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LANDSAT THEMATIC MAPPER GEODETIC ACCURACY: IMPLICATIONS FOR GEOCODED MAP COMPATIBILITY*

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ABSTRACT

An in-depth analysis of the geodetic accuracy and geometric fidelity of corrected thematic mapper imagery has been undertaken at the JPL Multimission Image Processing Laboratory under the auspices of the Landsat Investigations Data Quality Analysis Program. The results of those investigations are reported here in a manner that highlights the ease with which the Thematic Mapper data can be interfaced with other geocoded data bases or used for cartographic purposes.

Landsat-5 Thematic Mapper, precision processed, P-Product, scenes were analysed to determine their geometric integrity and conformance to the earth's surface geometry. The geometric integrity tests performed included: band-to-band registration along a line, line-to-line registration within a swath, swath-to-swath registration, and scene-to-ground control location. Earth's surface geometry tests measured the actual versus projected position of Space Oblique Mercator (SOM) and Universal Transverse Mercator (UTM) processed products using P-tape calibration data and ground control points. These are tests similar to those performed previously on Landsat-4 data.

The geometric integrity tests showed TM-5 data to meet or exceed registration accuracies found on the TM-4. No problems were observed in the intraband analysis, and aside from indications of slight misregistration between bands of the primary versus bands of the secondary focal plane, interband registration and swath alignment was well within the specified tolerances. In addition, overall gemetric integrity of TM scenes was tested for conformance to ground control. A least-squares fit between the line/sample position and latitude/longitude for selected ground control points in each scene was computed. A root mean square error of 27.27 meters across entire scenes was observed. This closely approximates the accuracy specifications for the TM. Moreover, a significant portion of the error component may be attributable to the precision of ground control point selection.

The test for assessing conformity of the P-Product data to earth surface geometry revealed problems with using the Space Oblique Mercator Projection (SOM). A Chi-Squared goodness of fit test between projected and observed northing and easting position on a UTM grid for ground control points revealed a significant exceeding of the error budget. Subsequent analysis showed that the image center data computed from ephemeris information was in error. This creates discontinuous distortions from the actual earth geometry which can only be retrieved by use of a number of somewhat uniformly distributed control points per scene and the application of a third order mapping function. Avoidance of this problem for the SOM projection can be achieved by the ground processing system either receiving a more accurate ephemeris from using the GPS (Global Positioning System) or identifying a select number of ground control points along an orbit path. The user can avoid this problem by specifying UTM formatted P-data, identifying three or more ground control points in a scene, and computing the offset within the UTM zone.

A final set of tests were applied to determine the impact, if any, of topographic relief upon Thematic Mapper data conformed to earth surface geometry and the ability to measure relief from adjacent image overlays. TM-4 scenes of Harrisburg, PA and Salton Sea, CA were used for this analysis. The results of these tests have shown that relief has virtually no impact on horizontal map accuracy statistics in all terrain types except those with very large relief displacement over short distances. The effect of terrain can, however, affect the pixel-for-pixel registration between scenes in the same path and row acquired at different dates. The measurement of relief using the stereo effect at overlap between adjacent paths proved marginal at best. While stereo effect can be observed, the very large height to base

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ratio and 30 meter resolution precludes accurate topographic mapping.

In summary, users can expect Landsat Thematic Mapper digital products to meet or exceed 1:100,000 map accuracy standards for horizontal control. Using UTM projected P-format data should provide nearly edit-free data for registering other geocoded information in vector or image format. The Thematic Mapper should not be considered for elevation mapping purposes, but may be a useful analytic tool in some terrain types.

1.0 INTRODUCTION

Since the initiation of the Landsat Project, and the Thematic Mapper (TM) development, there has been concern over the geometric accuracy criteria. Performance requirements have been defined in terms of end product goals, but until recently have not precisely detailed the conditions under which that accuracy is to be achieved. The Thematic Mapper is a sensor with higher spatial resolution and finer spectral discrimination than any previous NASA satellite system. In order to achieve the higher spatial and spectral resolutions, the TM sensor was designed to image in both forward and reverse mirror sweeps, in two separate focal planes. The established MSS ground data processing systems required major changes to correct the new data's geometry and radiometry. Scanner imaging systems suffer from continuous along-track and across-track geometric distortions which can be mitigated by both hardware systems and ground processing software corrections. Both hardware and software have been augmented and changed during the course of the Landsat TM developments to achieve improved geometric accuracy. The changes instituted in spacecraft and sensor hardware to achieve project objectives have required adaptation in ground segment processing algorithms and procedures. The purpose of this research has been to verify the accuracy of the geometric corrections applied and to assess the overall geometric integrity of the data.

