Comparative Evaluations of the Geodetic Accuracy and Cartographic Potential of Landsat-4 and Landsat-5 Thematic Mapper Image Data

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ABSTRACT: Geodetic rectifications of Landsat-4 and Landsat-5 TM data in CCT-pt formats have produced RMSExy values of ±0.23 to ±0.93 pixel for data sets of Iowa and Georgia. Polynomials of the first degree and as few as four GCPs have proved sufficient to fit full- and quadrant-sized scenes to the UTM map coordinate system to subpixel accuracies. Comparisons of data sets produced on Scrounge and TIPS indicate a slight geometric superiority for the TIPS. System and scene corrected Landsat-5 CCT-pt's of Iowa cast on the UTM projection and processed on TIPS produced residual errors of ±0.23 and ±0.26 pixel, respectively. These values are within NMAS for 1:24,000 scale maps. Overall, the Landsat-4 and Landsat-5 TM data meet accuracy standards for maps of 1:50,000 scale or smaller and are well-suited for image maps of 1:100,000 scale. Other potential cartographic applications include the revision of existing maps and the production of orthoimages from DEMs prepared from sidelapping data sets by automatic stereo correlation techniques.

INTRODUCTION

As part of the National Aeronautics and Space Administration's (NASA) Landsat Image Data Quality Analysis (LIDQA) Program, studies are underway to evaluate the geometric fidelity of Landsat-4 and Landsat-5 Thematic Mapper (TM) data in computer compatible tape (CCT-pt) formats. Specific objectives include: (1) determination of scene-to-map rectification accuracies for system corrected data produced on both the Scrounge and TM Image Processing System (TIPS); (2) direct comparisons of the geodetic accuracy of Landsat-5 system and scene corrected data sets for the same area; (3) identification and quantification of error sources, including those attributable to spatial resolution, digitizing/map errors, and terrain relief; and (4) assessments of the cartographic quality of Landsat-4 and Landsat-5 data as related to the detail and geometric accuracy requirements for various scales of map products.

The Landsat-4 and Landsat-5 systems provide image data of significantly better geometric fidelity than were obtained from the earlier Landsat missions. Specifications call for temporal registration to within ±0.3 pixel and geodetic rectification to ±0.5 pixel at the 90 percent level of confidence. Because cross-track and along-track errors are considered separately, it is convenient to convert these values to root-mean-square planimetric (X, Y) vector errors (RMSExy) commonly employed by photogrammetrists and cartographers to denote accuracies at the 68 percent level of confidence. Thus, for the TM data, the specifications equate to ±.26 and ±.43 pixel, respectively, for temporal registration and geodetic rectification.

A pixel in the above calculations (and in this discussion) is equated to the instantaneous field-of-view (IFOV) with an angular value of 42.5 μrad or 30 m on the ground. Thus, the equivalent RMSExy values that conform to the Landsat-4 and Landsat-5 specifications are ±7.8 m for temporal registration and ±12.9 m for geodetic rectification. The latter value is compatible with U.S. National Map Accuracy specifications (NMAS) for cartographic products of 1:50,000 scale and smaller.

Factors which influence the geometric fidelity of the Landsat TM data include the pointing and stability of the multimission modular spacecraft (MMS) and the correction procedures applied to the data in the Scrounge and TIPS ground segments. Specifications for Landsat-4 and Landsat-5 call for a pointing accuracy of 0.01° (1 sigma) and an attitude stability of 10^{-6} °/sec (1 sigma), which represent approximately two and four orders of magnitude improvement, respectively, over the previous Landsat systems. Webb and Watt (1984) report that the Precision Attitude Central System of Landsat-4 and Landsat-5 has performed within the design specifications and that earth pointing is routinely main-

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tained to within 0.015° and attitude is known to better than 10 arc seconds at the three sigma level of confidence.

The TM ground processing of Landsat-4 data for the LIDQA investigations was initially performed on the Vax 11/780-based Scrounge system at NASA's Goddard Space Flight Center. Its purpose was to process TM data in an engineering mode during the period between TM instrument activation and the implementation of data processing on TIPS. During this period, which extended from September 1982 to August 1983, system corrected CCT-pt's were produced at the rate of one scene per day in a band-sequential (BSQ) format (NOAA, 1983).

The now operational TIPS is designed to provide CCT's of 6250 or 1600 bits per inch (bpi) in BSQ or band-interleaved by line (BIL) formats. One quadrant of scene data is contained on a single 6250 bpi or three 1600 bpi CCTs.

The main functions of both processing systems have been the radiometric and geometric correction of the TM data. Geometric correction matrices are derived from the payload and mirror scan correction data and take into account: sensor and satellite attitude; satellite ephemeris; high frequency structural disturbances; TM optics and the location of the detectors on the focal planes; nonlinearities in the scan mirror profile and scan line corrector; and desired cartographic projections (Beyer and Salomonson, 1984; Irons, 1985). In addition, control point processing is being used in TIPS to remove bias and drift errors in system corrected data and to generate geodetic or scene corrected data. Scene corrected CCT-pt's involve the location of up to 25 ground control points (GCPs) per scene by automatic correlation with data stored in a control point library. The system and scene corrected CCT-pt's are registered to either the Space Oblique Mercator (SOM) or Universal Transverse Mercator (UTM) projection, and resampled by a cubic convolution algorithm to 28.5 m × 28.5 m pixels. TIPS also permits nearest neighbor resampling.

STUDY AREAS AND DATA SETS

Study areas in Georgia and Iowa have been used for these comparative evaluations (Figure 1, Table 1). Two scenes were acquired over north Georgia in late 1982 by the Landsat-4 TM, corresponding to path 18, row 36 (P18R36) (7 November 1982) and path 19, row 36 (P19R36) (16 December 1982) in the Landsat Worldwide Reference System (WRS) (Figure 1a). An initial set of CCT-pt's for these scenes was processed on the Scrounge system without reference to ground control (system corrected) and cast on the SOM projection. A second system corrected CCT-pt for the same P19R36 scene was subsequently processed on TIPS and provided to the investigators for comparison with the Scrounge data set.

The Landsat-4 scenes for Georgia are characterized by a blend of urban and rural land use features with terrain relief varying from about 1000 m in the rugged Appalachians of Georgia, Tennessee, and North Carolina, to less than 30 m on the Piedmont areas of Georgia and South Carolina. Much of the Piedmont is agricultural with randomly scattered small towns and cities (Plate 1a). The varied nature of the landscape and the absence of a regular, systematic pattern of roads and transportation features complicates the identification of GCPs. Typically, GCPs included road intersections, bridges across rivers, or other natural features that were readily identifiable on U.S. Geological Survey (USGS)

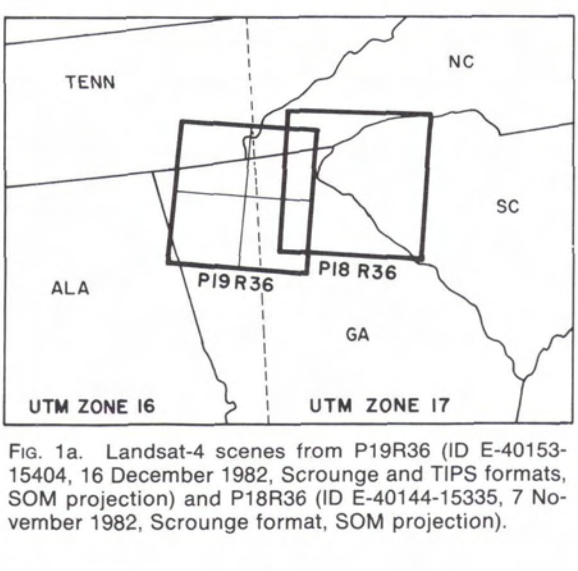


FIG. 1a. Landsat-4 scenes from P19R36 (ID E-40153-15404, 16 December 1982, Scrounge and TIPS formats, SOM projection) and P18R36 (ID E-40144-15335, 7 November 1982, Scrounge format, SOM projection).

