Evaluation of Thematic Mapper Interband Registration and Noise Characteristics

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ABSTRACT: Landsat-4 and Landsat-5 Thematic Mapper data were examined for band-to-band registration, absolute geodetic registration, and periodic noise. The block correlation approach proved to be a highly accurate and consistent method of obtaining subpixel estimates for interband registration. Within focal planes, bands were registered well within the very precise specifications. Between focal planes, appreciable misregistrations existed in early data products that exceeded specifications. Subsequent corrected products met specifications except possibly the thermal band. The analysis of absolute geodetic registration used only system-corrected data because ground control point-corrected P-tapes were unavailable. Geodetic registration errors were lower than expected for system-corrected data. Periodic noise at four spatial frequencies was observed in Landsat-5 Thematic Mapper data by using Fourier analysis on small areas over water. Magnitudes of periodic noise components in each detector were consistent within a scene and generally small.

INTRODUCTION

THE THEMATIC MAPPER (TM) INSTRUMENTS aboard the Landsat-4 and Landsat-5 spacecraft have provided the first digital imagery of the Earth's surface with a resolution sufficient to distinguish cultural features easily. These instruments have new spectral bands in the blue, shortwave infrared, and thermal infrared. In addition, they feature improved placement of the green, red, and near-infrared bands (compared to the Multispectral Scanner or MSS) so as to avoid confounding effects and water vapor absorption lines. Rather than attempting to explore all these advantages simultaneously, the National Aeronautics and Space Administration's (NASA) Landsat Image Data Quality Analysis (LIDQA) Program set the more modest goal of trying to quantify specific attributes of the new sensor. The question was asked: how well did the TM meet the difficult technical specifications set out for it in terms of various types of image registration, resolution, radiometric fidelity, noise, and image interpretability? The present work was sponsored by the LIDQA Program to study several of these aspects of data quality for both the Landsat-4 and Landsat-5 instruments. This paper describes the results of studies designed to investigate the band-to-band registration, geodetic registration to a map base, and periodic noise.

BACKGROUND

BAND-TO-BAND REGISTRATION

Accurate band-to-band registration is essential for the multivariate analysis of multispectral data, since a basic assumption is that all components of a vector of spectral values (component i being the spectral response in band i for a given pixel) refer to the same ground location. An important example is the classification of spectral data into land-use categories by discriminant analysis. The accuracy of map products generated by this technique can be seriously degraded when the average registration error is as small as 0.3 pixel (Swain *et al.*, 1982). In anticipation of the strict band-to-band registration requirement, prelaunch specifications were stringent: 0.2 pixels between bands in the same focal plane, and 0.3 pixels between bands in different focal planes. (TM bands 1–4 were in the primary focal plane, and bands 5–7 were in the secondary, or cooled, focal plane). The objective of this portion of our LIDQA work was to develop and implement an objective method for quantifying band-to-band registration that has statistical validity, and to apply the method to estimate the average registration error for several available TM images.

Other LIDQA investigators have reported work on interband registration accuracy. Walker *et al.*

PHOTOGRAMMETRIC ENGINEERING AND REMOTE SENSING,
Vol. 51, No. 9, September 1985, pp. 1417-1425.

0099-1112/85/5109-1417$02.25/0

(1984) evaluated TM P-data of Washington, DC, Harrisburg, PA, and Salton Sea, CA, using line-to-line phase correlation with a fast Fourier transform technique and concluded that misregistration in the along-scan direction between bands of the primary focal plane (bands 1–4) was not significant. However, between bands of the primary focal plane and bands of the secondary focal plane, they measured a pixel offset that frequently fell in the range of −0.75 to −1.25 pixels. Yao and Amis (1985), using a program very similar to the block correlation program of the present investigators (called the JSC Registration Processor) to analyze three dates of TM data for Webster County, IA, found that the within-focal-plane bands of the TM Scrounge data were well registered to each other. But again, significant offsets were found between focal planes, the offsets being larger in the across-scan direction than in the along-scan direction.

Geodetic Registration

In the past, Landsat MSS data has been provided in two geometrically corrected formats: system-corrected—which accounted for all known sources of geometric error contributed by the system (line length variation, mirror scan profile, attitude variations, altitude changes, and earth rotation), and ground control point-corrected (GCP-corrected)—which attempted to remove any residual errors by referring to fixed features on the Earth's surface. In retrospect, the use of ground control points (GCPs) was necessary because system variables were not sufficiently controlled or measured. The pointing accuracy of earlier Landsat platforms was 0.7 degrees with an attitude stability of 0.01 degrees/second. Bernstein (1976) found that the original distortions in the data, of the order of 200–300 m, could be reduced to about 100 m within a scene by the use of a well-distributed network of GCPs. Even so, the translational error between scenes could be large due to lack of precise control of the orbital track (up to 37 km error).

The advent of the newly designed Landsat-4 platform brought with it far greater stability, control, and measurement capability. The pointing accuracy was increased to 0.01 degrees and the attitude stability was improved to 0.000001 degrees/second. Trackline error was reduced to within 4 km of the nominal track. In addition, the Thematic Mapper was fitted with an angular deplacement sensor to measure high frequency motions up to 100 Hz. With respect to geodetic accuracy or registration to a map, these improvements gave promise not only of much less distortion within the scene in a relative sense, but of good geolocation in an absolute sense. No specification was quoted for geodetic accuracy of system-corrected TM data, but the specification for GCP-corrected TM data was that a point shall be within 0.5 pixels of its true location in geodetic space 90 percent of the time. It is this specification that is being tested in the current work.

