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Abstract

The objective of this work is to provide a broad assessment of Thematic Mapper data quality in addition to specific investigations of particular topics including band to band registration, scene to scene registration, geodetic rectification, interdetector responses, and spatial resolution. Preliminary results for investigations of band to band registration and interdetector responses are presented. Based on the Thematic Mapper images analyzed so far, the band to band registration accuracy of this complex instrument is very good. For bands within the same focal plane, the mean misregistrations are well within the specification, 0.2 pixels. For bands between the cooled and uncooled focal planes, there is a consistent mean misregistration of 0.5 pixels along-scan and 0.2-0.3 pixels across-scan. It exceeds the permitted 0.3 pixels for registration of bands between focal planes. If the mean misregistrations were removed by the data processing software, an analysis of the standard deviation of the misregistration indicates all band combinations would meet the registration specifications except for those including the thermal band. The large registration error for the latter may be due to conceptual problems in registering data of different spatial resolutions. Analysis of the periodic noise in one image indicates a noise component in band 1 with a spatial frequency equivalent to 3.2 pixels in the along-scan direction.

Keywords: Thematic Mapper, image quality, band to band registration, periodic noise.

Introduction

Recent failures of components aboard Landsat-4 and problems with deployment of the Tracking and Data Relay Satellite (TDRS) have severely constrained the volume of Thematic Mapper (TM) scenes available for analysis. Even before these recent developments, the anticipated volume of TM scenes was to be small and provision was made for this eventuality in the original mission planning. NASA decided to concentrate investigations on data quality to offset the anticipated shortfall in data quantity. Another major reason for adopting this approach was that previous analyses of data quality--as in the case of the Multispectral Scanner (MSS) on previous Landsats--were reported only in limited circulation engineering reports. The benefit of this direct attack on the issue of data quality is that it provides the remote sensing community with a better perspective of the details of the complex TM instrument and the characteristics of the output data it provides. The danger of this approach is that it leads to a concentration on problems and may give the unwarranted impression that the instrument is a poor one.

The present study attempts to provide a broad assessment of TM data quality in addition to specific investigations of particular topics including band to band registration, scene to scene registration, geodetic rectification, interdetector responses and spatial resolution.

Band to band registration is essential for multispectral uses of the data. Swain[1] has shown that even a 0.3 pixel error in registration affects classification accuracy. Band to band registration is being investigated by a number of techniques: flickering images on a display screen, band to band subtractions, block correlations of subwindows scattered throughout the scene, and examination of the effects of precisely located mirrors reflecting sunlight into the scanner. The block correlation technique will also be used to investigate issues relating to scene to scene registration. Evaluation of the geodetic registration of the scene will employ a large number of manually located control points in image and map space to check image location and develop an independent regression whose residuals will be a measure of the ultimate geodetic accuracy to be achieved by the Thematic Mapper.

An examination of interdetector responses will look at the phenomonon of sixteen line striping and other periodic noise. The procedure will employ a factorial experiment on selected areas of uniform brightness. An analysis of variance will test the significance of the factors (detector number and brightness). A related task will involve the development of an image of the periodic noise in the scene using Fourier techniques and use it to generate a noise-free image. Before and after classifications with the same set of multispectral clusters will display any reduction in classification striping, one of the most troubling effects of interdetector variations.

In a cooperative investigation with R. A. Schowengerdt of the University of Arizona, the spatial resolution of the TM will be studied by a number of techniques: a power spectrum analysis used to determine the modulation transfer function of the first Landsat MSS instrument[2], edge gradient analysis using edges carefully selected for sharpness and spectral uniformity on either side, determination of the point spread function from the mirror experiments mentioned earlier, and a side by side comparison of classifications of strip cropped areas in Montana by the TM and MSS instruments.

This paper will report on results of preliminary investigations of some of these aspects of Thematic Mapper data quality--primarily band to band registration and, to a lesser extent, interdetector response and other periodic noise.