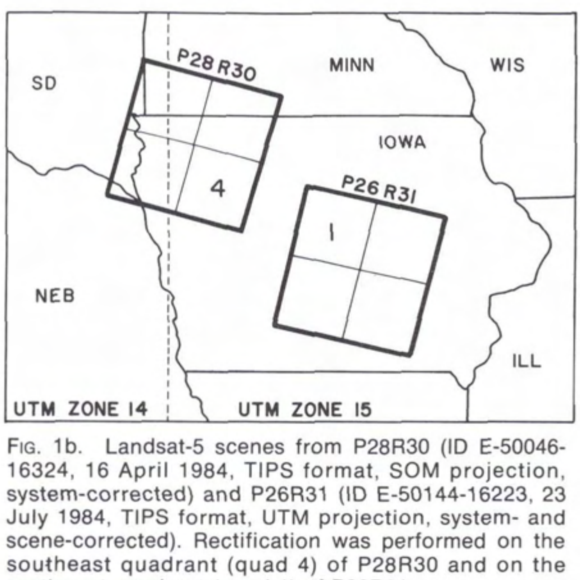


FIG. 1b. Landsat-5 scenes from P28R30 (ID E-50046-16324, 16 April 1984, TIPS format, SOM projection, system-corrected) and P26R31 (ID E-50144-16223, 23 July 1984, TIPS format, UTM projection, system- and scene-corrected). Rectification was performed on the southeast quadrant (quad 4) of P28R30 and on the northwest quadrant (quad 1) of P26R31.

TABLE 1. LANDSAT-4 AND LANDSAT-5 DATA SETS

Satellite	WRS-No.	Scene Location	Projection	Correction	Processing System
Landsat-4	P18R36	Georgia	SOM	System	Scrounge
Landsat-4	P19R36	Georgia	SOM	System	Scrounge, TIPS
Landsat-5	P26R31	Iowa	UTM	System, Scene	TIPS
Landsat-5	P28R30	Iowa	SOM	System	TIPS

1:24,000 scale maps compiled or revised between 1964 and 1974. The relief and distribution of landforms in relation to the ground track of the spacecraft make the Georgia scenes ideally suited for evaluations of the impact of relief on the accuracy of geodetic rectification.

Scenes aquired over northwest and central Iowa have been employed to assess the geodetic accuracy of Landsat-5 data and to conduct comparative evaluations of system and scene-corrected CCT-pt's produced on TIPS (Figure 1b). A scene for P28R30 recorded on 16 April 1984 was corrected for system errors and processed to the SOM projection. Because this scene is split by the boundary between UTM zones 14 and 15, and defects were noted in the data for quadrants (quads) 1 and 2, all geometric evaluations have been undertaken with the quad 4 data set which falls entirely within UTM zone 15. A second Landsat-5 scene is located in central Iowa (P26R31) and was acquired on 23 July 1984. Both system- and scene-corrected CCT-pt's cast on the UTM projection were produced for this scene, which is located near the middle of UTM zone 15. The northwest quadrant (quad 1) was selected for evaluation because of the relatively uninterrupted gridded road network.

Both of the Iowa scenes feature low relief (less than 110 m) and gridded road networks at one mile intervals characteristic of the Public Land Survey System (Plate 1b). The regular grid of high contrast road intersections provide excellent GCPs (based on visual identification) for which the UTM coordinates can be accurately determined from recent (1975–1984) USGS map coverage of Iowa. These characteristics, in combination with the level terrain, make the Iowa scenes ideally suited for evaluations of the geometric fidelity of Landsat-5 CCT-pt data.

RECTIFICATION PROCEDURES

The geodetic rectification of TM image data in CCT-pt formats involves the following steps:

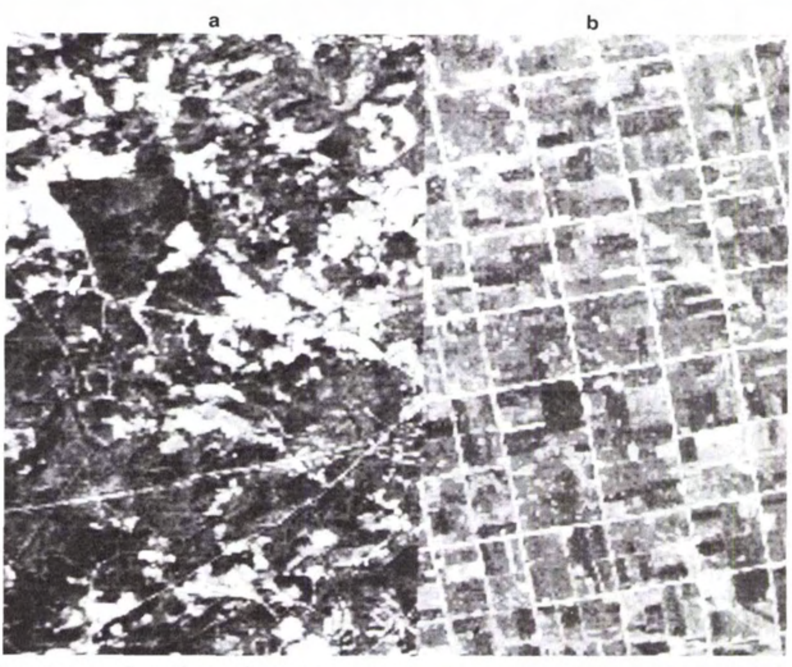


PLATE 1. The Piedmont area of northeast Georgia (a) is characterized by irregular road and field patterns, whereas the Iowa (b) landscape is formatted by a regular grid of high-contrast roads, greatly facilitating the identification of GCPs.

(1) Location of GCPs in the image (pixel and line coordinates) and on USGS 1:24,000 scale topographic maps (UTM coordinates) of the study area;
(2) Checks to eliminate points of questionable reliability; and
(3) Least squares solution of polynomial rectification equations using GCPs scattered throughout the data set to determine the coefficients which must be applied to the image coordinates in order to derive UTM map coordinates.

The location of GCPs in the image data is accomplished with the aid of an ERDAS 2400 interactive image processing system. Typical GCPs are shown in Plates 2–4.

The GCP's are identified using the color CRT on which the data for TM bands 2, 3, and 4 are displayed as a false color composite image yielding maximum contrast between land, vegetation, and water features. Image coordinates for the GCPs can be determined to a fraction of a pixel by enlarging the pixels displayed on the CRT or by reformatting/resampling image data to smaller pixels which are then redisplayed at large scale.