Since TM pixels are originally 30 m, the geodetic accuracy specification of 0.5 pixels translates into 15 m on the ground. The National Map Accuracy Standard for a cartographic map product is for recognizable points to be within 0.5 mm (0.020″) of their true location on the map, regardless of scale, 90 percent of the time. For a 1:24,000 scale map, the standard 7.5′ quadrangle, the 0.5 mm allowable error represents 12 m on the ground. Furthermore, many older maps do not meet the present quality standards. Clearly, the potential map error is of the same order as the specified allowable error in geodetic location for GCP-corrected TM data; use of 7.5′ quadrangles can only provide an approximate test for the geodetic accuracy of TM data.

TM data tapes contain information in the HAAT Ancillary Major Frame 1 record that is sufficient to locate any pixel in geodetic space. The information includes the type of projection, the scene center latitude and longitude, the pixel offset from the scene center, and the rotation angle from the nominal map projection. Thormodsgard and DeVries (1985) developed a program to use this information and predict the location of a pixel given either its geodetic or image coordinates. For the two TM images that they analyzed, both system-corrected images, they found mean errors of 35.3 and 44.2 pixels. However, the errors were primarily translational, i.e., the standard deviations were small, one or two pixels. Unfortunately, no GCP-corrected images were available for evaluation.

Periodic Noise

Except for striping patterns due to small inequities in gain among the six detectors in each band, earlier MSS data had almost no observable noise. Part of the reason was that the 64-level digitization scheme created radiometric bins larger than the inherent noise of the detectors, thus the noise was effectively lost. TM data, digitized into 256 levels, has more potential for displaying noise characteristics. Thematic Mapper noise specifications and measurements are quoted in terms of noise equivalent reflectance changes. Table 1 gives the noise equivalent reflectances for each band according to the original specification and as measured prior to

TABLE 1

THEMATIC MAPPER BAND	SPECIFICATION FOR NOISE-EQUIVALENT REFLECTANCE CHANGE	MEASURED NOISE-EQUIVALENT REFLECTANCE CHANGE		NOISE-EQUIVALENT DN
		LANDSAT-4	LANDSAT-5	LANDSAT-5
1	0.008	0.0016	0.0016	0.9
2	0.005	0.0018	0.0021	0.6
3	0.005	0.0020	0.0023	0.8
4	0.005	0.0019	0.0022	0.6
5	0.01	0.0023	0.0025	1.2
7	0.024	0.0041	0.0037	1.5

launch for the Landsat-4 and Landsat-5 instruments. The noise equivalent reflectances for Landsat-5 were also converted into digital counts using a formula developed by Santa Barbara Research Center (1984) and their nominal constants for each band (assuming the sun was in the zenith). The measured values are much better than the specified values, ranging from 0.6 to 0.9 counts for TM bands 1–4 and 1.2 and 1.5 counts for TM band 5 and TM band 7, respectively. The measured noise derives from various kinds of shot, resistance, and capacitance noises and represents an integrated value over all frequencies.

Wrigley *et al.* (1984) examined an A-tape of the 2 November 1982 Landsat-4 Washington, DC, scene and observed several components of periodic noise over a uniform section of Chesapeake Bay. The strongest periodic component was at a spatial frequency of 0.31 cycles/sample and was present in TM bands 1–4 but not in TM bands 5 or 7. The magnitude of this noise component compared favorably with magnitudes measured at Goddard Space Flight Center before launch (J. Barker, personal communication, 1982). Wrigley *et al.* (1984) observed additional periodic components at 0.07 and 0.055 cycles/sample. They used notch filters in the Fourier domain to remove all these periodic noise components and found the noise-free (inverse) image revealed low contrast patterns not apparent in the original image. Bernstein *et al.* (1984) observed both the 0.31 and 0.055 cycles/sample components and suggested that the former may have been generated from the chopping frequency of a power supply. Anuta *et al.* (1984) also observed these two components as well as one at 0.07 cycles/sample. Kieffer *et al.* (1985) found all of the above noise components as well as one at 0.04 cycles/pixel. In addition, they found small frequency shifts between two scenes as well as significant variability in the magnitude of the 0.07 cycles/sample component.

METHODS

BAND-TO-BAND REGISTRATION

Several informal methods of evaluating band-to-band registration accuracy were tried in the early part of the effort, both for quick-look results and for checks on more precise methods. Among these were flickering between band images on a video display screen and generation of hard-copy difference images, described in Card *et al.* (1985) and Wrigley *et al.* (1984). These techniques were discontinued after experience showed that the block correlation method was reliable and robust to editing procedures.

Block correlation is a method for selecting control points automatically for image registration by correlating blocks of pixels surrounding approximately corresponding points in each image. Terminology varies although others have used a similar technique: Schowengerdt (1983) calls it a "moving spatial window" approach. The block correlation software used in this investigation is a fast Fourier transform version of a program developed for scene-to-scene registration (Card *et al.*, 1985). Schowengerdt (1983) gives the mathematical details of the correlation procedure, and Anuta (1970) discusses the fast Fourier transform implementation. Informally, the procedure followed by the program is as follows: locations (pixel coordinates) are selected from a TM image on a systematic grid (16 × 20 for Scrounge format, 13 × 20 for Thematic Mapper Image Processing System (TIPS) format). For a comparison of two bands, one band is arbitrarily selected as the primary image and the other as the secondary image. For each location in the grid, a block of 64 × 64 pixels surrounding the grid point is copied from the primary image, and a block of 32 × 32 pixels is copied from the secondary image. The block pairs are edge enhanced using a gradient operator (Card *et al.*, 1985), and the correlation is computed via the two-dimensional fast Fourier transform for every possible location of the smaller block within the larger block.

The resulting 32 × 32 pixel set of correlations is searched for the correlation of maximum absolute value (different bands may be light/dark reversed), and the corresponding pixel coordinate is taken to be the best registration position in terms of an integral number of pixel shifts. Subpixel estimates of shift in the along-scan and across-scan directions are obtained by fitting a quadratic surface to the eight pixels surrounding the integral shift pixel and computing the surface maximum.