1.1 Background

Understanding and compensation for geometric positioning errors is important for two reasons. First, there is the need to achieve map projection positioning to determine site location and register ancillary data encoded by latitutde/longitude. Second, there is the need to register multiple passes of imagery to develop multitemporal data sets for change detection and crop mensuration. Thus, while it is accepted that the higher spatial resolution of the TM will fulfill object recognition requirements for larger scale maps than the MSS, it has been the object of this research to determine if the TM meets the National Map Accuracy Standards for geometric accuracy at larger scales.

The variety of sensor and spacecraft geometric properties contributing to positional error estimates have been reviewed by Prakash and Beyer[1]. The error budget analyses performed show that the TM systematic geometric error may present problems with pixel level registration between acquisitions in level terrain. This may be the case for two reasons: a) the scanner system geometry is more complex than MSS (i.e., forward and reverse acquisitions), and b) the smaller IFOV (i.e., 30 x 30 meters vs. 57 x 80 meters) presents a high probability of band-to-band misregistration within one scene acquisition and a greater incidence of pixel misalignment between two acquisitions. The degree of misalignment will be mitigated by ground control point processing. The impact of relief and simple elevation upon the projective geometry of scanning systems is well understood. What is not fully appreciated, nor could be adequately examined until flight data became available, is the interaction of horizontal displacement due to interworking of scan angle from nadir, surface relief, and the movement of the nadir track and altitude associated with different acquisitions.

1.2 Positional Accuracy Requirements

Early MSS systems suffered from along-track and across-track geometric distortions which had to be mitigated with ground processing software corrections. Scan line problems caused errors on the order of up to 7 pixels per line in some scenes. After corrective processing, root mean square (RMS) vector errors of the digital data were reduced to the one pixel target, Bernstein[2] reported an RMS vector error of 60.6m for the data, while the 'good' scenes evaluated by Graham and Luebbe[3] the accuracy of the ground control point (GCP) corrected data varied between one and two pixels. At this level of precision, the digital data met the National Map Accuracy Standards for scales at or above 1:125,000.

When the latest generation of multispectral scanner, Thematic Mapper, was being designed, rigorous specifications for the corrected data's geometry were established. Not only were the geometric requirements more stringent than for MSS, but also the smaller IFOV and the necessary hardware design changes presented more possibilities for interband misregistration and other image geometry problems. A single band was required to be accurate to within 0.5 pixels of true Earth-surface locations at any point over 90% of the image. With its 30 meter pixel resolution this figure was equivalent to 15 meters on the Earth's surface, or between 4 and 8 times as precise as its MSS predecessor had proven to be. Between band (interband) registration accuracies were stipulated to be within a 0.3 pixel tolerance (9 meters) over 90% of the data. The same figure was established for the registration between scenes of different dates (temporal registration) of the same area.

It has been the object of this research to determine the degree to which the TM geometric accuracy criteria has been achieved on Landsat 4 and 5, and and the implications of the accuracy achieved to geographic information systems applications.

2.0 METHODS AND RESULTS

2.1 Overview

For the purposes of this investigation, two TM4 and five TM5 scenes were analyzed. Table 1 summarizes the analysis performed on each scene. Five characteristics related to image geometry were investigated: a) Single band geometric integrity, with particular regard to mirror-scan swath alignments; b) The registration between the 30 meter resolution bands (bands 1 - 5, and 7) of the same image; c) Image to image conformity; d) Conformance of the images to a ground control; and e) Conformance of the image projective geometry to a mapped earth geometry.

2.2 Tests of Intraband Integrity and Interband Registration

2.2.1 Technique:

The band-to-band and line-to-line registration was measured at one hundred pixel spacings along a line using the phase correlation image alignment method developed by Kuglin and Hines[4] and adapted to a one-dimensional FFT correlation technique. Misregistration of swaths on forward and reverse scans of the TM was suspected. If that had been the case, phase correlation of the last line of preceding scan and first line of the subsequent scan would have shown an offset, which could have varied along the line, due to nonlinearity of scan velocity with time. A program was developed that allowed sampling of each line of the image in a number of locations (corresponding to ground features) and determine the offset in each location relative to the other line.

