Geometric Accuracy of Landsat-4 and Landsat-5 Thematic Mapper Images

*W. T. Borgeson**
R. M. Batson
H. H. Kieffer
U.S. Geological Survey, Flagstaff, AZ 86001

ABSTRACT: The geometric accuracy of the Landsat Thematic Mappers was assessed by a linear least-square comparison of the positions of conspicuous ground features in digital images with their geographic locations as determined from 1:24,000-scale maps.

For a Landsat-5 image, the single-dimension standard deviations of the standard digital product, and of this image with additional linear corrections, are 11.2 and 10.3 m, respectively (0.4 pixel). An F-test showed that skew and affine distortion corrections are not significant. At this level of accuracy, the granularity of the digital image and the probable inaccuracy of the 1:24,000 maps began to affect the precision of the comparison. The tested image, even with a moderate accuracy loss in the digital-to-graphic conversion, meets National Horizontal Map Accuracy standards for scales of 1:100,000 and smaller.

Two Landsat-4 images, obtained with the Multispectral Scanner on and off, and processed by an interim software system, contain significant skew and affine distortions. The single-dimension standard deviations for the standard-product digital images are 42 and 45 m (about 1.5 pixels). The same images corrected for skew and affine distortion have standard deviations of 21 and 24 m (about 0.8 pixel).

INTRODUCTION

LANDSAT THEMATIC MAPPER (TM) images of an area including northwestern Iowa, southwestern Minnesota, and southeastern South Dakota (Path/Row = 28/30) were selected for study because of the area's minimal topography and well-developed orthogonal road system. Fully corrected digital data sets were obtained for the following TM images:

Landsat		Date	Scene ID
4	MSS-ON	25 Aug 1982	40040-15321
4	MSS-OFF	26 Sep 1982	40072-16325
5		16 Apr 1984	50046-16324

The Landsat-5 image, because it was produced by a spacecraft and a ground-processing system that are still operational, was analyzed in greater detail than the Landsat-4 image. The Landsat-5 image is, therefore, the subject of all the following sections except the last.

We determined the geometric accuracy of the TM images by comparing a set of image-point coordinates with their ground coordinates through the medium of a linear least-square adjustment. This adjustment also allowed an assessment of the amounts and significance of image skew and affine (nonuniform) magnification distortion. Similar comparisons of TM images with ground control have been made by Borgeson and Batson (1984), Bryant *et al.* (1985), Walker *et al.* (1984, 1985), Welch and Usery (1984), and Welch *et al.* (1985).

* Retired.

DETERMINATION OF IMAGE COORDINATES

Bands 2, 3, and 4 were displayed on an interactive color-display system. Each of the four ¼-frame quadrants was treated as a separate image during control-point selection.

Photographs were made from band 3 data of each of the four quadrants except the southwest quadrant, which was made from band 4 data (see below). The scale was 10 pixels/mm. Corresponding points were selected and circled both on these prints and on the 1:24,000-scale U.S. Geological Survey topographic maps. Image points were picked at the periphery of each quadrant in accordance with photogrammetric experience that such locations have maximum influence on the subsequent mathematical processing. Almost all points were right-angled crossroads, in the familiar pattern of the public land suveys. About 70 points were picked for each quadrant, 283 points in all.

Image coordinates were obtained by a computer-driven digital image display system. The system could handle image segments up to 512 lines by 512 samples in three colors. Its color capabilities were

PHOTOGRAMMETRIC ENGINEERING AND REMOTE SENSING,
Vol. 51, No. 12, December 1985, pp. 1893-1898.

0099-1112/85/5112-1893$02.25/0

found to be of minor significance; however, its ability to "stretch" the contrast of each band to use the full brightness range of the display was very helpful.

After a careful comparison of the vicinity of each point on both the print and on the display screen, a single-pixel cursor was placed on the screen location. Then a 2× or 4× enlargement of the local area was made and the final coordinates were determined. The coordinate values for each of the three bands were automatically stored. In no case did the values differ. In a few cases, a location was estimated to the nearest 0.5 pixel and recorded for later modification of the unit pixel record.