After deleting blocks along empty scene borders, approximately 297 block (210 blocks for TIPS format) remain for analysis. These remaining blocks were edited to discard those with correlations of low absolute value. Visual inspection has shown that failure of the correlation usually results from cloud cover, lack of edge detail, or low contrast. Registration shift means and variances are generated interactively on the MINITAB system (Ryan *et al.*, 1976) and tabulated.

GEODETIC REGISTRATION

Due to the unavailability of GCP-corrected P-tapes, a system-corrected Landsat-4 Scrounge tape of the 1 February 1983 scene of Sacramento, CA, was evaluated for geodetic accuracy. Staff of the Geometronics Branch of the U.S. Geological Survey were consulted regarding categories of control points which would be most accurate on 7.5′ quadrangle maps. Fourteen such points were selected on 13 quad sheets, and the image point locations were visually determined from an image display system to the nearest 0.5 pixel in the line and sample directions. These points were then digitized to the nearest 0.00001 degrees (1.1 m).

The software package assembled at EROS Data

Center by Thormodsgard and DeVries (1985) was used to compute map projection coordinates for any geodetic location described by latitude and longitude. The software converted latitude/longitude coordinates to map projection coordinates to image location coordinates, or image coordinates to map projection to latitude/longitude coordinates.

Periodic Noise

Small areas over uniform water in both the 2 July 1984 Great Salt Lake Landsat-5 scene A-tape and the 28 October 1984 White Sands B-tape were examined for the presence of along-scan periodic noise. A 256 × 256 pixel area over dark water and a 512 × 256 pixel area over lighter water (medium water) were selected from quadrant 4 of the Salt Lake scene. The forescans and backscans were extracted to make two separate images so that the effect of scan direction on noise could be determined. A 128 × 128 pixel image over water in quadrant 2 of the White Sands scene was also selected for analysis.

The noise frequencies in each band were visually identified from the two-dimensional Fourier transform of each image on an interactive digital display system. The energy associated with each noise frequency in each detector was measured on peak-to-peak spectra of the 512 × 256 pixel image from the Salt Lake scene. A spectrum was formed for each detector as the root mean square spectrum of 16 scanlines. The peak-to-peak magnitude, $M(f)$, at a given frequency was estimated from the two magnitudes P and Q at two spatial frequencies ($n/256$ and $[n + 1]/256$ cycles/sample) which bracketed the underlying frequency, f. Two background values (A and B) at $(n - 2)/256$ and $(n + 3)/256$ cycles/sample were subtracted from P and Q to yield an estimate of the noise without the background:

$$M(f) = \sqrt{(P^2 + Q^2) - (A^2 + B^2)} \qquad (1)$$

These magnitudes were compared between images to determine the consistency of noise content with scan direction and location within scene.

RESULTS

Band-to-Band Registration

A total of eight Thematic Mapper images have been examined for band-to-band registration accuracy. The first image, of Detroit, MI, acquired on 25 July 1982, was analyzed only by the informal quick-look methods, and results were presented in an earlier paper (Wrigley *et al.*, 1984). Because of artifacts in the data (rectangular blocks of misregistered pixels), the Detroit scene was not subjected to the block correlation procedure. The second and third images acquired were northeastern Arkansas (22 August 1982) and Sacramento, CA (1 February 1983), and were the first images to be extensively analyzed by the block correlation method. Complete discussions of the Arkansas scene (Scrounge format) and the Sacramento February scene have been presented elsewhere (Card *et al.*, 1983; Wrigley *et al.*, 1984). Results for the other five scenes will be discussed below. A summary of results of the band-to-band registration analysis for the seven scenes exclusive of the Detroit scene is presented in Table 2. Only the mean shifts are shown in order to simplify comparisons.

Examination of Table 2 shows that mean shifts for a given band pair and satellite (Landsat-4 or Landsat-5) are remarkably consistent. For any given satellite, the stability of these results for a given band pair is of the order of a few hundredths of a pixel for most band pairs. Table 2 also shows the initial misregistration between focal planes for Landsat-4 and the results of two apparently different attempts to correct it (compare the two Arkansas scenes and the two Sacramento quadrants for 12 August 1983). Also shown is the initial misregistration problem with the Landsat-4 thermal band and its subsequent correction.

The other Arkansas and Sacramento TM scenes were acquired in order to compare results with earlier analyses and to evaluate the TM Image Processing System (TIPS)-corrected data (northeastern Arkansas, 22 August 1982, quadrant 4 and Sacramento, CA, 12 August 1983, quadrants 1 and 4). Results of the block correlation for quadrant 4 of the corrected northeastern Arkansas scene are given in Table 3. Although results reported earlier (Card *et al.*, 1985) for the Arkansas scene included correlation blocks from the entire scene (Scrounge format) and not just quadrant 4, the results for misregistrations between bands in the same focal plane are almost identical to the earlier results, generally within hundredths of a pixel (cf., Table 2, columns 1 and 2). For band pairs between the cooled and uncooled focal planes (3 versus 5 and 3 versus 7), the results for quadrant 4 of the northeastern Arkansas scene show that the corrections for the initial misregistration have reduced the average shifts to levels that meet prelaunch specifications (0.3 pixel

TABLE 2

SUMMARY OF BAND-TO-BAND REGISTRATION RESULTS FOR THEMATIC MAPPER BAND COMBINATIONS FOR SEVERAL LANDSAT-4 AND LANDSAT-5 SCENES. THE UNIT OF MISREGISTRATION (SHIFT) IS PIXELS.