Background

The Thematic Mapper (TM) is a complex instrument and no attempt will be made to describe it in detail but a few of the pertinent characteristics will be mentioned. Gordon[3] recently provided an excellent account of the complex spatial/temporal relationships between the TM bands; some of his points are repeated here. The detectors for all seven TM bands are in the optical focal plane whereas MSS used fiber optic bundles to conduct light to photomultiplier tubes and photodiodes. The TM arrangement is conceptually better because light losses in the fiber optics are eliminated, but the physical size of the detectors and their amplifiers means that large pixel offsets between bands will be necessary. Indeed, 25 pixels separate each of the four visible/near infrared bands for a total offset of 75 pixels. From the blue band to the thermal band there is a total 180.75 pixel offset (in ground distance that represents 5.4 km). In simple terms, large offsets mean that different bands are not imaged simultaneously as the scan mirror sweeps across the ground. For the maximum case, when the blue band senses a given pixel, the thermal band senses a pixel 5.4 km down the scan line. The middle and thermal infrared bands are in a separate, cooled focal plane joined to the other bands by transfer optics so that any misadjustment of the transfer optics could be serious. Software exists to correct these spatial/temporal offsets but its job is made more difficult by the fact that TM collects data in both sweep directions, forward and back: the spatial/temporal offsets must be reversed in the back-scan mode. It is even more difficult to reverse the effects of electronic filtering. Because of the large inter-band offsets, small or erratic spacecraft motions, caused by the MSS mirror hitting its stops or TDRS antenna movements, can cause spectral misregistrations. To correct for such motions, the TM has an attitude displacement sensor for motion frequencies up to 100 Hz and software to use its information. The software attempts to meet very stringent specifications for band to band registration: 0.2 pixels between bands in the same focal plane, i. e. bands 1-4 and 5-7, with 0.3 pixels permitted between bands in different focal planes, i. e. TM1 and TM5. On the positive side, the TM photodiode detectors have such stable calibrations compared to the MSS photomultiplier tubes that little 16 line striping should be noticeable (each of the reflective bands has 16 detectors instead of 6 as with MSS).

Methods

The analysis of band to band registration accuracy was addressed by several methods. The simplest involved displaying two or more bands of the same area on an interactive display system and flickering between them. With appropriate expansions (2-4 pixel replications), this technique was a quick and powerful way for an analyst to survey small areas for misregistrations. In fact, it permitted discovery of all significant misregistrations discussed below, but did not provide a convenient mechanism for quantifying them. To display a visual pattern of a large area more permanently, band to band subtraction proved quite useful. Treatment of a 4096 pixel square portion of an early TM image was performed using the VICAR software system and included both the subtraction and automatic stretch of the result. The image was subsequently displayed on the interactive display as well as on film by a digital film recorder. An example of the film output will be shown below. The technique used to generate the most quantitative results for band to band registration was block correlation, a method normally used for scene to scene registration. Basically, a set of square blocks of 32x32 pixels from one band was statistically correlated with a corresponding set of 64x64 pixels from another band. Each block pair was centered with respect to the other and treated with a gradient operator to enhance edges. The correlation coefficient was computed for every possible location of the smaller block within the larger block. The position of the maximum correlation was considered to be the best estimate of registration for the block pair. Subpixel accuracy for location of the correlation maximum was obtained by bi-quadratic interpolation on the eight pixels surrounding the maximum correlation pixel. Shifts of the maximum correlation from the nominal position were recorded for both along-scan and across-scan directions. By correlating one band with itself, Card et al.[4] showed the subpixel interpolation contributed standard deviations for the shifts of only 0.01 and 0.04 pixels in the across-scan and along-scan directions, respectively. Block correlations were conducted at 320 locations throughout a TM image on a 16 by 20 grid covering the whole image. After scene border deletions, some 297 blocks remained for analysis. These remaining blocks were edited to discard those with low correlations or very large

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shifts. Such effects were usually due to clouds or lack of edges in the block. Card et al.[4] also showed that the summary statistics of the shifts (mean, standard deviation) were not sensitive to the editing procedure. The final technique for measuring band to band registration, using mirrors to reflect sunlight into the satellite during an overpass and creating single pixel spikes of light, has not been used to date. The mirror technique would be limited in accuracy to a major fraction of a pixel (0.5-0.7) because of problems involved in estimating placement of the mirror within the pixel. The technique was considered to be a back-up method in case the block correlation method proved inaccurate due to spurious spectral correlations. The latter does not appear to be the case. The study of interdetector variations and other periodic noise has only just begun, but Fourier transform techniques have been used to examine one data set for periodic noise components. A 128x128 pixel window of one band was tested by a Fast Fourier Transform on a minicomputer and the magnitude of the

Figure 1. Band to band subtraction of bands 1 and 3 from Thematic Mapper scene of Detroit, Michigan. A few of the misregistered blocks are underlined.

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output image examined on an interactive display system. Image selection from processed scenes is in progress to select candidates for analysis that have large uniform areas. Ideally, the same scene should include several such areas, each with a different brightness level to determine the effects of the latter on periodic noise.