2.2.2 Intraband Integrity:

A test was developed to check a single band's geometric integrity on a mirror-scan swath basis. Band 3 (0.63 - 0.69) from each scene was chosen as the test case. To guarantee that swath edges were included, four lines in the vicinity of the presumed swath edges (multiples of 16 lines) were used in this test. It was verified that swath borders were included computing swath positions on Thematic Mapper Image Processing System (TIPS) products.

An analysis of the tabulated and plotted results revealed that line-to-line misregistration was on the order of 0.3 pixel maximum. Plots failed to show any systematic misregistration effects that can be directly associated with local jitter. These figures indicate that there are no apparent problems in the alignment of the corrected mirror scan swaths within a single band for TM5 TIPS products. Our findings are comparable to those of other Landsat-4 investigators. Band-to-band misregistration findings for this scene are essentially the same as those found by Barker[5], Bender[6], Berstein[7], Gurney and Eng[8], and Card[9].

2.2.3 Interband Registration:

A similar test using the modified Kuglin and Hines method was performed to assess the interband registration of the high spatial resolution bands (i.e., all except band 6) of TM. Rather than looking at adjacent scan lines of one band, the same scan line of different bands were taken to evaluate how closely they correlated. The assumption was made that although the bands were sensed in different spectral regions, their patterns would be similar for a given line of registered data. Systematic offsets in a certain direction (positive or negative) would be judged as misregistration between bands, whereas randomly variant (and small) offsets would be indicative of well-registered data sets. It should be noted that mismatches in correlation sometimes occurred between different bands because of normal variation in scene patterns or anomalous features.

For the Landsat-5 TM, Washington DC an Northwest Iowa scenes of P-data only were investigated. Bands 1 through 4, all in the PFP, appeared to be well registered with one another. Offsets determined by the correlation technique were both positive and negative and were randomly distributed about zero (Figures 1 & 2). Between bands 1 (PFP) and 5 (SFP), however, in both TM5 scenes analyzed, 85-90% of all offsets were negative, indicating a strong probability of systematic misregistration between those bands (Figure 7). The offsets were generally of small magnitude (i.e., <0 and ≥0.35 pixels). Questionably large offsets occurred between band 7 and all other bands in both the PFP and the SFP. They were so large that they are probably a result of either a failure in the correlation technique or a large dissimilarity of spectral reflectances between band 7 and all other bands for the areas examined.

2.3 Image-to-Image Conformity

A third part of this investigation concerned the conformity P-tapes from the TIPS processed TM5 data to the SCROUNGE processed TM4 data. For this test, roughly 80 ground control points (GCP) were obtained for each of the TM4 scenes. The Iowa scene GCPs were collected by the USGS facility at Flagstaff, Arizona. It should be noted that another test of image-to-image conformity could have been undertaken if two acquisitions for the same path/row from the same Landsat using ground control points had been available.

The procedure used in comparing the scene pairs involved using an algorithm which performs automated two-dimensional image correlations. Three independently established tiepoints between each scene pair were found, and based upon these tiepoint pairs, the routine computed a model transformation between the scenes. The line-sample coordinates of the input (TM4) were transformed into predicted output coordinates in TM5. The algorithm then computed the two-dimensional correlation function on a 64 x 64 pixel area surrounding the predicted point, and by finding its maximum, determined the point which best corresponded to the input tiepoint. Along with each 'best-fit' point in TM5 the algorithm computed the value of a correlation function which indicated how well the output point chosen fit the input TM4 GCP. Due to changes in relative spectral characteristics of some areas, the algorithm failed to locate some of the points at or above the threshold correlation value. These points were discarded from further analysis. The routine was rerun with only the well-matching points. The conformity of the TM5 scenes to their TM4 counterparts was reduced to linear equations describing the affine transformation from TM4 to TM5 scene.

For Iowa:

(TM5 line) = 1.0001346*(TM4 line)+0.000976*(TM4 sample)-54.83

(TM5 sample) = 0.000828*(TM4 line)+1.0001051*(TM4 sample)+109.8

The coefficients of these equations indicate very little scene rotation and aspect distortion.

In general, the algorithm located points in the TM5 scene which deviated only slightly from the point predicted by the initial model based upon the three points. These fits indicate an undistorted geometric correspondence between the SCROUNGE processed data and the TIPS processed image. They also indicate that after computing offset, the user should find scene to scene registration at the subpixel level for areas the size of a TM quadrant or less in regions of low relief.