TM BANDS	SHIFT DIRECTION	NE ARK SCROUNGE	NE ARK-4 TIPS*	SAC' TO 2/1/83	SAC' TO-1 8/12/83*	SAC' TO-4 8/12/83*	CORPUS-1 3/6/84	HUNTS-1 3/15/84	PARMER-4 6/8/84
3 VS 1	ACROSS-SCAN	-0.04	-0.04	-0.05	-0.04	-0.05	-0.03	-0.03	-0.03
	ALONG-SCAN	-0.03	-0.04	-0.04	-0.05	-0.04	0.01	0.00	0.00
3 VS 2	ACROSS-SCAN	–	0.02	–	0.01	0.02	-0.03	-0.04	-0.04
	ALONG-SCAN	–	-0.02	–	-0.03	-0.02	0.00	0.00	-0.01
3 VS 4	ACROSS-SCAN	0.01	0.00	0.02	0.01	-0.01	-0.02	-0.02	-0.01
	ALONG-SCAN	0.01	0.07	0.01	0.02	-0.01	-0.03	-0.03	-0.01
3 VS 5	ACROSS-SCAN	0.25	0.10	0.33	0.17	0.16	–	-0.65	-0.71
	ALONG-SCAN	0.49	-0.10	0.57	0.14	0.12	–	0.13	0.21
3 VS 7	ACROSS-SCAN	0.16	0.04	0.20	0.11	0.10	–	-0.66	-0.72
	ALONG-SCAN	0.49	-0.10	0.58	0.14	0.11	–	0.12	0.17
5 VS 7	ACROSS-SCAN	-0.06	-0.06	–	-0.06	-0.05	–	-0.01	-0.01
	ALONG-SCAN	0.01	0.00	–	-0.01	0.00	–	-0.03	-0.03
6 VS 7	ACROSS-SCAN	-3.2	0.39	0.3	0.29	0.16	–	0.03	-0.05
	ALONG-SCAN	-3.0	-0.12	-2.8	-0.03	0.02	–	0.10	-0.42

LANDSAT-4 | LANDSAT-5

* CORRECTED FOR POST-LAUNCH MISREGISTRATION OF SECONDARY FOCAL PLANE.

TABLE 3

SUMMARY STATISTICS FOR BAND-TO-BAND REGISTRATION OF THEMATIC MAPPER BAND COMBINATIONS FOR THE NE ARKANSAS SCENE OF AUGUST 22, 1982 (QUADRANT 4) IN TIPS FORMAT. ALL CORRELATION BLOCKS WITH THE CORRELATION COEFFICIENT <0.6 WERE DISCARDED (<0.3 FOR BANDS 6 VS 7). THE UNIT OF MISREGISTRATION (SHIFT) IS PIXELS.

TM BANDS	SHIFT DIRECTION	NUMBER OF BLOCKS	MEAN SHIFT	STD. DEV.	95% CONFID. INTERVAL FOR MEAN SHIFT
3 VS 1	ACROSS-SCAN	197	-0.04	0.06	-0.04 TO -0.03
	ALONG-SCAN	197	-0.04	0.06	-0.05 TO -0.04
3 VS 2	ACROSS-SCAN	203	0.02	0.07	0.01 TO 0.03
	ALONG-SCAN	203	-0.02	0.05	-0.03 TO -0.01
3 VS 4	ACROSS-SCAN	56	0.00	0.14	-0.04 TO 0.04
	ALONG-SCAN	56	0.07	0.17	0.03 TO 0.11
3 VS 5	ACROSS-SCAN	168	0.10	0.15	0.06 TO 0.12
	ALONG-SCAN	168	-0.10	0.17	-0.12 TO -0.07
3 VS 7	ACROSS-SCAN	198	0.04	0.11	0.02 TO 0.06
	ALONG-SCAN	198	-0.10	0.10	-0.11 TO -0.08
5 VS 7	ACROSS-SCAN	207	-0.06	0.09	-0.07 TO -0.05
	ALONG-SCAN	207	0.00	0.10	-0.01 TO 0.02
6 VS 7	ACROSS-SCAN	130	0.39	1.99	0.05 TO 0.73
	ALONG-SCAN	130	-0.12	1.80	-0.43 TO 0.19

between focal planes). The misregistrations across-scan were reduced from 0.25 to 0.10 for bands 3 versus 5 and from 0.16 to 0.04 for bands 3 versus 7, as can be seen in the first two columns of Table 2. The misregistration of bands 5 versus 7 remained the same at −0.06 pixel. In the along-scan direction, the misregistration was reduced from 0.49 to −0.10 pixel, which indicates that an overcorrection was made, although the misregistration is well within the allowable value of 0.3 pixel between focal planes.

Note the transitive nature of the relationship between bands 3, 5, and 7; the shift between 3 and 5 is equal to the sum of the 3-7 shifts and the 7-5 shifts. This relationship holds exactly for the Arkansas TIPS-corrected data and the across-scan Arkansas Scrounge data, and is within only 0.01 pixel of holding for the along-scan Arkansas Scounge data. In fact, perusal of Table 2 for every scene having bands 3, 5, and 7 shows that the relationship fails by more than 0.01 pixel in only two cases out of twelve, and the maximum failure is by only 0.03 pixel. This consistency is remarkable, in that no attempt at forcing transitivity was made in the statistical analysis and different numbers of blocks were involved in different estimates. In fact, this consistency suggests that the actual along-scan correction applied was 0.59 pixel and the actual across-scan correction was 0.12 pixel for the Arkansas scene.

The thermal band (band 6) misregistration in the Scrounge tape for the northeastern Arkansas scene showed a three-pixel offset in both the vertical and horizontal directions (Table 2). Table 3 shows the across-scan misregistration of bands 6 versus 7 for quadrant 4 of the TIPS product as 0.39 pixel and the along-scan misregistration as −0.12 pixel. The across-scan misregistration still exceeds the specified maximum allowable misregistration of 0.2 pixel in the corrected product. Since the thermal band pixels, as acquired from the satellite, are four times larger than those for nonthermal bands, the specification should perhaps be interpreted as 0.2 of the larger pixel; i.e., 0.8 small pixel. In that case, the misregistration of 0.39 pixel is well within the specification.