Once the provisional GCPs have been located, their UTM map coordinates must be digitized from 1:24,000 scale USGS topographic maps. This is accomplished by orienting an Altek SuperMicro digitizer (±25 μm resolution) to the map coordinate system based on the UTM grid ticks in the margins of the maps, or to the UTM grid lines shown on more recent quadrangles, and recording the coordinates to a fraction of a meter in the UTM system. The reliability of the digitized coordinates is evaluated by noting the residual errors at neighboring UTM tick marks or grid intersections.

Coordinates of the GCPs in image (pixel, scanline) and map (easting, northing) space must be checked to identify suspect points. The procedure developed for these studies is referred to as a point-pair distance check and involves the computation and comparison of map and scaled image distances between all possible combinations of point-pairs. By performing distance checks, suspect points can be quickly eliminated. The point-pair distances are then recomputed and the RMS difference in distance between the map and scaled image values determined. The RMS distance difference value reflects the reliability of the GCPs, is an indicator of the internal geometric fidelity of the CCT-pt image data, and is a reliable surrogate measure for RMSExy values determined from the subsequent rectification process (Welch and Usery, 1984). Typically, RMS distance difference values of less than ±1 pixel have been obtained for the GCP distributions used in the rectification of TM data sets.

An efficient method for rectifying Landsat data involves the use of polynomials of the form:

$$UTM = c_0 + c_1x + c_2y + c_3x^2 + c_4xy + c_5y^2 + c_6x^3 + c_7x^2y + c_8xy^2 + c_9y^3 + \ldots \quad (1)$$

where x, y are the known image coordinates in pixel and scanline values of GCPs. Once the coefficients (c) have been determined by the method of least squares, these equations may be used to solve for

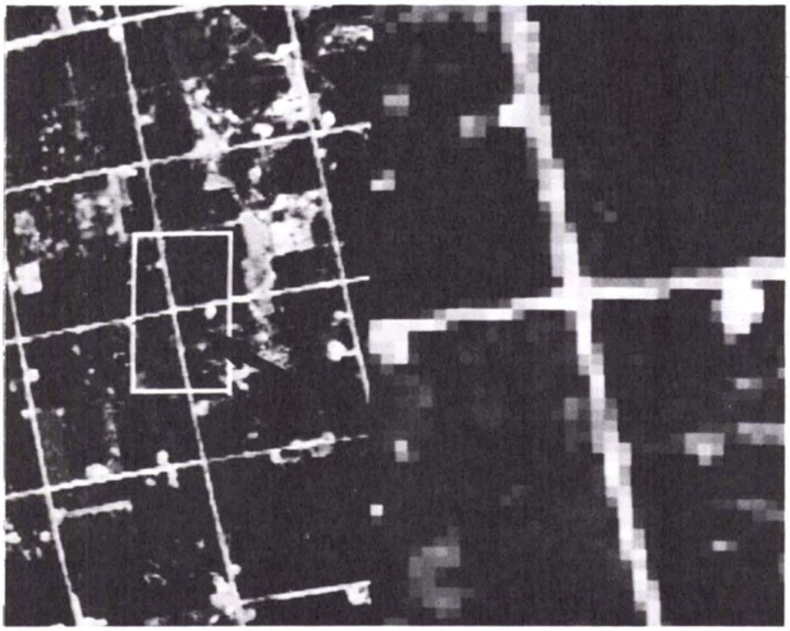


Plate 2. High contrast, rectangular road intersections are easily identified on the Iowa scenes. Enlarging the original image four times permits identification of GCP image coordinates to approximately ±0.25 pixel.

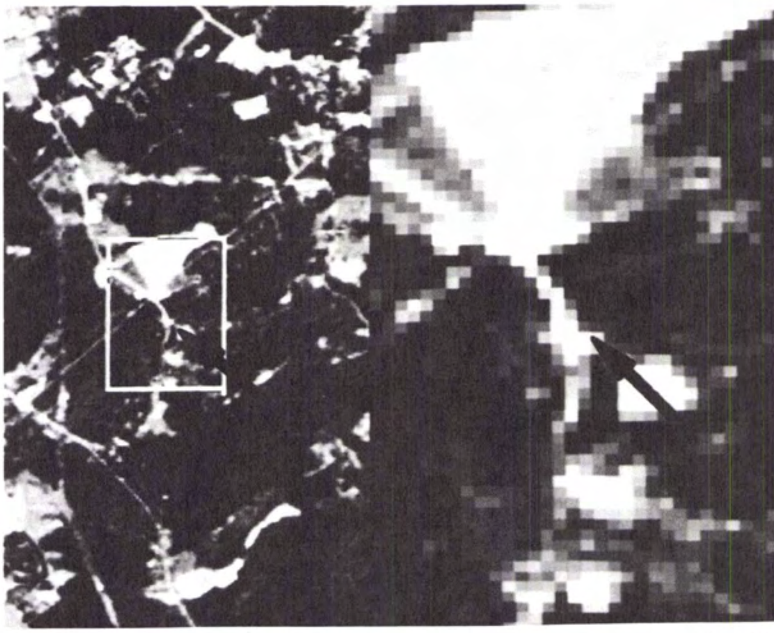


PLATE 3. Control points in Georgia, such as this bridge, can be located to approximately ±0.5 pixel in the image coordinate system.

easting and northing coordinates in the UTM system. Correspondingly, the image coordinates may be determined by an inverse procedure.

The minimum number of GCPs required to establish the unknown coefficients is dependent on the degree of the polynomials used in the rectification process. For example, first, second, third, fourth, and fifth degree polynomials require a min-

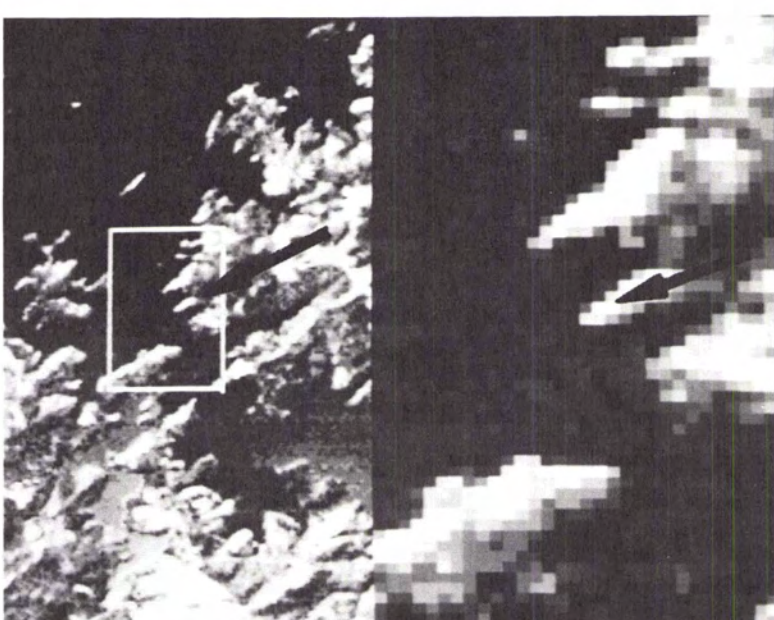


PLATE 4. In rural Georgia, a lack of manmade details necessitates the use of natural features for GCPs. In this example, the tip of the peninsula is difficult to define to better than ±1.0 pixel in the image coordinate system.

imum of 3, 6, 10, 15, and 21 GCPs, respectively. An obvious advantage of low order polynomials is that few GCPs need to be located to fit the image data to the UTM map coordinate system.