The software considers the coordinate system to originate at the upper left corner of a quadrant and takes the line number as the x value and the sample number as the y value. This gives a right-handed coordinate system (necessary for comparison of image x, y with ground X, Y), but rotated about 90° clockwise.

Because of tape-copying difficulties, the data for the southwest quadrant were obtained from an image of band 4 only. There were no subjective difficulties due to this lack of color; subsequent processing showed no significant decrease in precision.

After preliminary processing of each quadrant to detect and remove blunders, data from the northeast, southwest, and southeast quadrants were converted to the coordinate system of the northwest quadrant by adding, as appropriate, 0.0 or 2983.0 to the recorded x (line number) and 0.0 or 2747.0 to the recorded y (sample number). Trial-and-error testing of fractional pixel changes from these nominal values resulted in negligible changes in the standard errors. The point common to the four quadrants was found to be lat. 43.185° N., long. 95.604° W., whereas the scene center is listed on the tape label as lat. 43.117° N., long. 95.556° W., a discrepancy of 5.4 km.

DETERMINATION OF GROUND COORDINATES

Ground coordinates were obtained from the 1:24,000-scale maps with a computer-controlled digitizer to convert digitizer coordinates in inches (0.001-inch least count) to metres on the ground. The corner locations of each map were measured to establish the actual scale and orientation of the maps. (The least-square procedure employed compensates for both map skew and affine paper distortion, so scale-stable map materials were not needed.)

Obtaining ground coordinates was a two-stage process, repeated for each map. First, multiple cursor settings were made on each map corner (and occasionally on one or more other graticule points). From the known latitude and longitude the corresponding ground X, Y values were computed. A least-squares procedure computed the six linear transformation constants that converted the observed digitizer values to ground values.

Then, multiple observations of each map point were made. The six transformation constants were applied to the averaged digitizer values to convert the ground X, Y values in metres.

The projection was a Transverse Mercator system with a central meridian of 95° 31′, a central parallel of 43° 11′, and a scale factor at the central meridian of 0.99994429. These parameters were chosen to minimize scale variation over the TM image. A UTM projection, Zone 15, might have been chosen but the scale variations would have been larger, as the west boundary of Zone 15 is well within the TM-image area. It should be noted that the computer algorithms for the chosen projection were the same as those for UTM, except for the different parameter values.

For all maps, the software provided the standard errors of (1) cursor setting on map-graticule points, (2) fit of map-graticule points to their computed Transverse Mercator X, Y values, and (3) cursor settings on control points. The accuracy of cursor setting on graticule points was about 0.5 m ground equivalent in x and in y (1042 degrees of freedom). The standard error of fitting graticule points to their ground X, Y values was 2.0 m in X and 0.5 m in Y (142 degrees of freedom each). Finally, the standard errors in measuring control-point locations were about 0.6 m for both ground X and Y values (713 degrees of freedom each). The 2-m error in X for fitting the maps to the computed projection is most likely due to the use of an area-wide Transverse Mercator projection to fit maps constructed on three different State Plane Coordinate Systems.

DATA PROCESSING PROGRAM

A computer program (MAGCMP) compared the image and ground-control data sets through the medium of a least-square adjustment procedure. Six linear adjustment parameters were computed that, when applied to the image coordinates, transformed them to the best-fit approximation of the ground values. (This was not the same program used to fit digitizer x, y to ground X, Y coordinates.) MAGCMP was designed to generate meaningful physical transformation parameters rather than abstract mathematical ones. The transformation equations are

$$y' = y + x * \sin(\text{SKEW})$$
$$X = \text{XOFF} + \text{XMAG}*\cos(\text{ROT})* x + \text{YMAG}*\sin(\text{ROT})*y'$$
$$Y = \text{YOFF} + \text{XMAG}*\sin(\text{ROT})* x + \text{YMAG}*\cos(\text{ROT})*y'$$

where

X, Y are the least-square approximation of control coordinates (metres) after transformation of image coordinates (pixels);

x, y are image coordinates (line number and sample number);

XOFF, YOFF are offsets (metres) that transform the image-coordinate origin to the control origin;

XMAG, YMAG are magnification factors from the x and y image units to metres on the ground;

ROT is the rotation angle used to make the image-coordinate frame parallel to the ground-coordinate frame; and

SKEW is an angle that corrects the image's y value for image skew.