Results for the block correlation analysis for quadrant 1 of the Sacramento scene for 12 August, 1983 in TIPS format are shown in Table 4. These results are very similar to those shown in Table 3 for the northeastern Arkansas scene in TIPS format. All the measured misregistrations are less than the specified maxima. Except for band pairs 3 versus 5 and 3 versus 7, the 95 percent confidence limits overlap for corresponding band pairs between the two sets of results. For these two band pairs, the across-scan shifts are greater for the Sacramento scene by approximately 0.06 pixel and the along-scan shifts switch from negative to positive with a total magnitude of 0.24 pixel. Granted that one might not expect tests of the band-to-band misregistrations between two different scenes taken a year apart to be consistent at a level of hundredths of a pixel, but that indeed seems to be the case except for band pairs 3 versus 5 and 3 versus 7. This suggests that the cooled and uncooled focal plane offsets may have been different for the two data sets. Using the same logic that was applied to the northeastern Arkansas results, the authors are tempted to deduce that the across-scan correction actually applied was 0.08 pixel and the along-scan correction applied was 0.35 pixel instead of 0.12 and 0.59 pixel, respectively, for the northeastern Arkansas scene.

A second quadrant (quadrant 4) for the same Sacramento, CA, scene was tested for its consistency with quadrant 1, since results with the northeastern Arkansas scene in TIPS format and with the quadrant 1 Sacramento scene suggested that different correc-

TABLE 4

SUMMARY STATISTICS FOR BAND-TO-BAND REGISTRATION OF THEMATIC MAPPER BAND COMBINATIONS FOR QUADRANT 1 OF THE SACRAMENTO, CA SCENE OF AUGUST 12, 1983 IN TIPS FORMAT. ALL CORRELATION BLOCKS WITH THE CORRELATION COEFFICIENT <0.6 WERE DISCARDED (<0.3 FOR BANDS 6 VS. 7). THE UNIT OF MISREGISTRATION (SHIFT) IS PIXELS.

TM BANDS	SHIFT DIRECTION	NUMBER OF BLOCKS	MEAN SHIFT	STD. DEV.	95% CONFID. INTERVAL FOR MEAN SHIFT
3 VS 1	ACROSS-SCAN	181	-0.04	0.08	-0.05 TO -0.03
	ALONG-SCAN	181	-0.05	0.06	-0.06 TO -0.04
3 VS 2	ACROSS-SCAN	182	0.01	0.08	0.00 TO 0.02
	ALONG-SCAN	182	-0.03	0.04	-0.03 TO -0.02
3 VS 4	ACROSS-SCAN	134	0.01	0.22	-0.03 TO 0.05
	ALONG-SCAN	134	0.02	0.17	-0.01 TO 0.06
3 VS 5	ACROSS-SCAN	177	0.17	0.14	0.15 TO 0.19
	ALONG-SCAN	177	0.14	0.15	0.12 TO 0.16
3 VS 7	ACROSS-SCAN	166	0.11	0.11	0.09 TO 0.12
	ALONG-SCAN	166	0.14	0.15	0.12 TO 0.16
5 VS 7	ACROSS-SCAN	183	-0.06	0.09	-0.07 TO -0.04
	ALONG-SCAN	183	-0.01	0.08	-0.04 TO 0.00
6 VS 7	ACROSS-SCAN	131	0.29	1.35	0.06 TO 0.52
	ALONG-SCAN	131	-0.03	1.23	-0.18 TO 0.24

tions had been applied to the two scenes. The results are shown in Table 5. Columns 4 and 5 of Table 2 show that all the measured misregistrations are within 0.03 pixel for similar band pairs between the two quadrants and the 95 percent confidence intervals overlap. Thus, the discrepancy between the corrections for the Sacramento and northeastern Arkansas TIPS format scenes seems to be real.

Three Landsat-5 scenes of TM data were tested for band-to-band registration. The Corpus Christi, TX (26/41) scene from 6 March 1984 had only the first four bands, but scenes of Huntsville, AL (20/36) from 15 March 1984 and one from Parmer County, TX (31/36) from 8 June 1984 had all seven bands. The Corpus Christi results are shown in Table 6 for quadrant 1 which was completely over land areas. Results for quadrant 1 of the Huntsville scene are shown in Table 7 and those for quadrant 4 of the Parmer County scene in Table 8. For comparable band pairs in the uncooled focal plane, all three Landsat-5 scenes show almost identical shifts—within 0.01 pixel in all cases except Parmer County band 3 versus 4 along-scan, in which it is 0.02 pixel. In each instance, the shifts are well within the allowed misregistration of 0.2 pixel.

Band pairs 3 versus 5 and 3 versus 7 again show a significant misregistration between the primary and secondary focal planes, as they did in the earlier Landsat-4 data. The across-scan misregistration of −0.66 pixel and −0.71 pixel for the Huntsville and Parmer County scenes are each over twice the allowed misregistration of 0.3 pixel and should be corrected. The along-scan misregistrations are 0.13 and 0.21 pixel for bands 3 and 5 and 0.12 and 0.17 for bands 3 and 7 for the same two scenes. This is within the permitted misregistration but should be corrected also. (A negative shift means that with the band first listed being the primary band, the other band must be shifted vertically or left to be in registration.)

TABLE 6

SUMMARY STATISTICS FOR BAND-TO-BAND REGISTRATION OF THEMATIC MAPPER BAND COMBINATIONS FOR QUADRANT 1 OF THE LANDSAT-5 CORPUS CHRISTI, TX SCENE OF MARCH 6, 1984 IN TIPS FORMAT. ALL CORRELATION BLOCKS WITH THE CORRELATION COEFFICIENT <0.6 WERE DISCARDED. THE UNIT OF MISREGISTRATION (SHIFT) IS PIXELS.

