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MEASUREMENT OF THEMATIC MAPPER DATA QUALITY

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ABSTRACT

Thematic Mapper data from Landsat-4 and Landsat-5 were examined for band-to-band registration, absolute geodetic registration, periodic noise and spatial resolution. Between focal planes, appreciable misregistrations existed in early data products but were corrected in later data products. The analysis of absolute geodetic registration used only system-corrected data because ground control point-corrected data were unavailable. Geodetic registration errors averaged only 9.7 pixels, less 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 were consistent within a scene. The modulation transfer function was determined for two Landsat-4 scenes. The effective instantaneous field of view was 40.8 meters in one case, and 48.6 meters in the other.

I. INTRODUCTION

The Thematic Mapper (TM) instruments aboard the Landsat-4 and Landsat-5 spacecraft have provided the first 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, NASA's LIDQA program set the more modest goal of trying to quantify specific attributes of the new sensor. The question was asked, how well does 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 band-to-band registration, geodetic registration to a map base, periodic noise and spatial resolution.

II. BACKGROUND

A. BAND-TO-BAND REGISTRATION

Accurate band-to-band registration is essential for the use of multivariate analysis of multispectral data, since a basic assumption of the latter is that all components of a vector of spectral values refer to the same ground location. The accuracy of products generated by multispectral classification 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, pre-launch specifications were stringent: 0.2 pixels between bands in the same focal plane, and 0.3 pixels between bands in different focal planes. The objective of this portion of the 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 inter-band registration accuracy. Walker et al. (1983) evaluated TM P-data of Washington, D.C., Harrisburg, PA, and Salton Sea, CA using line-to-line phase correlation with a fast Fourier transform (FFT) 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 (1983), 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, Iowa, 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.

B. GEODETIC REGISTRATION

In the past, Landsat MSS data has been provided in two geometrically corrected formats: system-corrected, which account 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 attempt to remove any residual errors by refering 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 meters, could be reduced to about 100 meters 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. 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% of the time. It is this specification that is being tested in the current work.

Since TM pixels are originally 30 meters, the geodetic accuracy specification of 0.5 pixels translates into 15 meters 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% of the time. For a 1:24,000 scale map, the standard 7.5' quadrangle, the 0.5 mm allowable error represents 12 meters 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 (1983) developed a program to use this information to 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 their evaluation.

C. 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 for this 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 launch for the Landsat-4 and Landsat-5 instruments. The noise equivalent reflectances for Landsat-5 were also converted into grey levels using a formula developed by Santa Barbara Research Center (1984) along with 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 11/2/82 Landsat-4 Washington, D.C. 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 (John 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. (1983) found all of the above noise components as well as one at 0.4 cycles per 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.

D. SPATIAL RESOLUTION

The spatial resolution of the Thematic Mapper represents the most obvious improvement when viewed in comparison to the MSS. While the 80 meter instantaneous field of view (IFOV) of the MSS compared to the 30 meter IFOV of the TM is the most obvious measure of the improvement in spatial resolution, other factors contribute to spatial resolution such as electronic filtering, pixel sampling (Park et al., 1984) and ground data processing (Fischel, 1984). The need remains to estimate the overall system spatial resolution as it is normally encountered by the user, that is, within the imagery itself.

Wrigley et al. (1984) began the process by examining the effects of the forward and reverse scanning of TM on the modulation transfer function (MTF). They found no difference between the forward and reverse scans. Similarly, they examined the differences between A-data and P-data of the same scene (Washington, DC of November 2, 1982) and found that they could be attributed to the cubic convolution used in resampling the A-data. Wrigley et al. (1984) did not provide any estimate of the width of the point spread function (the Fourier transform of the MTF), but Anuta et al. (1984) estimated its width at half maximum from field edges to be between 39 and 45 meters, depending on the band and the type of smoothing applied. They noted that their estimates were significantly greater than that expected for the optical system itself.

III. METHODS

A. BAND-TO-BAND REGISTRATION

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, 1983). Schowengerdt (1983) gives the mathematical details of the correlation procedure and Anuta (1970) discusses the fast Fourier transform implementation.