2.4 Conformance to Ground Control

2.4.1 Technique:

The sensor and spacecraft geometric calibration analysis was checked using existing software and procedures developed recently[10]. Those procedures developed for mosaicking Landsat MSS scenes, were used to identify the offset from a least squares surface plane projected through ground control points located in the TM images and on 1:24,000 and/or 1:62,500 topographic maps. Only those points which could be precisely located on both the CRT and a map were selected. The GCP earth coordinates were digitized from the maps with the dominant measurement error being a roundoff down to the nearest 1/10,000 of a degree. The next step was to compute the linear least-squares fit between the earth and image coordinate systems. This could not be done with a straight-forward linear function, however, since the TM data had been processed into a unique map projection called the Space Oblique Mercator (SOM).

2.4.2 The SOM Projection:

An *a priori* knowledge of a satellite image's projection is essential in order to assess its conformity to Earth-surface geometry. Without its consideration, projection-induced deformations can result in trends of 'errors' of such magnitude that real sensor or processing errors are effectively obscured.

The standard projection in which Thematic Mapper data are processed, the SOM, was conceptualized by Colvocoresses in 1973, and mathematically derived by Snyder (1978) and Junkins (1977) working independently[11]. The SOM requires minimal pixel resampling and consequently reduced computer processing time, both of which are very important considerations in the handling of the immense data load of TM. Until recently, software which projects Earth coordinates into SOM coordinates (and the reverse) has not been available. One of the key steps in this research was the acquisition and implementation of the newly-developed SOM software from John Snyder at the National Cartographic Information Center (NCIC).

Before the SOM software was acquired, a preliminary linear least-squares fit between the unprojected Earth coordinates and the image coordinates was computed in order to better understand the SOM projection and its effects on image geometry. The mean residuals were close to ten pixels (300m), and their standard deviations were near six pixels (108m). The residual vectors, plotted in two dimension, produced systematic patterns which were attributable in part to the SOM projection (not shown here).

2.4.3 The Least-Squares Fit:

The SOM software, once received, was put into an Image Based Information System (IBIS)* routine through which the Earth coordinates were projected into their SOM equivalents. A linear least-squares fit was then performed on the TM Northwest Iowa scene using the SOM coordinates as the independent variables (since the map accuracies were known) and the image coordinates as dependent variables. Both coordinates were input in terms of meters. The parameters of the

* The Image Based Information System (IBIS) is a computer based system enabling the analysis of a variety of phenomena in a geographic context. As a subset of the VICAR (Video Image Communication and Retrieval) processing system, it allows for the vector and tabular as well as raster data-type inputs[12].

linear fit (which related the TM image to absolute locations on Earth) were not studied, since the early ground processing of TM data did not utilize ground data reference to accurately locate absolute position.

On the first run a few of the GCPs had unreasonably large residuals. Consequently, those GCPs were removed from the analysis. In the edited data the resulting residual distance was 27.27 meters. A two-dimensional plot of the residual vectors, magnified by a factor of 60 to enhance visibility, is presented for the Northwest Iowa scene in Figure 4. No significant trends were detectable in the two-dimensional plots of the residuals. These results are similar to those found by Wrigley, et al, and Welch and Usery[13].

2.5 Conformance of Image Projections to Mapped Projections

With the decreasing IFOVs of satellite sensors, the closeness of approximation of GCP locations has become a crucial factor in the assessment of data geometric properties. Chi-square tests of confidence in the geometric conformity of the Northwest Iowa TM5 scene was undertaken. The TM5 TIPS product analysis is reviewed here:

2.5.1 SOM Error Budget:

The error specified for the TIPS product was half of a pixel 90% of the time. This meant that the SOM-projected pixels should be within 15 meters of where they would be in a perfect SOM map of the area. Note that this is an accumulated system error bound, including all errors prior to TIPS processing.

The method is to find ground control points (GCPs) on 1:24,000 maps in latitude/longitude coordinates. Applying the SOM transformation on these yields a SOM coordinate position which may still be off by a linear transformation from the SOM-projected Landsat. (This is a general linear transformation that includes slides, rotates, and skews.) The statistical assumption that the transformation is linear is tested by performing linear regression and calculating chi-squared for the residuals:

$$2 = \frac{1}{n-2} \quad \overset{n}{\underset{i=1}{}} \quad \frac{e_i^2}{{}_i^2}$$

where e_i is the residual error reported for the i^{th} GCP in the SOM projected image and ${}_i$ is the root mean square measurement error in e_i.