TM BANDS	SHIFT DIRECTION	NUMBER OF BLOCKS	MEAN SHIFT	STD. DEV.	95% CONFID. INTERVAL FOR MEAN SHIFT
3 VS 1	ACROSS-SCAN	174	-0.03	0.06	-0.03 TO -0.02
	ALONG-SCAN	174	0.01	0.07	0.00 TO 0.02
3 VS 2	ACROSS-SCAN	180	-0.03	0.05	-0.03 TO -0.02
	ALONG-SCAN	180	0.00	0.06	-0.01 TO 0.01
3 VS 4	ACROSS-SCAN	157	-0.02	0.15	-0.05 TO 0.00
	ALONG-SCAN	157	-0.03	0.12	-0.05 TO -0.01

Geodetic Registration

The latitude and longitude location to the nearest 0.00001 degree of the 14 points were transformed to line and sample coordinates. In Table 9, the visually-derived coordinates for the 14 points are listed under Image Location. The software-derived coordinates are listed under Predicted Location, and the differences in the two methods are listed under Error. The errors are much lower than expected for system-corrected data. The mean errors and standard deviations for the 14 points are 0.0 ± 1.2 lines and −9.7 ± 1.7 samples. Since the mean errors found by Thormodsgard and DeVries (1985) were 35.3 and 44.2 pixels for two scenes, the Sacramento scene results should not be considered typical. Once again, there is no specification for geodetic registration with system-corrected data; these results can only indicate the accuracy possible with such data.

TABLE 5

SUMMARY STATISTICS FOR BAND-TO-BAND REGISTRATION OF THEMATIC MAPPER BAND COMBINATIONS FOR THE SACRAMENTO SCENE OF AUGUST 12, 1983 (QUADRANT 4) IN TIPS FORMAT. ALL CORRELATION BLOCKS WITH THE CORRELATION COEFFICIENT <0.6 WERE DISCARDED (<0.3 FOR BANDS 6 VS. 7). THE UNIT OF MISREGISTRATION (SHIFT) IS PIXELS.

TM BANDS	SHIFT DIRECTION	NUMBER OF BLOCKS	MEAN SHIFT	STD. DEV.	95% CONFID. INTERVAL FOR MEAN SHIFT
3 VS 1	ACROSS-SCAN	189	-0.05	0.10	-0.04 TO -0.03
	ALONG-SCAN	189	-0.04	0.07	-0.05 TO -0.03
3 VS 2	ACROSS-SCAN	191	0.02	0.09	0.00 TO 0.03
	ALONG-SCAN	191	-0.02	0.05	-0.03 TO -0.01
3 VS 4	ACROSS-SCAN	83	-0.01	0.25	-0.06 TO 0.04
	ALONG-SCAN	83	-0.01	0.22	-0.06 TO 0.04
3 VS 5	ACROSS-SCAN	161	0.16	0.14	0.14 TO 0.19
	ALONG-SCAN	161	0.12	0.14	0.09 TO 0.14
3 VS 7	ACROSS-SCAN	167	0.10	0.12	0.08 TO 0.12
	ALONG-SCAN	167	0.11	0.10	0.10 TO 0.13
5 VS 7	ACROSS-SCAN	197	-0.05	0.08	-0.06 TO -0.04
	ALONG-SCAN	197	0.00	0.07	-0.01 TO 0.01
6 VS 7	ACROSS-SCAN	130	0.16	1.47	-0.09 TO 0.41
	ALONG-SCAN	130	0.02	1.21	-0.19 TO 0.23

TABLE 7

SUMMARY STATISTICS FOR BAND-TO-BAND REGISTRATION OF THEMATIC MAPPER BAND COMBINATIONS FOR THE LANDSAT-5 HUNTSVILLE, AL SCENE OF MARCH 15, 1984 (QUADRANT 1) IN TIPS FORMAT. ALL CORRELATION BLOCKS WITH THE CORRELATION COEFFICIENT <0.6 WERE DISCARDED (<0.3 FOR BANDS 6 VS. 7). THE UNIT OF MISREGISTRATION (SHIFT) IS PIXELS.

TM BANDS	SHIFT DIRECTION	NUMBER OF BLOCKS	MEAN SHIFT	STD. DEV.	95% CONFID. INTERVAL FOR MEAN SHIFT
3 VS 1	ACROSS-SCAN	172	-0.03	0.06	-0.04 TO -0.02
	ALONG-SCAN	172	0.00	0.07	-0.01 TO 0.01
3 VS 2	ACROSS-SCAN	191	-0.04	0.05	-0.04 TO -0.03
	ALONG-SCAN	191	0.00	0.05	-0.01 TO 0.00
3 VS 4	ACROSS-SCAN	126	-0.02	0.09	-0.04 TO -0.01
	ALONG-SCAN	126	-0.03	0.10	-0.05 TO -0.02
3 VS 5	ACROSS-SCAN	179	-0.65	0.15	-0.67 TO -0.63
	ALONG-SCAN	179	0.13	0.12	0.11 TO 0.14
3 VS 7	ACROSS-SCAN	186	-0.66	0.14	-0.68 TO -0.64
	ALONG-SCAN	186	0.12	0.12	0.10 TO 0.13
5 VS 7	ACROSS-SCAN	193	-0.01	0.05	-0.01 TO -0.00
	ALONG-SCAN	193	-0.03	0.06	-0.04 TO -0.02
6 VS 7	ACROSS-SCAN	57	0.03	2.63	-0.65 TO 0.72
	ALONG-SCAN	57	-0.10	2.13	-0.65 TO 0.46

TABLE 8

SUMMARY STATISTICS FOR BAND-TO-BAND REGISTRATION OF THEMATIC MAPPER BAND COMBINATIONS FOR QUADRANT 4 OF THE PARMER CO., TX SCENE OF JUNE 8, 1984 IN TIPS FORMAT. ALL CORRELATION BLOCKS WITH THE CORRELATION COEFFICIENT <0.6 WERE DISCARDED (<0.3 FOR BANDS 6 VS 7). THE UNIT OF MISREGISTRATION (SHIFT) IS PIXELS.