B. GEODETIC REGISTRATION

Due to the unavailability of GCP-corrected P-tapes, a system-corrected Landsat-4 Scrounge tape of the February 1, 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 test 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 meters).

The software package assembled at EROS Data Center by Thormodsgard and DeVries (1983) 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.

C. PERIODIC NOISE

Small areas over uniform water in the July 2, 1984 Great Salt Lake Landsat-5 scene A-tape and the October 28, 1984 White Sands Landsat-5 B-tape were examined for the presence of along-scan periodic noise. A 256x256 pixel area over dark water and a 512x256 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 128x128 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 256x256 pixel images from the Salt Lake scene. A spectrum was formed for each detector as the root mean square spectrum of 16 scan lines. The peak-to-peak magnitude, M(f), of a given frequency was estimated from the two magnitudes P1 and P2 at two spatial frequencies [n/256 and (n+1)/256 cycles/sample] which bracketed the underlying frequency, f. Two background values (B1, B2) at (n-2)/256 and (n+3)/256 cycles/sample were subtracted from P1 and P2 to yield an estimate of the noise without the background:

$$M(f) = SQRT\{[P1^2 + P2^2] - [B1^2 + B2^2]\} \quad (1)$$

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

D. SPATIAL RESOLUTION

The determination of the MTF of the Thematic Mapper utilized a target of opportunity, namely the San Mateo Bridge across the southern portion of San Francisco Bay, as a line source feature. To measure the line spread function, the one dimensional analog of the point spread function, a scene with known spatial, spectral and radiometric properties must be used. Since this is not generally possible, targets of opportunity with appropriate characteristics must be used. The Fourier transform of the imaged bridge is the transfer function, whose modulus is the MTF. The San Mateo Bridge makes an angle of 31.1 degrees with respect to the TM scan direction. Two dimensional analysis was performed to extract the image profile perpendicular to the bridge. Furthermore, there is a changing spatial phase between the pixel samples and the bridge from scan line to scan line. This phasing was treated by averaging its effect on the overall system transfer function.

A 128x128 pixel area which included a straight section of the bridge was extracted from two TM scenes of San Francisco (12/31/82 and 8/12/83). The two dimensional fast Fourier transform and its squared modulus, the power spectrum (PS), were calculated for these areas. The PS values along the spatial frequency direction orthogonal to the bridge contain most of the energy in the PS. Spreading of the PS energy away from this direction is caused by the effects of the changing sample-scene phase and other sources of noise in the image (Wrigley et al., 1984). Assuming that the bridge profile has a perfect rectangular radiance function, the average system MTF is given by

$$MTF(v') = \sqrt{PS(v')} / | sinc(Wv') | \quad (2)$$

where W is the width of the bridge and v' is the spatial frequency in the direction perpendicular to the bridge (v' = v/sin 31.1). The sinc term corrects for the finite, sub-pixel width of the bridge. The system MTFs derived by Equation 2 were a somewhat noisy function of v', so a final smoothing step fitted the data with a power series polynomial of the form:

$$P(v') = A + Bv'^2 + Cv'^4 + Dv'^6 + Ev'^8 \quad (3)$$

Only even terms are allowed in Equation 3 since the MTF is a symmetric function of v' about v' = 0. Further details of this method are given by Schowengerdt et al. (1985).

IV. RESULTS

A. 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, Michigan, acquired on July 25, 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 of northeastern (NE) Arkansas (August 22, 1982; seven bands) and Sacramento, California (February 1, 1983; seven bands), and were the first images to be extensively analyzed by the block correlation method. Complete discussions of the Arkansas Scrounge scene and the Sacramento February scene have been presented elsewhere (Card et al., 1983 and Wrigley et al., 1984). Results for the other five scenes will be discussed in detail 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 8/12/83). Also shown is the initial misregistration problem with the Landsat-4 thermal band and subsequent correction.