The Northwest Iowa scene was used for this test. Fifty GCPs were chosen from 1:24,000 paper maps of the area and the corresponding line-sample locations were identified by cursor (a computerized cross-hair) on an image display screen with enlargement capability. The map latitude/longitudes were converted to SOM coordinates using a computer routine with negligible error. A least-squares linear fit of the SOM coordinates to the pixels' locations was performed with negligible error. The resulting residual error was 31.4 meters RMSE. Thus,

$$2 = \frac{N}{N-2} \cdot \frac{\text{mean}(\text{residual}^2)}{2}$$

Table 2 shows an allocated error budget for calculating . The TIPS processing error is included, and is reduced from the 90% fraction to a one sigma error distance. The resulting ^{2} is 1.906 which gives weak confidence that the TIPS product is linearly related to an SOM map of the Earth's surface.

The next step is to enlarge the TIPS error bound to bring ^{2} below 1.0 which would correspond to a confidence level of 0.5 that the TIPS product met its error bound. By allowing the TIPS RMSE to be 23.89 meters a ^{2} of 1.0 results. This corresponds to an error of 39.5 meters or less, 90% of the time, or about one and one-third pixels.

Referring again to Figure 4, note that most of the GCPs were chosen around the perimeter of the Iowa scene, so the statistical test was somewhat stringent.

2.5.2 Spacecraft Ephemeris and the SOM Projection:

The lack of conformity of the SOM projected latitude/longitude position of a ground control point (GCP) and the observed position of that GCP revealed by the chi-squared goodness of fit test initiated a search for the cause. It was first noted that the SOM uses the centerpoint for a given frame and the center pixel for the first and last line in a scene to compute a unique projective geometry for that scene and that scene alone. The centerpoint pixel determines the northing from the equator and the center pixels of the first and last scene determine the prime meridian orientation (see Snyder)[11]. This point is illustrated in Figure 5, maps the exaggerated vector offsets between a SOM projected version and UTM projected version of the Landsat 5 Harrisburg scene were ground control points used. It can be seen from the figure that the distortion surface is not affine, but rather a complex polynomial that can only be recovered by the selection of a number of GCPs. Conversely, the development of a correct SOM projection depends on an accurate assignment of latitude and longitude to the centerpoint of a scene, and any deviation from absolute positioning knowledge will incur projection distortions recoverable only by the selection of a number of GCPs and the development of a complex polynomial surface.

The accuracy of the SOM for any scene is only as good as the orbit ephemeris data. The ephemeris constraints, as specified in the

Landsat Ground Station Interface Description[14], are rigorous, but not rigorous enough to enable the SOM to be used without ground control or the Global Positioning System (GPS) to obtain the actual nadir track and scene centerpoint positions. Table 3 summarizes these findings for selected TM5 scenes. Avoidance of this problem for the SOM projection can be achieved if the TIPS processing segment were to systematically receive a more accurate ephemeris by using the GPS or identifying a select number of ground control points along an orbit swath.

Further investigations showed that another alternative exists if the TM data are projected in the UTM projection. The UTM projection has a designated prime meridian within a zone, rather than the SOM choice of the nadir track as a prime meridian. Because of this fact, when the TM ephemeris is calculated in the absence of ground control, but projected in UTM, any discrepancy is the function of a Northing and Easting offset. Figure 12, which displays the vector offsets for the Landsat 5 Des Moines, Iowa scene projected to UTM, one with and one without ground control, illustrates this point. The vectors, all uniform, represent the actual versus observed centerpoint difference of 54.339 meters easting and 279.772 meters northing. Thus, the user can avoid any need to apply complex polynomial surface fits to data sets he wishes to register to a TM scene if he specifies UTM projected data (<u>not</u> the default option) and identifies three or more GCPs to calculate an offset correction to apply to the nominal header information.

2.6 <u>Relief Impacts</u>

A final set of tests were applied to determine the impact, if any, of topographic relief upon Thematic Mapper data map projected to conform to earth surface geometry. Horizontal displacement due to elevation off the nadir track is known to cause misregistration of multitemporal overlays, local distortions to true geodetic position, and are used by photogrammetrists in areas of adjacent scene overlap to measure elevation. Two Landst-4 Thematic Mapper images were analyzed for relief displacement impacts, a Harrisburg, PA scene wherein 219 ground control points were identified and a Salton Sea, CA scene, wherein 165 ground control points were identified. Two tests were applied. The first compared GCP residuals from the initial surface fit to residuals from a modelled surface that removed offsets due to elevation at eavh GCP. The second compared residuals from the initial surface fit with residuals from a surface developed from a subset of GCPs displaying both large elevation variance from the mean and located far from the nadir track.