TM BANDS	SHIFT DIRECTION	NUMBER OF BLOCKS	MEAN SHIFT	STD. DEV.	95% CONFID. INTERVAL FOR MEAN SHIFT
3 VS 1	ACROSS-SCAN	182	-0.03	0.07	-0.04 TO -0.02
	ALONG-SCAN	182	0.00	0.07	-0.01 TO 0.01
3 VS 2	ACROSS-SCAN	196	-0.04	0.05	-0.04 TO -0.03
	ALONG-SCAN	196	-0.01	0.04	-0.01 TO 0.01
3 VS 4	ACROSS-SCAN	150	-0.01	0.11	-0.02 TO 0.00
	ALONG-SCAN	150	-0.01	0.13	-0.04 TO 0.01
3 VS 5	ACROSS-SCAN	188	-0.71	0.16	-0.73 TO -0.69
	ALONG-SCAN	188	0.21	0.14	0.19 TO 0.23
3 VS 7	ACROSS-SCAN	174	-0.72	0.15	-0.74 TO -0.69
	ALONG-SCAN	174	0.17	0.12	0.16 TO 0.19
5 VS 7	ACROSS-SCAN	193	-0.01	0.06	-0.01 TO 0.00
	ALONG-SCAN	193	-0.03	0.08	-0.05 TO -0.02
6 VS 7	ACROSS-SCAN	126	-0.05	1.25	-0.27 TO 0.17
	ALONG-SCAN	126	-0.42	1.18	-0.63 TO -0.21

Although great care was taken to use only the best test points available, the standard deviations for the mean errors were 1.2 and 1.7 pixels. There are a number of possible sources of error beyond simple location (map error, relief displacement, scanner nonlinearities), but it appears to be difficult to reduce the standard deviation much below one pixel. Since the expected accuracy of GCP-corrected data is 0.5 pixel, the present technique resulting in standard deviations higher than 1 pixel may not be adequate.

Periodic Noise

Periodic noise components at spatial frequencies of 0.053, 0.088, 0.174, and 0.213 cycles/sample (cps) were detected by visual inspection of two dimensional Fourier transforms on the Salt Lake study areas. The 0.088 and 0.174 cps (probably a harmonic of 0.088 cps) frequency noise components were noted in TM bands 1–5, and 7. All four noise components were present in TM bands 2, 3, and 4. Noise components at 0.055, 0.086, 0.172, and 0.203 cycles/sample were observed in the Fourier transform of a 128 × 128 pixel area in the White Sands scene in TM bands 2 and 3. Bands 4 and 5 were not usable and therefore not analyzed. Due to the smaller size of the study area and higher background frequency peak-to-peak magnitudes, it could not be determined if TM bands 1 or 7 did or did not contain frequencies observed in the Salt Lake scene.

TABLE 9

GEODETIC REGISTRATION TEST
SACRAMENTO, CA (44/33), FEBRUARY 1, 1983
SYSTEM CORRECTED SCROUNGE FORMAT

CONTROL POINT	IMAGE LOCATION (L/S)	PREDICTED LOCATION (L/S)	ERROR (L/S)
1. CLARKSVILLE	3624.0/5531.0	3623.4/5540.6	0.6/- 9.6
2. ROCKLIN-A	2926.0/5229.0	2923.7/5238.5	2.3/- 9.5
3. ROCKLIN-B	3165.0/5042.0	3168.1/5056.6	-3.1/-14.6
4. ELK CREEK	792.0/ 633.0	791.8/ 642.6	0.2/- 9.6
5. SHIPPEE	247.0/3170.5	246.3/3181.1	0.7/-10.6
6. VALLEY FORD	5755.5/ 193.0	5757.9/ 200.8	-2.4/- 7.8
7. LINDEN	5836.0/6272.5	5835.2/6281.9	0.8/- 9.4
8. GALT	4830.0/5037.0	4831.3/5047.4	-1.3/-10.4
9. KENWOOD	5198.0/1235.0	5199.2/1244.5	-1.2/- 9.5
10. DETERT	4089.5/1242.0	4089.2/1256.6	0.3/-14.6
11. SUTTER BUTTES	2095.0/3029.0	2095.7/3038.6	-0.7/- 9.6
12. MAXWELL	1524.0/1800.0	1523.3/1808.7	0.7/- 8.7
13. PRINCETON	1154.0/2087.0	1154.4/2095.3	-0.4/- 8.3
14. LAKE COMBIE	2189.0/5431.0	2188.0/5439.8	1.0/- 8.8

MEAN ERROR (L/S): 0.0 ± 1.2/-9.7 ± 1.7

TABLE 10
PEAK-TO-PEAK MAGNITUDES AT PERIODIC NOISE FREQUENCIES

GREAT SALT LAKE – A-TAPE – JULY 2, 1984

SUMMARY OF PEAK-TO-PEAK MAGNITUDES ASSOCIATED WITH PERIODIC NOISE FREQUENCIES IN THE MEDIUM WATER BACKSCAN IMAGE.

	f = 0.053 cps		f = 0.088 cps		f = 0.174 cps		f = 0.213 cps		ALL
BAND	RMS	RANGE	RMS	RANGE	RMS	RANGE	RMS	RANGE	RSS
TM1	–	–	0.47	0.2 - 0.7	0.22	0.0 - 0.4	–	–	0.52
TM2	0.30	0.0 - 0.6	0.23	0.0 - 0.3	0.45	0.0 - 0.7	0.24	0.1 - 0.4	0.64
TM3	0.35	0.2 - 0.5	0.65	0.4 - 1.0	0.47	0.2 - 0.8	0.62	0.1 - 0.8	1.07
TM4	0.17	0.1 - 0.4	0.11	0.1 - 0.2	0.19	0.0 - 0.3	0.17	0.0 - 0.3	0.33
TM5	–	–	0.87	0.4 - 2.5	0.38	0.2 - 0.9	–	–	0.95
TM7	–	–	0.54	0.3 - 1.0	0.29	0.0 - 0.5	–	–	0.61