RECTIFICATION OF LANDSAT-4 TM DATA AND COMPARISONS OF SCROUNGE AND TIPS

Initial investigations of geodetic rectification accuracy were undertaken with the Georgia scene corresponding to P18R36 of the WRS processed on the Scrounge system. For the full scene, 80 GCPs were retained after the point-pair distance checks. Of these, 40 GCPs were withheld as test points to evaluate the accuracy of the rectification process. The RMSExy values obtained with polynomials of the first through fifth degree as functions of the number of GCPs used for the least squares solutions are presented in Figure 2. It is significant that for the 185 × 185 km scene, RMSExy values of ±0.83 to ±0.93 pixel (±25 to ±28 m) were obtained with first degree equations and as few as five GCPs. Rectifications of subscene areas of various sizes yielded RMSExy values of ±0.63 to ±0.9 pixels (±19 to ±27 m) and confirmed the previous observation that equations of the first or second degree are superior to higher order polynomials for the rectification of the Landsat-4 TM data.

SCROUNGE VERSUS TIPS–P19R36 (SYSTEM/SOM)

NASA-furnished CCT-pt data sets for P19R36 which were processed on both the Scrounge and TIPS, thus providing a basis for comparison of the two systems. Because of rugged relief and cloud cover conditions, only the lower right quadrant of the scene was judged suitable for these evaluations.

An image-to-image registration was first undertaken with the aid of 111 GCPs, of which 51 were used for a Scrounge-to-TIPS fit, and 60 withheld for accuracy evaluations. Examination of the affine transformation equations indicated that only a simple translation in X and Y was required to bring the two data sets into register (see also Walker, *et al.*, 1985). As shown in Table 2, the RMSExy values for points used in the least squares adjustment decrease from ±0.46 pixel (±13.7 m) for a first degree polynomial solution to ±0.37 pixel (±11.0 m) for a fifth degree polynomial. A more reliable indication of the fit between the two data sets is given by the RMSExy values for the 60 withheld points, which *increase* from ±0.45 to ±0.52 pixel (±13.4 to ±15.7 m) for polynomials of the first through fifth degree. The image-to-image registration reveals no significant differences between the data processed by the Scrounge and TIPS.

Following the image-to-image registration, the Scrounge and TIPS data sets for the 60 × 85 km area in UTM zone 17 were geodetically rectified using 30 GCPs distributed throughout the study area. Twenty GCPs common to both data sets were withheld for independent accuracy evaluations. As in the previous examples, the best fit to GCPs used in the least squares solution was obtained with fifth degree polynomials, whereas minimum RMSExy values of ±0.58 pixel (±17.4 m) (TIPS) to ±0.68 pixel (±20.5 m) (Scrounge) were developed from 20 withheld points using polynomial equations of the first degree (Figure 3). Overall, these rectifications indicate a marginal superiority for data processed on TIPS.

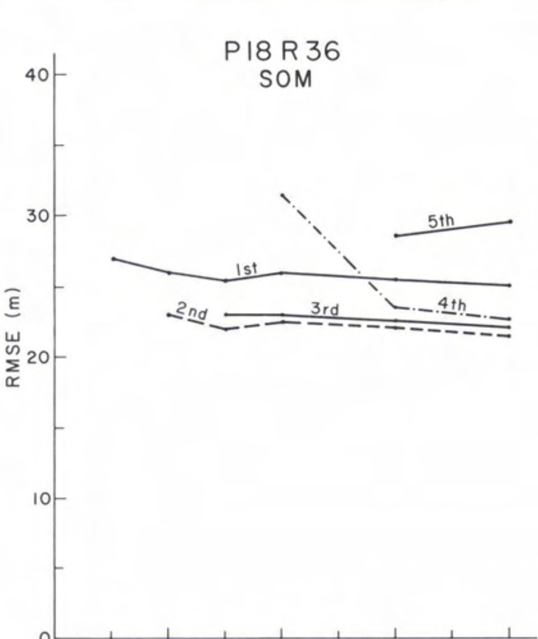


FIG. 2. RMSExy at 40 withheld test points as a function of the number of GCPs used to solve polynomials of the first through fifth degree for TM scene P18R36.

RECTIFICATION OF SYSTEM AND SCENE CORRECTED LANDSAT-5 DATA PROCESSED ON TIPS

The rectification of the Landsat-5 TM system and scene corrected data sets was undertaken to assess the geodetic accuracy of Landsat-5 CCT-pt's, and to determine the relative merits of data sets cast on the SOM and UTM projections. For these studies, quad 4 of the northwest Iowa scene (P28R30) and

TABLE 2. REGISTRATION OF SCROUNGE TO TIPS–P19R36

Polynomial Degree	51 Control Pts RMSExy		60 Check Pts RMSExy	
1	±0.46 pix	(13.7 m)	±0.45 pix	(13.4 m)
2	0.44	(13.2)	0.45	(13.4)
3	0.42	(12.5)	0.47	(14.1)
4	0.39	(11.8)	0.48	(14.3)
5	0.37	(11.0)	0.52	(15.7)