Additional 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 (NE Arkansas, August 22, 1982, Quadrant 4 and Sacramento, CA, August 12, 1983, Quadrants 1 and 4). For band pairs between the cooled and uncooled focal planes (3 versus 5 and 3 versus 7), the results for Quadrant 4 of the NE Arkansas scene show that the corrections for the initial misregistration have reduced the average shifts to levels that meet pre-launch specifications (0.3 pixels 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 pixels. In the along-scan direction, the misregistration was reduced from 0.49 pixels to -0.10 pixels, which indicates that an over-correction was made, although the misregistration is well within the allowable value of 0.3 pixels between focal planes. Results for the block correlation analysis for Quadrants 1 and 4 of the Sacramento scene for August 12, 1983 in TIPS format are also shown in Table 2. The results for bands 3 versus 5 and 3 versus 7 are very consistent for these two quadrants but different from those shown for the NE Arkansas scene in TIPS format. Quite possibly, different corrections were applied, but all the measured misregistrations are less than the specified maxima.

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

Three Landsat-5 scenes of TM data were tested for band-to-band registration. The Corpus Christi scene from March 6, 1984 had only the first four bands, but scenes of Huntsville, Alabama from March 15, 1984 and one from Parmer County, Texas had all seven bands. For comparable band pairs in the uncooled focal plane, all three Landsat-5 scenes show almost identical shifts -- within 0.01 pixels in all cases except Parmer County band 3 versus 4 along-scan, in which it is .02 pixel. In each instance, the shifts are well within the allowed misregistration of 0.2 pixels.

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 pixels and -0.71 pixels for the Huntsville and Parmer County scenes are each over twice the allowed misregistration of 0.3 pixels, the problem and should be corrected. The along-scan misregistrations are 0.13 and 0.21 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 up or left to be in registration.)

B. GEODETIC REGISTRATION

The latitude and longitude location to the nearest 0.00001 degree of the 14 test points were transformed to line and sample coordinates. In Table 3, 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 test points are 0.0 + 1.2 lines and -9.7 + 1.7 samples. Since the mean errors found by Thormodsgard and DeVries 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.

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 pixels, the present technique resulting in standard deviations higher than one pixel will not be adequate.

C. PERIODIC NOISE

Periodic noise components at spatial frequencies of .053, .088, .174, and .213 cycles/sample (cps) were detected by visual inspection of two dimensional Fourier transforms on the Salt Lake study areas. The .088 and .174 cps (probably a harmonic of .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 .055, .086, .172, and .203 cycles/sample were observed in the Fourier transform of a 128x128 pixel area in the White Sands scene in TM2 and TM3. 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 4 summarizes the peak-to-peak magnitudes of individual noise frequency components estimated according to Equation 1. Table 4 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 4 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 grey levels on several occasions, particularly for the .088 cps component. Detector 7 of TM band 5 had a magnitude of 2.5 grey levels for the .088 cps component. Table 4 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 grey 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. 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 grey 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% 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.

D. SPATIAL RESOLUTION

The average system MTF for TM was determined for each of the non-thermal spectral bands for the two Landsat-4 scenes of San Francisco. The lower resolution of the thermal band (120 meter IFOV) provided very low contrast between the bridge and water and prevented a useful measure of the thermal band MTF. Relatively high noise levels were found in the unsmoothed system MTFs for bands 1-3 of the December scene. This was attributed to the low sun angle on that date: both low light levels and the presence of the bridge's shadow (half the width of the bridge) appeared to be contributing factors. In the August scene, the contrast was higher and the shadow was insignificant so the system MTFs were all of good quality. The system MTFs for bands 4, 5 and 7 of the December scene and bands 1-5 and 7 of the August scene were averaged to yield system MTFs for each scene. The results are shown in Figure 2, along with a model of the sensor-only MTF developed by Markham (1984). Both of the system MTFs derived from the imagery are lower than the sensor-only model and the August scene, with the most reliable data, provides the lowest system MTF, i.e. the lowest resolution. The sensor-only model did not attempt to account for sampling, resampling and atmospheric effects. Of these, the original sampling into 30 meter pixels probably is the most important effect.

The effective instantaneous field of view (EIFOV) can be calculated as one-half the reciprocal of the spatial frequency at which the MTF drops to 0.5. The EIFOVs for the system MTFs for the two scenes analyzed and the sensor-only model are given in Table 5. The EIFOV for the December scene was 40.8 meters and the EIFOV for the August scene was 48.6 meters, compared to 33.8 meters for the sensor-only model. The EIFOVs for the two scenes compare favorably to the widths of the point spread function developed by Anuta et al. (1984).