It can be shown by algebraic manipulation that the above transformation parameters can be derived from the six constants in the first-degree (linear) transformation

$$X = A + B*x + C*y$$
$$Y = D + E*x + F*y$$

Because, in the general case, SKEW and ROT may be large and trigonometric functions are not linear, MAGCMP made the adjustment by iteration, accumulating corrections to initial estimates and recalculating trignometric functions until corrections were negligible.

MAGCMP allows any combination of parameters XOFF, YOFF, ROT, and SKEW to be optionally held fixed at zero; also XMAG = 1.0 and/or YMAG = XMAG may be optionally held.

DATA PROCESSING RESULTS

After preliminary processing to eliminate blunders, four MAGCMP computer runs were made (XOFF, YOFF, and ROT were always required to bring the two coordinate systems into coincidence and at least YMAG = XMAG to scale from pixels to ground metres):

- Run 1: All six parameters computed.
- Run 2: Five parameters computed; SKEW = 0.0 (no skew correction).
- Run 3: Five parameters computed; YMAG = XMAG (no differential magnification allowed).
- Run 4: Four parameters computed; SKEW = 0.0 and YMAG = XMAG. Run 4 evaluated the image as stored on tape without any linear corrections. This run was the standard by which any improvement could be judged.

The results are summarized in Table 1. The pixel projected to the ground is about 28.5-m square. From this value, it can be seen that the standard error in all runs is about 0.4 pixel, roughly the granularity of control selection on the original image data.

Table 2 summarizes the significance of correction parameters SKEW and YMAG: taken separately or together, the two corrections are insignificant.

Run 1 output the transformed approximations on the control X, Y for each point. These data were used to plot Figure 1, which shows the locations and error vectors for all the points. It should be noted that the scale for error vectors is 176 times the scale of the image shown in Figure 1. Plots for other runs would be visually indistinguishable from those in Figure 1.

DISCUSSION OF ERRORS

The achieved standard errors for the points range from 10.2 to 11.3 m (about 0.4 pixel), and are comparable to the likely errors of point location in the digital image. Digital image granularity is probably the most significant source of error in the digital image. The various map-reading errors of 0.5 to 2 m previously discussed can be assumed to have had no influence on the achieved standard error if error sources combine in quadrature (square root of the sum of the squared terms).

We then investigated the possible influence of errors in the 1:24,000-scale maps. The National Horizontal Map Accuracy Standard (NHMAS) for maps of 1:20,000 scale and smaller (Thompson, 1966, p. 1182) specify that not more than 10 percent of the points tested shall have errors greater than 1/50 inch (0.508 mm) at publication scale. This 0.508 mm translates to 12.2 m on the ground at 1:24,000 scale. The accuracy specification can be rephrased as: for a 1:24,000-scale map meeting the NHMAS, the maximum size of the error circle containing 90 percent of the test points is R $(p = 0.9) = 12.2$ m.

Further, assuming that this 12.2-m error radius

TABLE 1. RESULTS OF LEAST-SQUARE ADJUSTMENT OF DIGITAL IMAGE COORDINATES TO THEIR GROUND-CONTROL VALUES FOR LANDSAT-5

Run	Corrections		Standard Error After Adjustment (metres)	Degrees of Freedom	Variance
1	SKEW	= 0.0015°	10.3	560	106.4
	YMAG	= 0.99983*XMAG			
2	YMAG	= 1.0000005*XMAG	10.6	561	111.8
3	SKEW	= 0.0051°	11.0	561	120.9
4	None		11.2	562	126.4