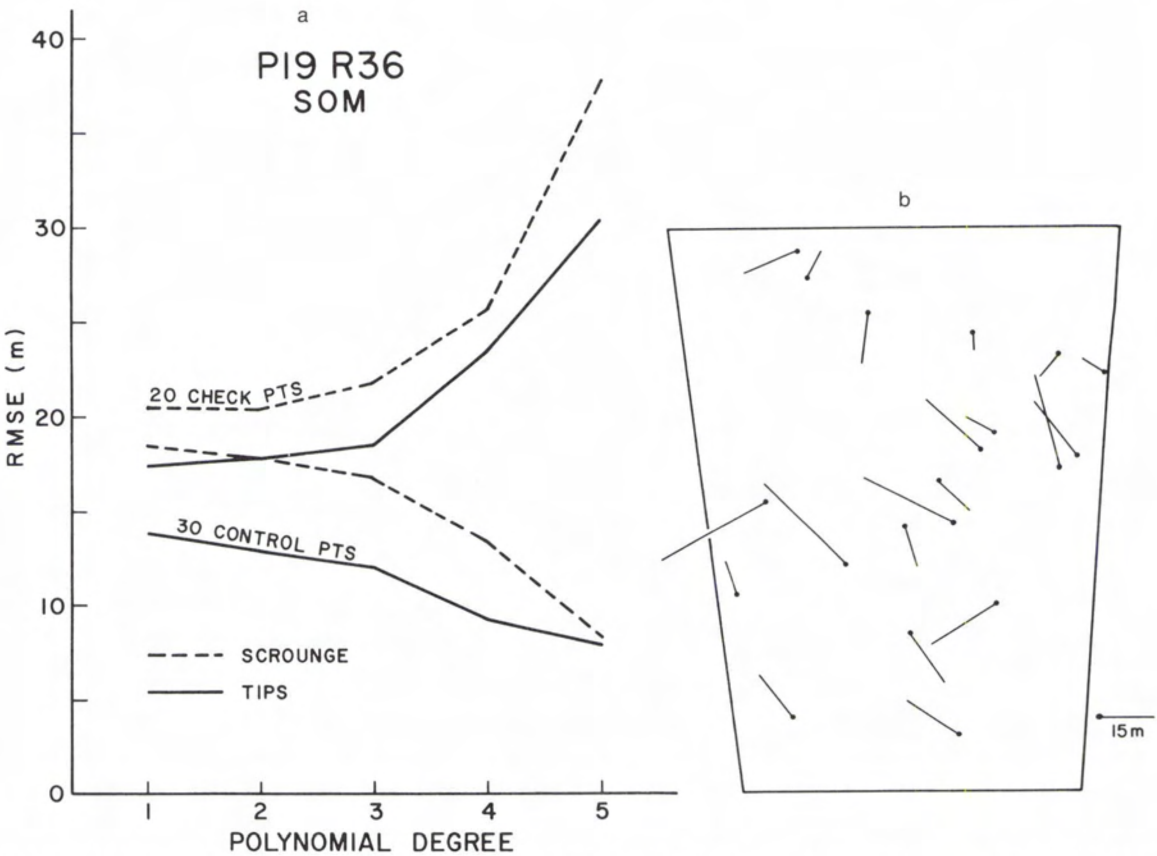


FIG. 3a. RMSExy for quad 4, P19R36 as a function of the degree of polynomial used for the rectification; based on residual errors at 30 GCPs used in the least squares solution, and at 20 withheld check points.
FIG. 3b. Error vectors for the 20 check points based on a first degree polynomial (TIPS).

quad 1 of the central Iowa scene (P26R31) were employed.

RECTIFICATION OF QUAD 4, P28R30 (SYSTEM/SOM)

From initial examinations of the quad 4 data set for P28R30 and the corresponding USGS 1:24,000 scale map sheets, 139 high contrast road intersections were identified as provisional GCPs. Of these 139 points, 38 were eliminated in subsequent point-pair distance checks, leaving 101 for the evaluation of geodetic rectification accuracy. Fifty-five of these GCPs were then selected to compute coefficients for polynomial equations of the first through fifth degree, and the remaining 46 GCPs withheld for independent determinations of the RMSExy values. Although the scene is cast on the SOM projection and split by the boundary between UTM zones 14 and 15, no attempt was made mathematically to transform the UTM map coordinates to X, Y values referenced to a local central meridian.

The rectification of quad 4 was undertaken with polynomials of the first through fifth degree. As shown in Figure 4, error values based on the 55 points used for the least-squares solution decreased as the degree of polynomial was increased. However, at the 46 withheld check points, the RMSExy values increased from ± 0.34 pixel (± 10.3 m) to ± 0.40 pixel (± 12.1 m), once again confirming the desirability of evaluating geodetic accuracies at independent test points.

The dense network of 55 GCPs is equivalent to having one control point every 12 km, which is an unrealistic expectation for operational cartographic applications involving the use of TM image data. Consequently, additional rectifications of quad 4 were undertaken with first order polynomials and 3, 4, and 5 GCPs to determine if comparable accuracies could be obtained by a simple scaling, rotation, and translation of the data to a minimal control configuration. The results are summarized in Table 3.

The results indicate that, provided the terrain is level and symmetric GCPs of high contrast are available, RMSExy values of approximately ± 0.33 pixel ($\sim \pm 10$ m) can be obtained when rectifying TIPS data cast on the SOM projection with first degree poly-

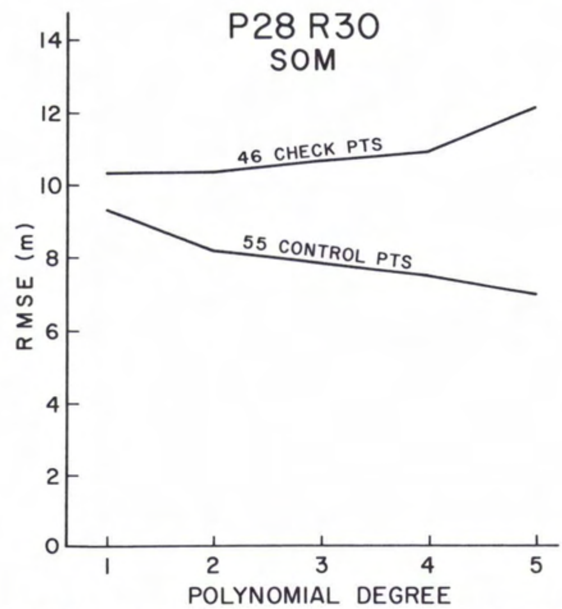


FIG. 4a. RMSExy for quad 4, P28R30 as a function of degree of polynomial used for the rectification; based on residual errors at 55 GCPs used in the least squares solution and at 46 withheld check points.

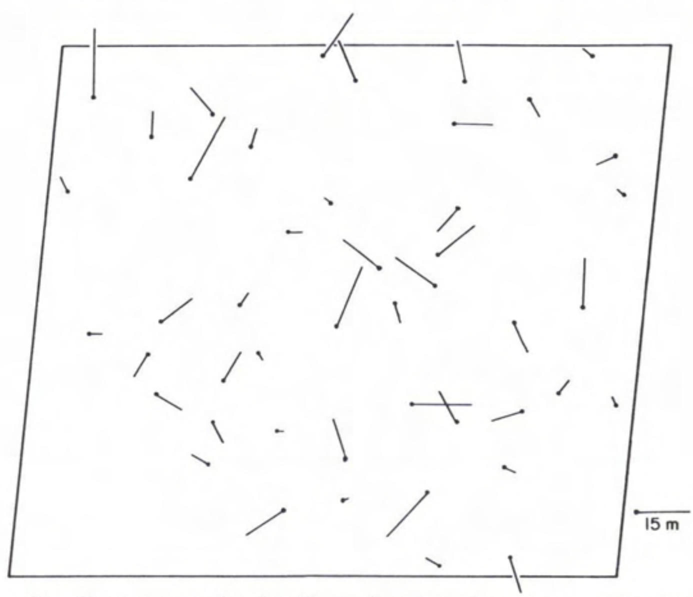


FIG. 4b. Error vectors for the 46 check points (first degree polynomial).

nomials and GCP coordinates in the UTM system. This is contrary to the findings of Walker, *et al.* (1984) who recommend against using polynomial solutions to fit SOM image data to the UTM coordinate system without first mathematically transforming the data sets.

REGISTRATION AND RECTIFICATION OF QUAD 1, P26R31 (SYSTEM AND SCENE/UTM)

For quad 1 of P26R31, 65 GCPs were initially identified in both the system- and scene-corrected data sets, of which only six were eliminated after the point-pair distance checks, leaving 28 for the determination of coefficients and 31 for the accuracy assessment. The scene-corrected CCT-pt for P26R31 had been previously rectified by NASA using 19 GCPs and automatic correlation techniques to establish the location of the control points.