V. 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. Registration between bands in the same focal plane, exclusive of the thermal band, proved to be within pre-launch 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 pixels in the along-scan direction and 0.2 - 0.3 pixels 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 misregistration between focal planes: -.66 to -.72 pixels across-scan and .12 to .17 pixels along-scan.

Geodetic registration investigations of a system-corrected Scrounge tape using a map projection program developed at EROS Data Center revealed errors 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 .088 and .174 cycles/sample. Other noise components at .053 and .213 cycles/sample were also observed in bands 2, 3, and 4. The .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.

Use of the San Mateo Bridge as a target of opportunity for the determination of the system MTF showed that for the two Landsat-4 scenes analyzed the MTF was lower than a sensor-only model of the MTF. The difference was due to the fact that the sensor-only model did not attempt to account for effects due to sampling, resampling or the atmosphere. The EIFOVs for the two scenes were 40.8 and 48.6 meters compared, to 33.8 meters for the sensor-only model.

Table 1. Noise specifications and measurements for the Thematic Mapper.

Thematic Mapper Band	Specification for Noise-Equivalent Reflectance Change	Measured Noise-Equivalent Reflectance Change		Noise-Equivalent Grey Level
		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	0.010	0.0023	0.0025	1.2
7	0.024	0.0041	0.0037	1.5

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	-.04	-.04	-.05	-.04	-.05	-.03	-.03	-.03
	Along-scan	-.03	-.04	-.04	-.05	-.04	.01	.00	.00
3 vs 2	Across-scan	--	.02	--	.01	.02	-.03	-.04	-.04
	Along-scan	--	-.02	--	-.03	-.02	.00	.00	-.01
3 vs 4	Across-scan	.01	.00	.02	.01	-.01	-.02	-.02	-.01
	Along-scan	.01	.07	.01	.02	-.01	-.03	-.03	-.01
3 vs 5	Across-scan	.25	.10	.33	.17	.16	--	-.65	-.71
	Along-scan	.49	-.10	.57	.14	.12	--	.13	.21
3 vs 7	Across-scan	.16	.04	.20	.11	.10	--	-.66	-.72
	Along-scan	.49	-.10	.58	.14	.11	--	.12	.17
5 vs 7	Across-scan	-.06	-.06	--	-.06	-.05	--	-.01	-.01
	Along-scan	.01	.00	--	-.01	.00	--	-.03	-.03
6 vs 7	Across-scan	-3.2	.39	.3	.29	.16	--	.03	-.05
	Along-scan	-3.0	-.12	-2.8	-.03	.02	--	.10	-.42

Landsat-4 | Landsat-5

* Corrected for post-launch misregistration of secondary focal plane.

Table 3. Geodetic registration test for the Sacramento, CA scene (44/33) of February 1, 1983 in system-corrected Scrounge format.

Test Points	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 4. Peak-to-peak magnitudes at specific periodic noise frequencies for the Great Salt Lake scene (39/31) of July 2, 1984 in A-Tape format. Summary of peak-to-peak magnitudes associated with noise frequencies in the medium water, backscan image. An rms average for the band as well as the range for individual detectors is shown.

Frequencies

	f = .053 cps		f=.088 cps		f=.174 cps		f=.213 cps		all
band	rms	range	rms	range	rms	range	rms	range	rss
TM1	-	--	.47	.2 - .7	.22	.0 - .4	-	--	.52
TM2	.30	.0 - .6	.23	.0 - .3	.45	.0 - .7	.24	.1 - .4	.64
TM3	.35	.2 - .5	.65	.4 -1.0	.47	.2 - .8	.62	.1 - .8	1.07
TM4	.17	.1 - .4	.11	.1 - .2	.19	.0 - .3	.17	.0 - .3	.33
TM5	-	--	.87	.4 -2.5	.38	.2 - .9	-	--	.95
TM7	-	--	.54	.3 -1.0	.29	.0 - .5	-	--	.61