Results

Band to Band Registration

Several images have been examined for band to band registration accuracy to date. The first image available, which had only the first four bands, was of Detroit, Michigan, acquired on July 25, 1982 (ID 4000915413). Flickering bands 1 through 3 from this image on an interactive display revealed a number of rectangular blocks that were misregistered. The blocks were approximately 16 pixels across-scan and 128 pixels along-scan and were scattered regularly throughout the image. They were more easily observable in highly patterned urban areas than in surrounding agricultural areas. Some blocks were 32 pixels high. Due to a strong negative correlation, no misregistration could be discerned when band 4, the near infrared band, was flickered with any of the others. Bands 1 and 3 were subtracted from one another and displayed on film using the film recorder. Figure 1 is an enlargement from the original 4096x4096 pixel image covering some 1200 pixels on a side. Detroit is in the upper central portion with Lake St. Clair in the upper right and the Detroit River in the center. A few of the misregistered blocks have been underlined so the subtle edge enhancement within the blocks can be observed. Note the stair-step pattern of the blocks themselves. Careful examination reveals more than 20 other blocks. When other band combinations were subtracted, misregistered blocks were located in different areas. Use of band 2 in a subtracted pair of bands caused 16 line striping due to repeated lines replacing data dropout from a faulty detector in band 2. Analysis showed that the top line within each block was a repeat of the one above and that lower lines were displaced downward. Hence, the misregistration was a full pixel. The block correlation technique would have difficulty measuring these misregistrations; few blocks would be situated correctly. Fortunately, the problem noted in the Detroit scene was fixed very early during de-bugging of the image processing software and has not recurred. On the other hand, Figure 1 illustrates the way TM imagery is pieced together. The 16 by 128 pixel blocks are treated as a unit with all the corrections available; that is, nominal offsets as well as information from the Attitude Displacement Sensor are used in block fashion. The second TM image examined was of north eastern Arkansas acquired on August 22, 1982 with all seven bands (ID 4003716031). Neither flickering nor band subtraction showed any effects similar to those in the Detroit scene. However, flickering did show an apparent misregistration between the visible bands (TM 1-3) and the middle infrared bands (TM 5,7) of approximately one half pixel in the along-scan direction. Flickering also showed a 3-4 pixel error in the thermal band in both the along-scan and across-scan directions, roughly a full thermal band pixel. Due to the lack of visual correlation between the thermal band and any other band, it was difficult to find areas where the registration could be checked. Card *et al.*[4] analyzed this image by the block correlation method and a summary of their results is shown in Table 1. These results not only confirm the flickering results but add a needed element of quantificaton.

Table 1

Summary statistics for band to band registration of Thematic Mapper band combinations fo the Arkansas scene, August 22, 1982. All correlation blocks with the correlation coefficient <0.6 were discarded (<0.3 for 6 *vs* 7). The unit of misregistration (shift) is pixels.

TM Bands	Shift Direction	Number of Blocks	Mean Shift	Std. Dev.	95% Conf. Int. for Mean Shift	
3 *vs* 1	Across-scan	256	-.04	.06	-.05	-.03
	Along-scan	256	-.03	.06	-.04	-.02
3 *vs* 4	Across-scan	40	.01	.16	-.01	.03
	Along-scan	40	.01	.16	-.01	.03
3 *vs* 5	Along-scan	215	.25	.25	.22	.28
	Along-scan	215	.49	.25	.46	.52
3 *vs* 7	Across-scan	264	.16	.20	.14	.18
	Along-scan	264	.49	.18	.47	.51
7 *vs* 5	Across-scan	280	.06	.09	.05	.07
	Along-scan	280	-.01	.07	-.02	.00
6 *vs* 7	Across-scan	96	-3.2	3.1	-3.8	-2.5
	Along-scan	96	-3.0	2.7	-3.5	-2.4

The mean shifts measured for bands within the same focal plane (3 *vs* 1, 3 *vs* 4, 7 *vs* 5) are all well within the specification of 0.2 pixels. The block correlation technique was able to estimate the misregistration between the visible bands and the near infrared band; the flickering technique was not able to do so even in the Detroit scene with large misregistrations. Note that the number of blocks remaining after editing dropped substantially when the near infrared band was included, probably due to the negative correlation. Because of the uncorrelated nature of the thermal band with respect to the others, the editing criteria was changed to include correlation coefficients down to 0.3 in order to incorporate more than four correlation blocks in the summary statistics of Table 1. Nonetheless, the shifts shown in Table 1 for bands 6 *vs* 7 are a more precise and informative estimate of the misregistration than could be obtained by the flickering technique. For future work, it may be possible to select specific blocks within the image that appear correlated for submission to the block correlation program.

This would have the effect of increasing the number of blocks with high correlation and thereby improving the quality of the results.