In order to obtain a direct comparison of the geometric fidelity of system and scene corrected CCT-

TABLE 3. RECTIFICATION OF A LANDSAT-5 QUADRANT WITH MINIMAL CONTROL (QUAD 4, P28R30)

No. of GCPs	No. of Check Pts	RMSExy
3	98	±0.36 pix (10.8 m)
4	97	0.35 (10.5)
5	96	0.35 (10.4)

pts produced on TIPS, an image-to-image registration was first conducted. Coefficients for a first degree polynomial were determined by fitting the system corrected data to 28 control points on the scene corrected (reference) image. The affine equations for computing image coordinates in the reference (X, Y) system are presented below:

$$X = 0.9999173x + 0.0000857y - 2.2351 \quad (2)$$
$$Y = 0.0000467x + 0.9998662y + 9.7992 \quad (3)$$

where x = system corrected pixel
y = system corrected line

The coefficients closely approximate 0 or 1, indicating negligible rotation and scale differences. Thus, these equations can be simplified to:

$$X = x - 2.2351 \quad (4)$$
$$Y = y + 9.7992 \quad (5)$$

Based on an evaluation of the system-to-scene fit at the 31 withheld points, the data sets were found to have equivalent geometric fidelity and, in this instance, could be registered to within ±0.26 pixel (±7.7 m) by a small translation in X and Y.

In order to further compare the system and scene corrected data sets, coefficients for rectification polynomials of the first through fifth degree were computed for the 28 GCPs and applied to the 31 withheld points (Figure 5). Root-mean-square error values of ±0.23 pixel (±6.8 m) and ±0.26 pixel (±7.9 m) for first degree polynomial solutions of system and scene corrected CCT-pt's confirm the remarkable geometric integrity of the Landsat-5 data. These values are compatible with NMAS for 1:24,000 scale maps.

As a basis for evaluating the cartographic quality, the rectifications were repeated using a first degree polynomial and four GCPs located at the corners of the quad, yielding RMSExy values at the 51 withheld points of ±0.31 pixel (±9.3 m) and ±0.27 pixel (±8.0 m) for system and scene corrected data, respectively. These rectifications further demonstrate the fidelity of the Landsat-5 data and indicate that comprehensive libraries of control points may not be required for processing Landsat-5 data to planimetric accuracies compatible with map products of 1:50,000 scale and smaller. It also appears that image data cast on the UTM projection will provide marginally better rectification accuracies than SOM image data when the geodetic rectification is based on UTM map coordinates.

GEODETIC RECTIFICATION ERROR ANALYSIS

The geometric fidelity of both Landsat-4 and Landsat-5 data is remarkably consistent and, in most instances, internal distortions are too small to quantify by normal assessment techniques. Brooks, *et al.* (1984) and Beyer (1985) have described the complex and thorough correction procedures employed to meet the temporal registration and geodetic rectification specifications of ±0.3 and ±0.5 pixel at the 90 percent level of confidence. However, there has been some question as to whether comparable values can be realized in practical applications involving the use of TM data.

From these studies, it is apparent that three major sources of error place limits on the accuracy to which TM data can be fitted to the UTM coordinate system using polynomial rectification procedures: (1) location errors caused by the spatial resolution of the TM data; (2) map errors attributable to the scale, quality, projection/coordinate system, and to the digitizing procedures; and (3) errors caused by terrain relief. Of these, the 30 m spatial resolution of the TM data is the most difficult problem to overcome. In the Georgia data sets, for example, variations in terrain and land cover and the absence of a systematic grid of high contrast roads make it difficult to define the location of GCPs to better than ±0.5 pixel (±15 m). This is reflected by the high percentage (~65 percent) of points eliminated during the point-pair distance check. On the other hand, the regular grid of high contrast road intersections superimposed on the level, homogenous Iowa landscape permit GCPs to be defined to about ±0.20 to ±0.25 pixel (±6.0 m to ±7.5 m) using visual estimation techniques (Figure 6).

The reference maps for both Georgia and Iowa are 1:24,000 scale USGS topographic maps constructed to U.S. NMAS which require 68 percent of the well-defined points (e.g., road intersections) to be within ±0.3 mm (or ±8 m) of the correct map location. A factor which may contribute to map errors is the difference between the map projections used to define the image and map coordinates. Landsat TM image data are typically cast on the SOM projection (Colvocoresses, 1974; Snyder, 1982), whereas the map coordinates are defined in relation to the UTM projection. The differences between the two projection systems are slight for image data sets of 185 × 185 km or smaller, but, in theory, the UTM coordinates should be converted to latitude and longitude values and then transformed to X, Y grid coordinates based on a local central meridian to avoid any errors. For TM quadrant sized (~90 × 90 km) image data sets located at the UTM zone boundary, the use of UTM coordinates with SOM data may result in errors of about ±4–5 m (Snyder, personal communication, 1985). This small error may be insignificant in relation to the total error budget and to planned cartographic applications, but can be detected under ideal conditions.

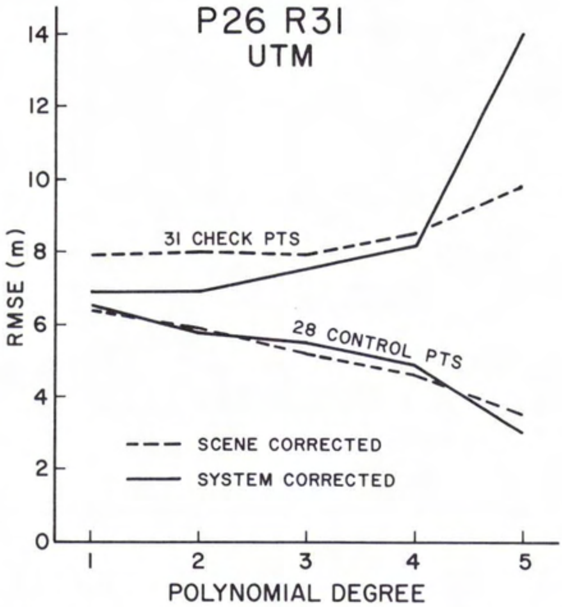


FIG. 5a. RMSExy for quad 1, P26R31 as a function of degree of polynomial used for the rectification; based on residual errors at 28 GCPs used in the least squares solution and at 31 withheld check points.

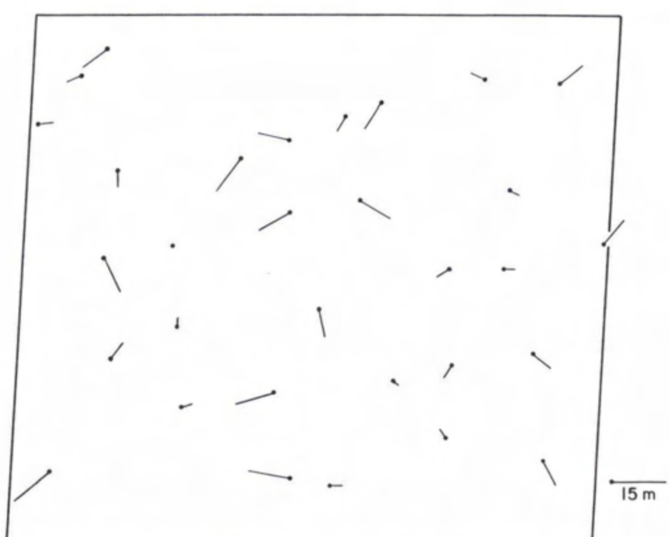


FIG. 5b. Error vectors for the 31 check points (system-corrected, first degree polynomial).