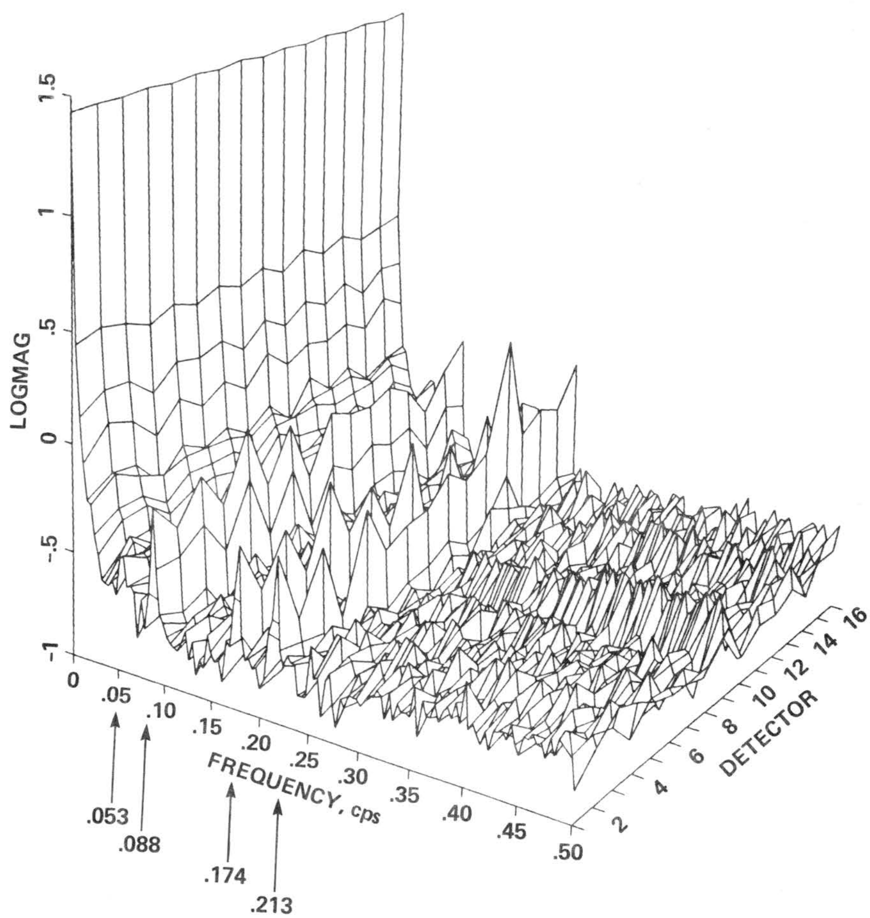

Figure 1. Fourier spectra of detectors 16 through 1 for the medium water backscans from the Great Salt Lake scene of July 2, 1984. Peak-to-peak values are plotted on a logarithmic scale.

Table 5. Effective instantaneous field of view for Landsat-4.

Data type	EIFOV (meters)
System-only model (Markham, 1984)	33.8
San Mateo Bridge (12/31/82)	40.8
San Mateo Bridge (8/12/83)	48.6

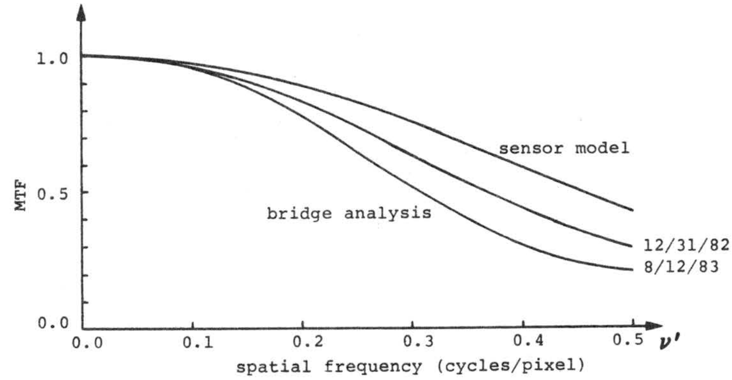

Figure 2. System modulation transfer functions for Landsat-4.

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