2.6.1 Modelled Relief Test

The first test applied a model that removed the offset computed to be associated with off-nadir relief displacement for all GCPs in each scene. This involved the computation of a curved earth parallax and then computing the positional error associated with the terrain elevation.* Given the height of the spacecraft, the earth can for all practical purposes be considered flat, so that horizontal offset associated with off-nadir viewing of mountainous terrain is the tangent of the view angle. Table 4 presents the results of the elevation compensation modelling. As expected, removal of offsets due to elevation resulted in both smaller mean residuals to the surface fit and a lower variance in GCP residual values.

2.6.2 Selected Points Test

The second test involved the selection of GCPs in each of the two analysis scenes that should provide the extreme coordinates in positional offset. Only those GCPs that were both in the left- or right-hand third of the scene and had an elevation which was more than one standard deviation from the mean elevation for all GCPs in the scene were selected. By choosing this subset of the GCPs, it was felt that the worst case for misregistration between multi-temporal acquisitions at the same path/row position and overlap of acquisitions at adjacent path/rows could be analysed. As a corollary, the results of such a test could help assess the utility of the stereographic effect associated with displacement under conditions of side-lap in computing elevation contours. Table 5 presents the comparison of surface fit residuals of the selected versus total populations of GCPs. The results show that for both scenes, the mean and variance of the residulas did deteriorate but not by a very large amount.

2.6.3 Relief Impact Analysis

The result of the elevation offst tests has illustrated four points of importance to individuals wishing to interface other geocoded map products and/or derive additional information from multiple TM scene analysis.

<u>First</u>: The horizontal displacement due to elevation in a scene still lies within the horizontal positional accuracy requirements for 1:100,000 scale maps under the worst case, and come close to achieving 1:50,000 map accuracy standards for the Harrisburg, PA scene. The TM is, therefore, an excellent map product.

<u>Second</u>: It would appear that misregistration of pixels in two or more scenes from the same path/row due to relief <u>should not</u> cause problems in most terrain conditions if UTM projected scenes are used. This statement can be made because the difference between horizontal positions before and after elevation offset compensation does not exceed the 0.3 pixel (i.e., 10 meters) requirement for TM. Further-

* W. D. Stromberg at JPL provided assistance in the computations and model development.

more, the study by Gunther[15], which showed that scene centers for Landsat-5 vary within 7.12 km of nominal, indicates that differences in nadir track positions are so slight as to not effect displacements associated with look angle differences.

Third: Misregistration of pixels from scenes in two adjacent paths due to relief should cause problems in moderate to high relief terrain conditions. This is because the cummulative difference in horizontal displacement would exceed 0.3 pixel (10 meters) on the average. As Billingsley[16] has pointed out, for field boundaries, misregistration causes the borders in a given set of bands to be closer than expected to a given pixel, with the result that the mixed materials in a pixel cause additional pixels to fall outside of class limits. As a result minimum field size configuration acceptable for TM analysis will be larger than originally assumed.

Fourth: The amount of horizontal displacement between adjacent paths where scene overlap occurs is not enough to measure relief and obtain relative or absolute elevation contours. As Welch[17] has shown, both the IFOV as well as the displacement due to parallax are critically interrelated elements if terrain measurement is desired. Offst associated with parallax on the TM is insufficient due to the very shallow view angle (7.5 degrees off nadir maximum) to recognize elevation differences. Moreover, the IFOV is too large to develop contour intervals of 250 meters or less regardless of the parallax effect.

3.0 CONCLUSIONS

The results of this investigation indicated that Thematic Mapper imagery, in terms of geometry, has come close to and in some cases exceeded its stringent specifications. Single bands appeared to have properly aligned forward and reverse scans in the corrected P-data, and interband registration, according to the methods used, was well within the required tolerances. The overall geometric quality of P-data was very good. The SOM-projected Earth coordinates left small residuals when fitted to the image coordinates with a linear least-squares function in the scenes scrutinized. The budgeted RMS errors were close to the mean residuals; thus the fit might very well have been better than the results indicated.