As an example, the rectification of the 90 × 90 km quad 4 SOM data set of P28R30 which lies at the edge of UTM zone 15 produced an RMSExy value of ±0.34 pixel (±10.3 m) based on the fit to 55 GCPs in the UTM system. On the other hand, the RMSExy values of ±0.23 pixel (±6.8 m) and ±0.26 pixel (±7.9 m) computed for the system- and scene-corrected data sets for quad 1 of P26R31 show an improvement of about 3 m over the RMSExy values for P28R30, corresponding to the approximate computed difference. Interestingly, Borgeson (personal communication, 1985) reports obtaining error values of about ±10 to ±11 m for the P28R30 scene when using GCPs referenced to a local meridian. Thus, it may be reasonable to conclude that errors caused by differences in the projection system are unlikely to be noticed except under ideal conditions.

Perhaps the best estimate of the map error is obtained by determining the residual errors at UTM tick marks near the GCPs being digitized. This procedure has produced an error of ±5 to ±10 m for maps of Georgia, compiled or revised prior to 1974, and ±2 to ±5 m for the more recent maps of Iowa which have the full UTM grid superimposed. Consequently, for these studies, map errors of ±10 m and ±5 m have been assumed for the Georgia and Iowa study sites, respectively.

The impact of image displacements due to relief depends on the magnitude of the relief, the distribution of the features relative to the center track of the satellite, and the vertical distribution of GCPs used to rectify the data sets. With relief of about 100 m or less, as is the case for the Iowa data sets, the resulting planimetric error should be less than ±0.1 pixel (±3 m), provided the GCPs used for the rectification are selected at midrange elevations. The Georgia study area, on the other hand, exhibits relief of 400 to 1000 m and for the GCP distribution and elevations used in the rectification and testing of P18R36, maximum displacements of about ±1 pixel (±30 m) could be expected at the east and west edges of the scene, with a value of about ±0.5 pixel (±15 m) a representative average.

Overall, the error budgets for the Georgia and Iowa data sets can be approximated as follows:

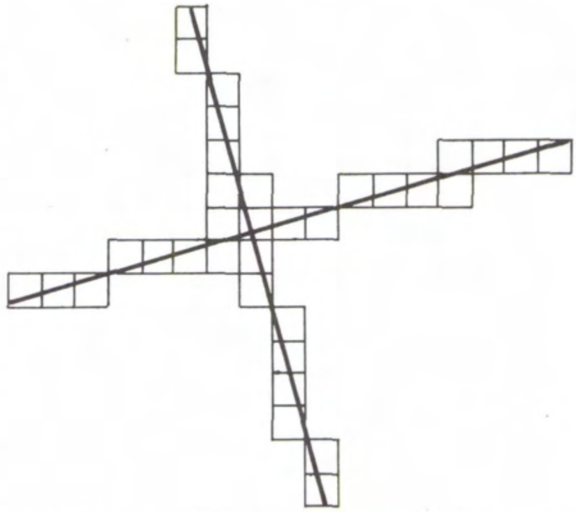


FIG. 6. Visual estimation techniques for determining image coordinates for a road intersection in Iowa. A pair of straight lines oriented at right angles can be superimposed on the CRT to aid in location of the GCP to a fraction of a pixel.

$$\begin{aligned} \text{RMSE}xy &\sim \sqrt{(\text{location error})^2 + (\text{map error})^2 + (\text{relief error})^2} \\ &\sim \pm 0.76 \text{ pixel } (\pm 23 \text{ m}) \text{ for Georgia} \\ &\sim \pm 0.3 \text{ pixel } (\pm 9 \text{ m}) \text{ for Iowa} \end{aligned} \quad (6)$$

These theoretical values are confirmed by the results summarized in Figure 7.

CARTOGRAPHIC POTENTIAL OF TM DATA

The Landsat-4 and Landsat-5 data offer considerable promise for the development of planimetric and image maps, and for providing structured raster data of sufficient accuracy to serve as coordinate reference systems for geographic data bases (Welch, 1984). In addition, the possibilities for deriving digital elevation models (DEMs) and orthoimages to accuracies compatible with standard map products are worthy of consideration.

In these studies, geodetic rectification accuracies ranged from ±0.23 pixel (±6.8 m) to about ±0.93 pixel (±28 m) for study sites in Iowa and Georgia. Consequently, for favorable conditions, the rectified TM data can meet NMAS for map products at scales to 1:24,000 but for typical GCP configurations and average terrain conditions will conform to standards for 1:50,000 to 1:100,000 scale maps.

Although the geodetic accuracy of the Thematic Mapper data is compatible with relatively large scale map products, the completeness of planimetric map detail that can be compiled from the images is limited to about 65–80 percent of that normally shown on maps of 1:24,000 to 1:250,000 scale (Welch and Mathews, 1983). For this reason, TM data are best suited for the production of image maps of 1:100,000 scale as demonstrated by the USGS maps of Dyersburg (1983), Washington, DC (1984), and Great Salt Lake (1985). Another potential use of the TM data is for the revision of existing maps, particularly for changes in the boundaries of urban areas and water bodies, or the relocation of major transportation features (Usery and Welch, 1984) (Plate 5). Perhaps most importantly, scene corrected TM data appear to offer no significant advantages over system-corrected CCT-pt's for the production of map products.

The possibilities for deriving elevations from two adjacent TM scenes were recently presented by Welch and Ehlers (1985). A 50 km^2 test area common to scenes P18R36 and P19R36 was identified to test stereo correlation algorithms and to assess the possibilities for deriving DEMs and orthoimages (see Figure 1a).

Subscenes forming the stereopair were rectified to a common set of GCPs forming a local datum, and residual displacements assumed to be caused by relief. Automated two-dimensional correlation techniques were then applied on a pixel-by-pixel

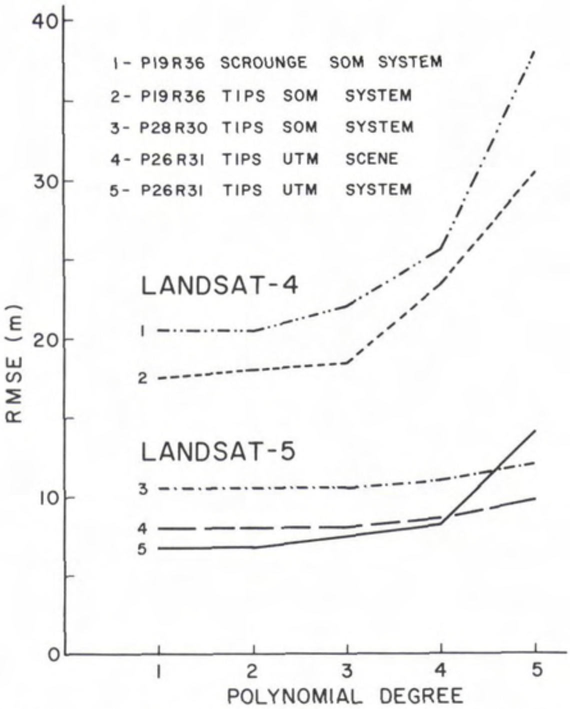


FIG. 7. Comparison of RMSExy values determined at withheld check points for the TM quadrant-sized data sets recorded over Georgia (1, 2) by Landsat-4 and Iowa (3, 4, 5) by Landsat-5, as a function of the degree of polynomial used for the geodetic rectification.

basis to derive the x-parallaxes. From these x-parallaxes, provisional terrain elevations were computed and calibration coefficients derived by means of a linear least squares fit to a few GCPs of known height distributed at elevations between 480 m and 920 m. The RMSEz value computed from independent check points was ±42 m.