Table 10 summarizes the peak-to-peak magnitudes of individual noise frequency components estimated according to Equation (1). Table 10 shows both the root mean square value of the peak-to-peak magnitudes of all detectors in a given band as well as the range of the peak-to-peak magnitudes in the band. Table 10 specifically refers to the Salt Lake medium water backscans, but the results are typical of the Great Salt Lake scene. The magnitude of the noise components in each detector approached or exceeded 1.0 gray levels on several occasions, particularly for the 0.088 cps component. Detector 7 of TM band 5 had a magnitude of 2.5 gray levels for the 0.088 cps component. Table 10 also shows the root sum square of the magnitudes at the four frequencies as a conservative measure of the total energy of the periodic noise in each band. TM bands 3 and 5 stand out as particularly noisy with TM band 4 as the least noisy. For comparison with the values in Table 4, the noise-equivalent gray levels in the last column of Table 1 should be multiplied by 2.8 to account for the difference between RMS and peak-to-peak values. When that is done, it is apparent that the periodic noise components are a small part of even the measured noise. Nevertheless, Wrigley, *et al.* (1984) showed that the periodic noise in Landsat-4 concealed patterns in low contrast areas. Figure 1 shows the noise spectra for each detector of TM band 3 for this image, plotted on a logarithmic scale (0.0 is 1.0 gray level). Note that detectors 16, 12, and 5 are especially noisy.

The regularity of these noise components was examined. Figure 1 demonstrates that the noise components and magnitudes vary by detector. The estimated peak-to-peak magnitudes of the individual noise components for the medium water backscans were compared to the corresponding forescan data and tested for significant differences by computing 90 percent confidence intervals based on stationary time series theory (Bloomfield, 1976) on a detector-by-detector basis for all bands except the thermal band. Significant differences were rare, and those instances were primarily in TM band 4, the least noisy band. Similar tests were conducted between the medium water backscan data and the dark water backscan data with similar results. The clear implication is that the periodic noise levels are constant on a detector-by-detector basis, at least for limited areas of the Salt Lake scene. Unfortunately, comparisons between the Salt Lake and White Sands scenes were not possible.

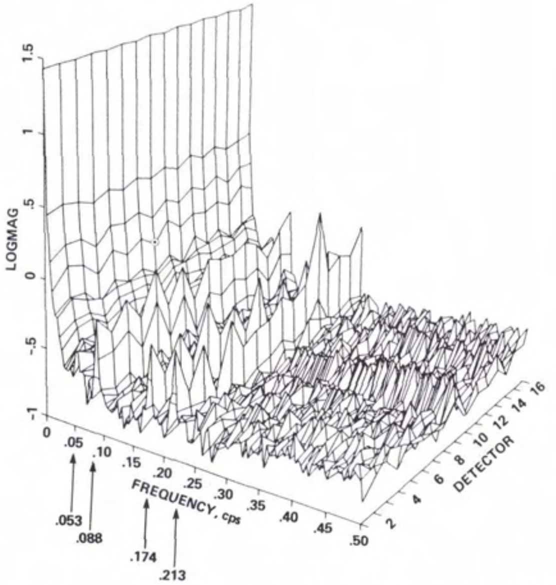

FIG. 1. Fourier spectra of detectors 16 through 1 in TM band 3 for the medium water backscans from the Great Salt Lake scene of 2 July 1984. Peak-to-peak values are plotted on a logarithmic scale.

SUMMARY

In the eight Thematic Mapper scenes analyzed, the band-to-band registration accuracy was high even before correction, and the correction for the shift between focal planes brought all bands into registration according to tight specifications. An objective, almost automatic method for quantifying mean pixel shifts between bands, called block correlation, provided estimates of standard deviations and therefore approximate confidence limits for misregistrations. Registration between bands in the same focal plane, exclusive of the thermal band, proved to be within prelaunch specifications and showed mean values for pixel shifts on the order of hundredths of a pixel. The thermal band presents special problems in that the IFOV is four times as large as that of the other bands, and therefore is resampled in system preprocessing, complicating the interpretation of correlation results. Between the cooled and uncooled focal planes, a misregistration in Landsat-4 data of 0.5 pixel in the along-scan direction and 0.2–0.3 pixel in the across-scan direction was eliminated by TIPS processing. Misregistrations proved to be stable over time prior to image correction. After correction, the Thematic Mapper met the registration specifications between focal planes for all bands. Landsat-5 data showed similar misregistrations between focal planes: −0.65 to −0.72 pixel across-scan and 0.12 and 0.17 pixel along-scan.

Geodetic registration investigations of a system-corrected Scrounge tape using a map projection program developed at EROS Data Center revealed an average error of 9.7 pixels, less than expected. Nothing could be concluded regarding geodetic accuracy of ground control point-corrected data due to the unavailability of GCP-corrected P-tapes.

Analyses of periodic noise indicated noise frequencies in bands 1–5 and 7 of Landsat-5 TM at spatial frequencies of 0.088 and 0.174 cycles/sample. Other noise components at 0.053 and 0.213 cycles/sample were observed in bands 2, 3, and 4. The 0.31 cycles/sample noise in Landsat-4 TM bands 1–4 was not apparent in Landsat-5. The other noise frequencies are similar to Landsat-4 noise frequencies or harmonics of them and may therefore be from the same source. The amount of periodic noise in Landsat-5 TM bands is less than the maximum total noise permitted in the TM specifications, but great enough to degrade the quality of low contrast areas in a scene.

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