The TM data were highly accurate to the UTM projection and good for SOM over the entire scenes. The absolute locations were unknown for early scenes due to the lack of geodetic control in the SCROUNGE ground processing system. For these scenes users must find three or more points to establish a georeference for the whole scene. Users are advised to obtain the SOM projection software from NCIC to locate within or process the scene. Polynomial fitting is not recommended for relating TM data to other geographic coordinate systems, as low-order polynomials do not fit TM well and higher order polynomials exhibit bad behavior in the corners of the scene.

The absolute projective geometry for TM scenes without ground control exceeds the limits of the chi-squared goodness of fit criteria when SOM projections are applied. This is a function of the SOM projection characteristics, and can easily be avoided by specifying UTM projected products, observing the absolute offset, and applying it to the scene.

A final set of tests to determine the impact, if any, of topographic relief upon Thematic Mapper data map projected to earth surface geometry and the ability to measure relief from adjacent image overlays. The results of these tests have shown that relief has virtually no impact on horizontal map accuracy statistics in all terrain types except those with very large relief displacement over short distances. The effect of terrain can, however, affect the pixel-for-pixel registration between scenees in the same path and row acquired at different dates. The measurement of relief using the stereo effect can be observed, the very large height to base ratio and 30 meter resolution precludes accurate topographic mapping.

In summary, users can expect Landsat Thematic Mapper digital products to meet or exceed 1:100,000 map accuracy standards for horizontal control. Using UTM projected P-format data should provide nearly edit-free data for registering other geocoded information in vector or image format. The Thematic Mapper should not be considered for elevation mapping purposes, but may be a useful analytic tool in some terrain types.

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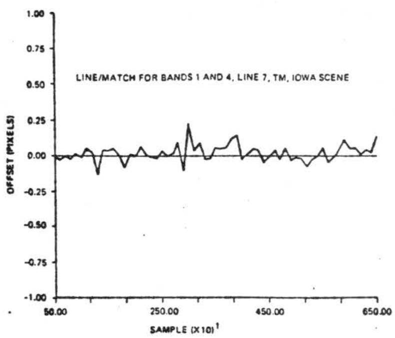

Figure 1: Between band linematch correlation between two bands of the primary focal plan (PFP), in this case between bands 1 and 4, for Northwest Iowa Scene 50046-16324, April 16, 1984.

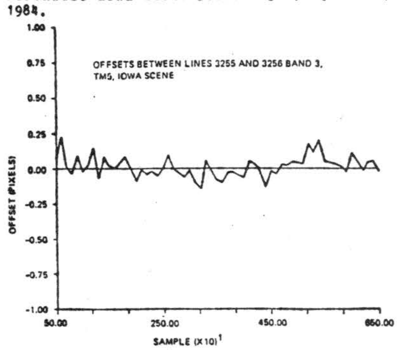

Figure 2: Plot showing offsets between a swath of a forward and a swath of a reverse scan in TM Band 3, for Northwest Iowa Scne 50046-16324, April 16, 1984.

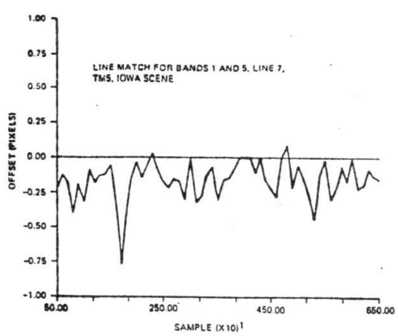

Figure 3: Between band linematch correlation between band 1 (PFP) and band 5 (secondary focal plane) for Iowa Scene 50046-16324, April 16, 1984.

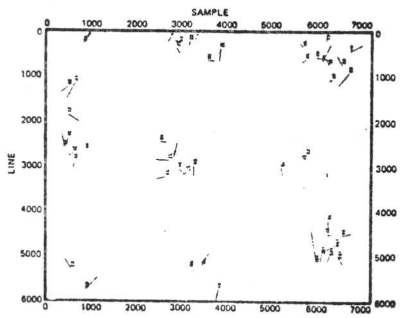

Figure 4: Two-dimensional plot of residuals between GCPs found in TM5 Northwest Iowa Scene (50046-16324) April 16, 1984, and SOM projected lat-longs of the same (magnification factor 300).

