, |shift|<10

TM Bands	Shift Direction	Number of Blocks	Mean Shift	S.D.	Min Shift	Max Shift	95% Conf. Int. for Mean Shift
3 vs 5	Across-scan	215	.25	.25	-1.0	1.1	(.22,.28)
	Along-scan	215	.49	.25	-0.4	1.9	(.46,.52)
6 vs 7	Across-scan	96	-3.16	3.06	-9.9	8.2	(-3.8,-2.5)
	Along-scan	96	-2.96	2.65	-9.8	8.4	(-3.5,-2.4)

Table 3

The effect of successive block deletion on estimates of band-to-band misregistration for Thematic Mapper bands 3 and 5 (Arkansas scene -- August 22, 1982). Band 3 was the primary band for the correlations. Blocks having correlation coefficients outside the range shown in the table were discarded. (Unit of shift is in pixels.)

Corr. Coef.	Shift Direction	Number of Blocks	Mean Shift	S.D.	Min Shift	Max Shift	95% Conf. Int. for Mean Shift
>.8	Across-scan	48	.17	.30	-1.0	.9	(.08,.26)
	Along-scan	48	.42	.26	-0.4	.9	(.34,.50)
>.6	Across-scan	217	.22	.73	-9.3	3.4	(.12,.32)
	Along-scan	217	.49	.41	-2.7	4.0	(.43,.55)
>.3	Across-scan	289	.33	1.23	-9.3	15.2	(.18,.47)
	Along-scan	289	.45	.90	-12.7	4.0	(.35,.55)
All	Across-scan	297	.26	1.67	-12.5	15.2	(.07,.45)
	Along-scan	297	.48	2.07	-16.0	16.0	(.24,.72)

near IR band. This is illustrated in Fig. 1, which compares histograms of the band 3 versus band 4 correlations with band 7 versus band 5 correlations. The mode of the distribution for anticorrelated bands 3 and 4 is approximately 0.3, whereas that of the distribution for correlated bands 7 and 5 is approximately 0.85, showing that the 3 versus 4 blocks correlated in general at lower values.

Table 1 also shows relatively larger and consistent shifts between bands in different focal planes(band 3 versus band 5 and band 3 versus band 7); the along-scan shift is larger than the permitted 0.3 pixel misregistration. This result confirmed the earlier experience with the flickering method, in which an approximate shift of a half pixel was noted in the along-scan direction when band 3 was flickered against band 5 on a video display screen. The shifts for band 3 versus band 5 and band 7 versus band 5 are remarkably consistent with each other--note that adding the 3-7 shifts to the 7-5 shifts equals the 3-5 shifts. This may be coincidental, but one might expect this kind of transitive relationship for real misregistration shifts. Given the fact that the data processing software for TM data can

Correlation Coeff.	Number of Blocks	
-1.0	0	
-0.9	0	
-0.8	0	
-0.7	0	
-0.6	0	
-0.5	0	
-0.4	1	*
-0.3	22	***********
-0.2	17	*********
-0.1	0	
0.0	0	
0.1	1	*
0.2	33	*****************
0.3	70	***********************************
0.4	66	*********************************
0.5	27	**************
0.6	30	***************
0.7	19	**********
0.8	5	***
0.9	4	**
1.0	2	*

(a)

Correlation Coeff.	Number of Blocks	
-1.0	0	
-0.9	0	
-0.8	0	
-0.7	0	
-0.6	0	
-0.5	0	
-0.4	0	
-0.3	0	
-0.2	0	
-0.1	0	
0.0	0	
0.1	0	
0.2	5	*
0.3	0	
0.4	3	*
0.5	7	**
0.6	7	**
0.7	44	*********
0.8	112	***********************
0.9	112	***********************
1.0	7	**

(b)

Fig. 1. Histograms of correlation coefficient (no deletions)
(a) Band 3 versus band 4 (each * represents 2 observations)
(b) Band 7 versus band 5 (each * represents 5 observations)

correct subpixel misregistrations, we suggest that the appropriate shifts to correct the misregistration between the uncooled and cooled focal planes would be 0.5 pixels along-scan and 0.2 pixels across-scan based on these results.