Based on the approximate base-to-height ratio of 0.19 for the Landsat-4 data, the ±42 m RMSEz corresponds to a planimetric correlation accuracy of better than ±0.3 pixel. Comparisons of 100 m contours traced from existing maps with those interpolated from the DEM derived from the TM stereo data show good correspondence. Consequently, these DEMs are of sufficient accuracy for the production of orthoimages or for the interpolation of contours for small-scale topographic maps.

These results validate the observations that elevations can be determined to subpixel accuracies by digital correlation techniques applied to data of high signal-to-noise ratio (Ehlers, 1985). In addition, they further confirm the excellent geometric fidelity of the TM data.

CONCLUSION

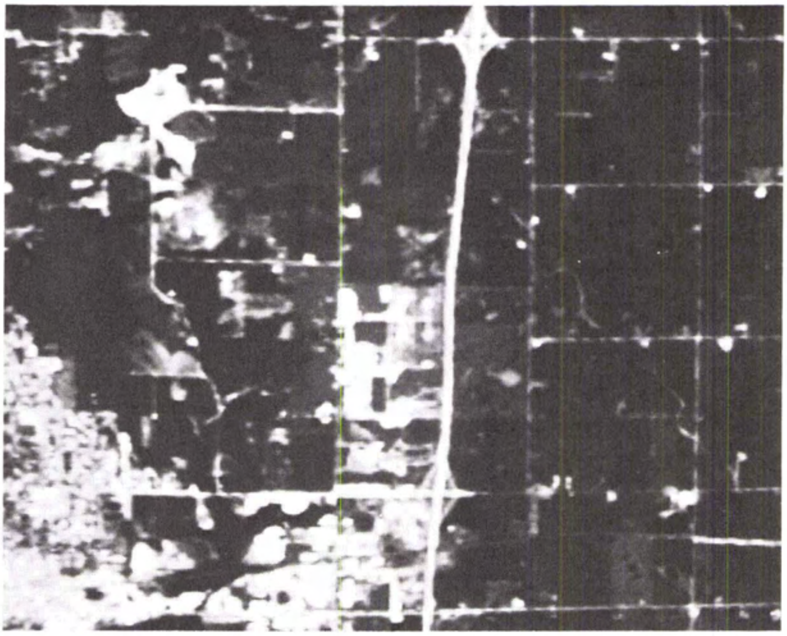
These studies demonstrate the Landsat-4 and Landsat-5 data in CCT-pt formats are of exceptionally good geometric quality, facilitating geodetic rectifications to subpixel accuracies with as few as five GCPs for a full scene. The rectification of system corrected CCT-pt's should be undertaken with first degree polynomials.

Landsat-4 data sets processed on both the Scrounge and TIPS produced RMSExy residuals of ±0.68 pixel (±20.5 m) and ±0.58 pixel (±17.4 m), respectively, indicating a slight geometric advantage for TIPS. The quality of TIPS processing is further confirmed by rectifications of Landsat-5 data sets of Iowa which have yielded RMSExy values of ±0.34 pixel (±10.3 m) for a TM quadrant at the edge of UTM zone 15 cast on the SOM projection, as compared to ±0.23 pixel (±6.8 m) for a quadrant at the center of UTM zone 15 cast on the UTM projection. These results indicate that under ideal test conditions errors caused by the projection may be detectable at the boundaries of the UTM zones. In general, however, it appears that quadrant-sized SOM data sets (or smaller) may be rectified with UTM map coordinates without significant error.

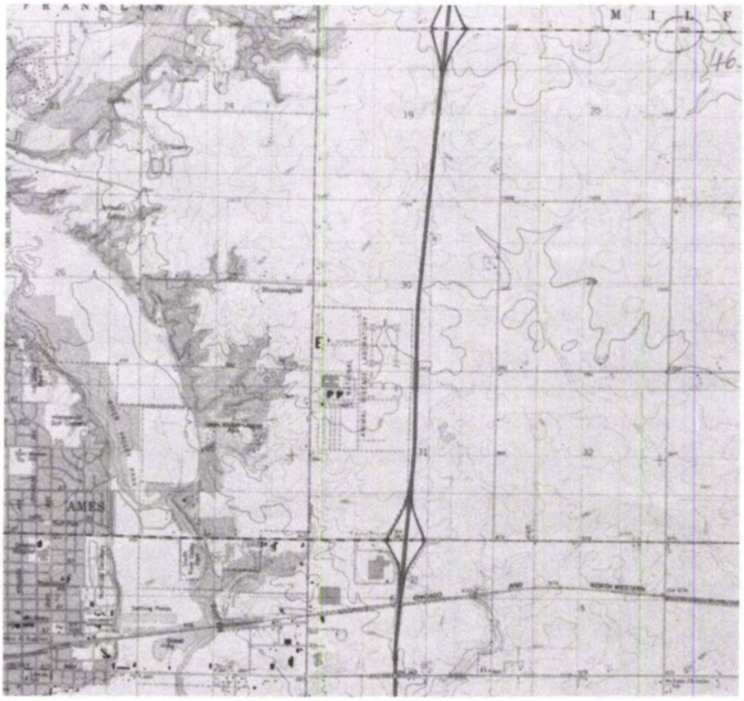
Registration of system- to scene-corrected Landsat-5 data sets of central Iowa revealed no significant differences in geometric fidelity. Geodetic rectifications with first degree polynomials yielded RMSExy values of ±0.23 pixel (±6.8 m) and ±0.26 pixel (±7.9 m), indicating that the system- and scene-corrected data sets are of comparable geometric quality. It does not appear necessary to build control point libraries for each scene.

The major errors that influence geodetic rectification are caused by the spatial resolution of the TM data which limits the location of GCPs in the image coordinate system to between ±0.20 and ±1.0 pixels. Errors attributable to the reference maps and coordinate systems vary from about ±0.2 to ±0.5 pixels. Planimetric displacements due to terrain relief normally can be reduced to a fraction of a pixel by selecting GCPs at or near the mid-range terrain elevations.

Although it is possible to meet U.S. NMAS for 1:24,000 scale map products, the Landsat-4 and Landsat-5 data are better suited for cartographic products of 1:50,000 scale and smaller. Because the 30 m spatial resolution severely limits the completeness of map detail, the most useful applications of TM data may be for the revision of line maps or the production of image maps at 1:100,000 scale or smaller. The excellent internal geometric properties of the raster data facilitate their use as a coordinate reference system for applications involving geographic data bases. Terrain elevations can be derived from adjacent (sidelapping) data sets by correlation techniques to RMSEz values of approximately ±40 m, permitting the generation of orthoimages and confirming the feasibility of automated mapping from satellite data of high resolution and geometric integrity.



a



b

PLATE 5. A rectified subset of scene P26R31 (a) is shown at approximately the same scale as a section of the corresponding USGS 1:24,000 topographic quadrangle (b). It is evident that the rectified TM image could be readily employed to update or revise the map to include new roads and extensions of the boundaries for the urban area.

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