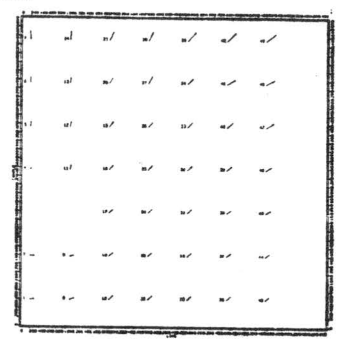

Figure 5: Two-dimensional plot of vector offsets between SOM and UTM projections of TM5 Scene (50099-15141) of Harrisburg, PA, dated June 8, 1984. Both scenes had TIPS processing with GCPs. Offsets reflect difference between UTM zonal and SOM scene specific projective geometries.

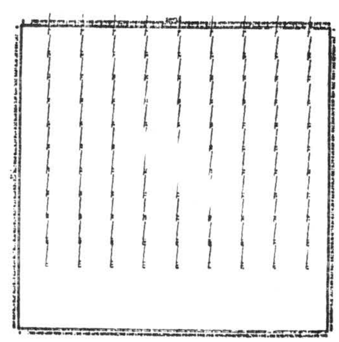

Figure 6: Two-dimensional plot of vector offsets between TIPS processed TM5 imagery of Des Moines, Iowa Scene 850114-16223) dated July 23, 1984, one with and the other without GCPs.

TABLE 1: SUMMARY OF LANDSAT THEMATIC MAPPER SCENES ANALYZED

	LOCATION	SCENE ID	DATE	ANALYSIS APPLIED
1.	Washington DC	50023-15112	03/24/84	a) A-tape and P-tape line matching within a band b) P-tape band-to-band matching in primary and secondary focal plane
2.	Northwest Iowa	50046-16324	04/16/84	a) P-tape band-to-band matching in primary and secondary focal plane b) Conformance of P-tape to TM4 scene c) Conformance of SOM projection to mapped earth geometry, without GCPs
3.	Harrisburg, PA	50099-15141		a) Comparison of SOM and UTM projections with TIPS GCPs
4.	Salton Sea, CA	50203-17462	09/20/84	a) Conformance of SOM projection to mapped earth geometry, with GCPs
5.	Des Moines, IA	50114-16223	07/23/84	a) Comparison of UTM projection with and without GCPs in TIPS processing

TABLE 2: ERROR BUDGET FOR CHI-SQUARED TEST OF SOM PROJECTED TM IMAGE TO EARTH'S GEOMETRY
Scene 50046-16324 (Elevation Excluded)

	PIXELS (RMS)	METERS (RMS)
TIPS Specified Error	0.302	9.07
GCP Location in Image	0.670	20.00
Map Accuracy (1:24,000)	0.250	7.50
		23.21

TABLE 3: CENTERPOINT LOCATION OF TM5 P-TAPE SCENES CALCULATED FROM EPHEMERIS VERSUS OBSERVED FROM GROUND CONTROL

	NORTHWEST IOWA (50046-16324) SOM	DES MOINES, IA (50114-16223) UTM
Ephemeris Calculated:		
Northing (km)	608.9104	4,623.8701766
Easting (km)	15,266.3305	499.5803424
Ground Control Point Observed:		
Northing (km)	607.8507	4,623,8647427
Easting (km)	15,266.0477	499.5523652
Difference:		
Northing (km)	1,059.7000	54.3390000
Easting (km)	282.5000	279.7720000

TABLE 4: ELEVATION COMPENSATION MODELLED RELIEF HORIZONTAL OFFSET ANALYSIS
Mean and Variance of Residual GCPs from a Linear Surface Fit

	WITHOUT ELEVATION REMOVAL	WITH ELEVATION REMOVAL
Harrisburg, PA Scene		
Mean:	26.95 meters	26.45 meters
Variance:	18.69 meters	17.89 meters
Salton Sea, CA Scene		
Mean:	40.46 meters	32.11 meters
Variance:	30.57 meters	23.85 meters

TABLE 5: COMPARISON OF HORIZONTAL OFFSET FOR ALL VS. SELECTED GCPs
Mean and Variance of Residuals from Each Linear Surface Fit

	ALL GCPS	SELECTED GCPS
Harrisburg, PA Scene		
Mean:	26.95 meters	30.62 meters
Variance:	18.69 meters	21.47 meters
Salton Sea, CA Scene		
Mean:	40.46 meters	45.55 meters
Variance:	30.57 meters	31.15 meters

NOTE: Selected GCPs were in left or right thirds of scenes and had elevations greater than one standard deviation from mean elevation for all GCPs in a scene.