TABLE 2. FORMAL SIGNIFICANCE OF CONTROL-POINT FIT TO A LANDSAT-5 THEMATIC MAPPER IMAGE

Run	Variance	F-Statistic Resulting from Comparison with Run 4	Critical F-Value at 1% Level
1	106.4	126.4/106.4 = 1.188	F0.01(562,560) = 1.1420
2	111.8	126.4/111.8 = 1.131	F0.01(562,561) = 1.1418
3	120.9	126.4/120.9 = 1.046	F0.01(562,561) = 1.1418

is determined by a joint distribution of errors of X and Y, uncorrelated and randomly distributed, with standard errors sigma (X) = sigma (Y), it can be shown that

$$\text{Sigma} = R\ (0.9)\ /2.146 = 12.2/2.146 = 5.7 \text{ m}$$

Even when combined in quadrature, a 5.7-m standard map error would be a significant part of overall standard error in the range of 10.3 to 11.2 m found here. This discussion is theoretical and worst-case; there was no evidence that map inaccuracy influenced the achieved standard error. Nevertheless, it was quite suprising to find that the inaccuracy of 1:24,000-scale maps may begin to affect the testing of spacecraft imagery acquired hundreds of kilometres from the Earth's surface.

Using the above equation for relating the error-circle radius and sigmas, we find that the standard error of 11.2 m resulting from run 4 yields

$$R\ (p = 0.9) = 11.2*2.146 = 24.0 \text{ m}.$$

This is the maximum value of R $(p = 0.9)$ for graphic material at a scale of 1:47,313 (practically 1:50,000).

A separate test was conducted to assess the geometric fidelity of the film writers used to produce hard-copy TM images at EROS Data Center and Goddard Space Flight Center (GSFC). Estar-based film images of test patterns have distortions of approxi-

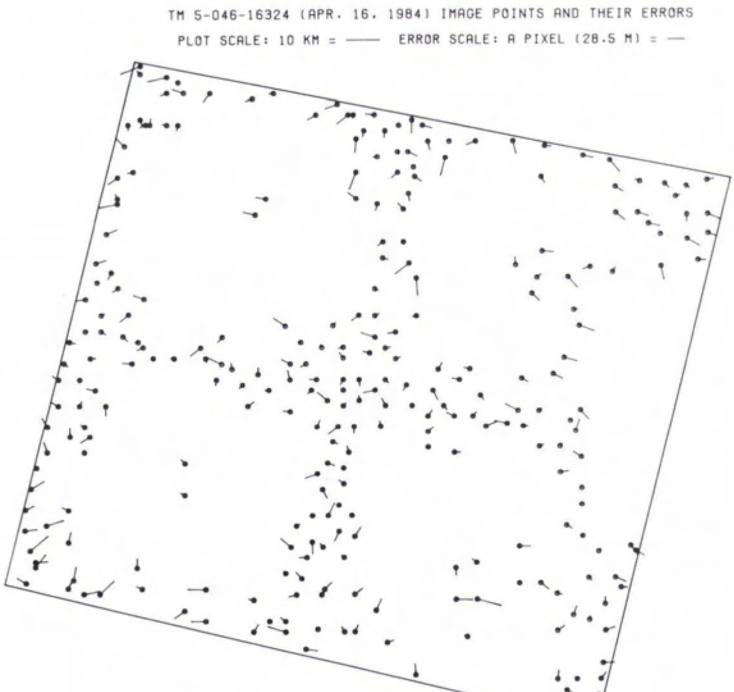

FIG. 1. Locations and error vectors of image test points. Image data are fully corrected digital data for a Landsat-5 Thematic Mapper image of northwestern Iowa obtained 16 April 1985 (scene identification 50046-16324). The data are corrected for skew and affine distortions on the basis of the 283 control points shown. The residual vectors are magnified 176 times (see bar scales).

TABLE 3. RESIDUALS OF CONTROL-POINT FIT TO LANDSAT-4 THEMATIC MAPPER IMAGES. CRITICAL F-VALUES AT THE 1% LEVEL FOR THE MSS ON AND OFF WERE 1.38 AND 1.36, RESPECTIVELY.

Run	Corrections	Standard Error After Adjustment (metres)	Degrees of Freedom	Variance
MSS ON: TM 40040-15321, 25 Aug 1982				
1	SKEW & YMAG	25.46	174	648.2
2	YMAG	37.04	175	1372.0
3	SKEW	36.65	175	1343.2
4	None	45.39	176	2059.3
MSS OFF: TM 40072-16325, 26 Sep 1982				
1	SKEW & YMAG	21.13	184	446.5
2	YMAG	34.18	185	1168.4
3	SKEW	31.76	185	1008.4
4	None	41.52	186	1724.0

mately 0.5 parts per thousand and do not support the accuracy inherent in the digital data (Batson and Borgeson, 1984).