The final image examined for band to band registration accuracy was of Sacramento, California acquired February 1, 1983 (ID 4020018145). The image had about thirty percent cloud cover. Flickering bands 1-5 showed no problems of registration except a fairly subtle one in combinations which used band 5. Unfortunately, bands 6 and 7 were not available for analysis. More spectral differences between bands 3 and 5 were noted for this image than in the Arkansas scene. Results of the block correlations for three band pairs are shown in Table 2. Once again, blocks with correlations less than 0.6 were edited out. Note that the number of blocks retained for TM3 vs TM1 and TM3 vs TM5 are significantly lower than for the Arkansas scene. To include more blocks in the analysis, the editing was repeated with the correlation criterion lowered to 0.3 and a few large outliers discarded. The number of blocks increased to 172, 131 and 209, respectively, but the means and standard deviations were unchanged. The results in Table 2 are remarkably similar to those for the Arkansas scene in Table 1. Mean shifts for TM3 vs TM1 and TM3 vs TM4 are essentially zero again with standard deviations of 0.1 and 0.2 pixels, respectively. Mean shifts for TM3 vs TM5 are marginally higher than for the earlier scene. On the other hand, the 95 percent confidence limits set by Card *et al.*[4] for the earlier scene overlap those for the Sacramento scene in all cases. The stability of these results with scenes taken more than five months apart is very high and contributes to confidence in the reliability of the block correlation technique as implemented at Ames.

The high stability of the block correlation results noted above suggests more importance might be attributed to the standard deviations than previously thought possible. For band pairs within the same focal plane (except for TM6), the standard deviations were smaller than permitted misregistrations, 0.2 pixels. This would indicate the bands would be registered within 0.2 pixels 68 percent of the time or better if the mean shifts were zero. According to the Arkansas scene results, this would also be true for TM3 vs TM7 if the mean misregistration were removed. The standard deviations for TM3 vs TM5 are close to the permitted 0.3 pixels in both cases and might indicate registration problems even if the mean misregistrations were removed. Since TM5 and TM7 were so well registered in the Arkansas scene, it is likely that something else is contributing to the standard deviation and that TM5 would also be registered if the mean shifts were removed. One possible contribution to the standard deviation might be the repeated line present in TM5 due to a detector that failed before launch. At a minimum, the repeated line would lower the correlation but its effect on the shift is unknown.

Table 2

Summary statistics for band to band registration of Thematic Mapper band combinations for the Sacramento scene, February 1, 1983. All correlation blocks with the correlation coefficient <0.6 were discarded. The unit of misregistration is pixels.

TM Bands	Shift Direction	Number of Blocks	Mean Shift	Std. Dev.	95% Conf. Int. for Mean Shift	
3 vs 1	Across-scan	87	-.05	.09	-.07	-.03
	Along-scan	87	-.04	.08	-.06	-.02
3 vs 4	Across-scan	44	.02	.19	-.04	.08
	Along-scan	44	.01	.17	-.04	.06
3 vs 5	Across-scan	68	.33	.32	.25	.41
	Along-scan	68	.57	.32	.49	.65

Periodic Noise

The task to evaluate interdetector variations and other periodic noise will examine TM imagery in the A-tape format. The A-tape format data has been corrected radiometrically but not geometrically. The geometric correction process resamples the data by cubic convolution so that individual detector outputs are no longer identifiable. The design of the factorial experiment for interdetector variations requires detector identification so the A-tape format will be necessary. The magnitude of a Fourier transform of a 128x128 pixel window of TM1 from a scene of Washington, DC acquired on November 2, 1982 (ID 4010915140) in A-tape format was examined. The area included only water for uniformity. A relatively strong peak in the magnitude of the Fourier image was centered at a spatial frequency of 5.33 pixels in the across-scan direction. Smaller peaks were observed at 16 and 32 pixels as well as other harmonics of the 16 line pattern. The peak at 5.33 pixels is a subharmonic and is not yet understood. A smeared peak was also observed at 3.2 pixels in the along-scan direction with across-scan components at 2.7 and 8.5 pixels which may correspond to noise. Since A-tape data contains along-scan offsets every 16 lines of 40-50 pixels, some of the smearing of these peaks may by caused by the offsets.

Summary

Based on the Thematic Mapper images analysed so far, the band to band registration accuracy of this complex instrument is very good and it promises to be excellent when the few anomolies found are corrected in the data processing. Simple techniques proved effective for detecting all the problems found. More sophisticated techniques, such as block correlation, provide quantitative estimates for the mean misregistrations as well as other very useful statistical descriptors such as standard deviation and confidence limits. Except for the thermal band, the registration of all bands with others in the same focal plane is not only within specifications, the mean shifts are so low as to be almost unmeasurable (0.01-0.06 pixels). Between the cooled and uncooled focal planes there is a consistent misregistration of 0.5 pixels in the along-scan direction and 0.2-0.3 pixels in the across-scan direction. The misregistration is so stable that the confidence limits overlap from two images acquired more than five months apart. Once this stable misregistration is removed, the Thematic Mapper should also meet its registration specifications between focal planes. The problem with the large misregistration of the thermal band may have more to do with the conceptual problem of merging this lower resolution band with the other bands than with physical misregistration. Preliminary analyses of periodic noise indicate a noise component in band 1 with a spatial frequency equivalent to three pixels in the along-scan direction. Work is continuing to evaluate the data quality of the Thematic Mapper in a number of aspects as data becomes available.

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