Band 6 presents a special problem, in that it had a very low correlation with band 7, and therefore editing was much more difficult as evidenced in Table 1 by the retention of only four blocks with correlations above 0.6. Flickering between bands 6 and 7 also showed poor visual correlation and verified an approximate four pixel shift. Fig. 2, a histogram of shifts for band 6 versus band 7 prior to editing, illustrates the difficulty of editing this band pair due to the large percentage of outliers and almost uniform nature of the distribution. Fig. 3 shows the histogram of shifts for band 3 versus band 5, for comparison with Fig. 2. (19 outliers were deleted from the data in Fig. 3 in order to show the shape of the distribution around the mean to better advantage.) As noted earlier, even with these difficulties, the shift estimates for band 6 versus band 7 seem to be quite robust to the editing procedure. Based on these results, we suggest correcting the band 6 misregistration by shifts of 3 pixels (28.5 meters) in both the along-scan and the across-scan directions.

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(a)

Shift	Number of Blocks
-16.0	8
-15.0	7
-14.0	4
-13.0	2
-12.0	7
-11.0	8
-10.0	7
-9.0	5
-8.0	7
-7.0	6
-6.0	19
-5.0	26
-4.0	29
-3.0	25
-2.0	20
-1.0	9
0.0	9
1.0	5
2.0	5
3.0	6
4.0	7
5.0	2
6.0	10
7.0	7
8.0	5
9.0	3
10.0	9
11.0	5
12.0	5
13.0	4
14.0	10
15.0	5
16.0	11

(b)

Shift	Number of Blocks
-16.0	15
-15.0	7
-14.0	4
-13.0	8
-12.0	8
-11.0	3
-10.0	2
-9.0	8
-8.0	7
-7.0	4
-6.0	12
-5.0	17
-4.0	29
-3.0	42
-2.0	15
-1.0	15
0.0	7
1.0	8
2.0	6
3.0	4
4.0	6
5.0	4
6.0	10
7.0	2
8.0	10
9.0	7
10.0	4
11.0	4
12.0	4
13.0	6
14.0	7
15.0	5
16.0	7

Fig. 2. Histogram of shifts for band 6 versus band 7
(no deletions)
(a) Across-scan (b) Along-scan

(a)

Shift	Number of Blocks
-1.0	1
-0.9	1
-0.8	1
-0.7	0
-0.6	0
-0.5	1
-0.4	0
-0.3	2
-0.2	2
-0.1	7
0.0	22
0.1	52
0.2	69
0.3	53
0.4	25
0.5	13
0.6	12
0.7	6
0.8	2
0.9	5
1.0	4

(b)

Shift	Number of Blocks
-0.8	1
-0.7	1
-0.6	0
-0.5	0
-0.4	1
-0.3	0
-0.2	1
-0.1	5
0.0	4
0.1	11
0.2	18
0.3	44
0.4	48
0.5	43
0.6	42
0.7	26
0.8	18
0.9	12
1.0	3

Fig. 3. Histograms of shifts for band 3 versus band 5 (blocks with |shift|>1 were deleted)
(a) Across-scan (each * represents 2 observations)
(b) Along-scan

CONCLUSIONS

For the band combinations studied:

(1) The misregistration of TM spectral bands within the non-cooled focal plane lie well within the 0.2 pixel target specification (TM bands 3 versus 1 and 3 versus 4).

(2) The misregistration between the middle IR bands (TM bands 5 and 7) is well within the 0.2 pixel specification.

(3) The thermal IR band (TM band 6) has an apparent misregistration with TM band 7 of approximately 3 pixels in each direction.

(4) TM band 3 has a misregistration of approximately 0.2 pixel in the across-scan direction and 0.5 pixel in the along-scan direction, with both TM bands 5 and 7.

Indications are that the block correlation method is a reasonable approach to the quantitative assessment of band-to-band misregistration. It is quite robust to the method of editing outliers and seems to result in estimates of registration error that are consistent with expectations.

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