LANDSAT-4 IMAGES

Analysis of Landsat-4 TM images was similar to that for Landsat-5, with the following exceptions: the Landsat-4 data were produced at GSFC by an interim processing system known as SCROUNGE; the data were obtained as full scenes, one band per 1600 bpi tape; the image positions for control points on Landsat-4 images were selected to the nearest pixel; and image positions were selected from band 5 data. Control points were concentrated around the four corners, the middle of each edge, and the center of the image. For scene 40040-15321, 92 points were picked and 90 used; for scene 40072-16325, 96 points were picked and 95 used.

Two images were obtained, the first with the Multispectral Scanner (MSS) operating, and the second with the MSS off. Because of the high spatial resolution of the TM, there was a possibility that the oscillation of the large MSS scan mirror might induce vibrations, and thence pointing errors, in the TM. Comparison of analyses of the two images (Table 3) shows that for each run the residuals are approximately 4 m larger for the case when the MSS was on. We consider this increase an upper limit on the potential influence of MSS operation on TM geometric fidelity, as we do not know if variations in the accuracy of the spacecraft orbital position or orientation might independently contribute to this difference.

Both images contain significant skew and affine distortions. Even after linear adjustments were made for these distortions, the standard errors are approximately twice those of the Landsat-5 image.

CONCLUSIONS

- The tested Landsat-5 image, uncorrected for skew and affine distortion, has a standard error of 11.2 m (0.4 pixel) with respect to ground control.
- The image would not be significantly improved by the application of skew and affine-distortion corrections.
- The image, in its digital form, meets the National Horizontal Map Accuracy Standard for publication at a scale of 1:50,000.
- The geometric quality of the fully corrected TM digital product is significantly better for Landsat-5 than for Landsat-4.
- On the Landsat-4 TM image, geometric quality was not significantly degraded by simultaneous operation of the MSS.
- The geometric quality of the standard TM digital product exceeds the capabilities of the photomechanical devices used to make hard-copy products.

ACKNOWLEDGMENT

This work was supported by the NASA Landsat Image Data Quality Assessment program.

REFERENCES

Batson, R. M., and W. T. Borgeson, 1984. Tests of Low-Frequency Geometric Distortions in Landsat-4 Images, *Landsat-4 Science Investigations Summary, NASA Conference Publication 2326*, Vol. II, p. 59, and *Landsat-4 Science Characterization Early Results, NASA Conference Publication 2355*, Vol. III, pt. 2, pp. 565-570.

Bryant, N. A., A. L. Zobrist, R. E. Walker, and B. Gokhman, 1985. An analysis of Landsat Thematic Mapper P-Product internal geometry and conformity to Earth surface geometry, *Photogrammetric Engineering & Remote Sensing*, Vol. 51, No. 9, pp. 1435-1447.

Thompson, M. M. (Editor), 1966. *Manual of Photogram-*

metry, 3rd edition, American Society of Photogrammetry, 1199 pages.

Walker, R. E., and A. L. Zobrist, N. A. Bryant, B. Gokhman, S. Z. Friedman, and T. L. Logan, 1984. An Analysis of Landsat-4 Thematic Mapper Geometric Properties, *Landsat-4 Science Investigtions Summary, NASA Conference Publication 2326*, Vol. II, p. 46-49.

Welch, R., and E. L. Usery, 1984. Geometric Accuracy of Landsat-4 MSS Image data, *Landsat-4 Science Investigations Summary, NASA Conference Publication 2326*, Vol. II, p. 83-84. and *Landsat-4 Science Characterization Early Results, NASA Conference Publication 2355*, Vol. III, pt. 1, p. I-123.

Welch, R., T. R. Jordan and M. Ehleris, 1985. Comparative Evaluations of the Geodetic Accuracy and Cartographic Potential of Landsat 4/5 TM Image Data, *Photogrammetric Engineering & Remote Sensing*, Vol. 51, No. 9, pp. 1249–1262.

(Received and accepted 24 June 1985)