Practical Paper

Relative Accuracy of Rectifications Using Coordinates Determined from Maps and the Global Positioning System

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Abstract

Global positioning systems (GPS) that use code phase receivers have the potential for providing more accurate coordinates for ground control points (GCPs) than do 7.5-minute quadrangle maps. To evaluate the effect of the greater accuracy of GPS in determining coordinates for satellite images, GCP coordinates were measured on maps and by GPS techniques and were then used to rectify Landsat Thematic Mapper, SPOT multispectral, and SPOT panchromatic images from the same area. There were major differences between rectifications using map and GPS coordinates. For Thematic Mapper data, 24 percent of the values assigned to pixels in the rectification performed using map coordinates differed from the values assigned to the same pixels in the rectification performed using the GPS coordinates. For SPOT multispectral and SPOT panchromatic images, the percentage of pixels with different assignments were greater than 40 percent. The improvements in accuracy when using the GPS data were substantial for even the relatively large Thematic Mapper pixels and warrant the use of GPS where position accuracy is essential.

Introduction

The coordinates of ground control points (GCPs) used to rectify satellite imagery are usually determined from 7.5-minute quadrangle maps published by the U. S. Geological Survey (USGS). The nominal horizontal accuracy of these maps is 12.2 m (i.e., U. S. National Map Accuracy Standards where 90 percent of the position errors for tested points are less than or equal to 12.2 m; Thompson, 1988). Global positioning systems (GPS) that use code phase receivers can rapidly measure coordinate locations to nominal accuracies of 7 to 12 m (i.e., 90 percent of errors are less than 7 to 12 m; Trimble Navigation, 1992). To achieve nominal accuracies less than 12 m, the GPS position data collected by the receiver at the GCP must be postprocessed and differentially corrected using data collected by a second GPS receiver at a base station of known location (Trimble Navigation, 1992; Gilbert, 1993). Although 7.5-minute quadrangle maps and single frequency GPS receivers have similar nominal accuracies, the coordinates obtained from maps may possess additional errors introduced by digitizing and map production. Map production errors include misplacement of untested features or modifications of feature positions to simplify map printing (Thompson, 1988).

Because GPS measurements are not subject to digitizing and map production errors, they have the potential for providing more accurate coordinates than 7.5-minute maps. This advantage of greater accuracy may, however, be offset by the greater expense involved in obtaining GPS receivers and visiting the GCP locations (Clavet *et al.*, 1993). Although the use of GPS coordinates has been shown to be comparable or preferable to map coordinates for developing orthoimages from aerial photographs (Perry, 1992) and SPOT panchromatic data (Clavet *et al.*, 1993), the improved accuracy of GPS may not be worth the additional expense where the pixel sizes are large relative to the nominal accuracies of maps and GPS. The purpose of this study is to evaluate the effect of the greater accuracy of GPS coordinates for satellite images composed of 30-m, 20-m, and 10-m pixels.

Methods

The effects of using map and GPS coordinates to rectify images were compared for (1) a 4096 by 4096 subsection from the center of a Landsat Thematic Mapper (TM) scene obtained on 14 April 1988, (2) a SPOT multispectral scene collected on 17 April 1988 with a viewing angle of + 23.0°, and (3) a SPOT panchromatic scene obtained on 22 October 1987 with a viewing angle of − 16.5°. These scenes have centers between 33° 14' N and 33° 17' N and between 81° 36' W and 81° 40' W. These centers are on the U. S. Department of Energy's Savannah River Site, a nuclear production facility in Aiken and Barnwell Counties, South Carolina. The images also contain portions of South Carolina and Georgia that are predominantly rural with a mixture of forest and agricultural land use. The area extends from gently rolling Piedmont terrain in the northwest to relatively flat Coastal Plain terrain in the southeast. The maximum elevation is < 225 m, and the minimum elevation is > 40 m.

Features in the images that were also depicted on USGS 7.5-minute quadrangle maps were chosen as GCPs. A total of 88 GCPs were established, but differences in image sizes and resolutions prevented the use of all GCPs in every image. There were 64 GCPs used in the Landsat TM image. For the SPOT panchromatic image, 22 of the GCPs used for the Thematic Mapper image were combined with 24 additional GCPs for a total of 46. For the SPOT multispectral image, 40 of the 46 GCPs for the SPOT panchromatic image were used. Most GCPs were road intersections where the roads joined at angles of 60° or more; however, the rural landscape, the lack of

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recent map revisions, and efforts to ensure that GCPs were evenly dispersed throughout the images required the use of seven oblique road intersections or alternative features.

The pixel coordinates of GCPs were determined to the nearest 0.25 pixel using a 4 by 4 cubic convolution procedure that enhanced pixel resolution (ERDAS, 1990b). To estimate the measuring error for pixel coordinates, each co-author independently determined the subpixel coordinates for each GCP.

The Universal Transverse Mercator (UTM) coordinates based on the 1927 North American Datum were measured for GCPs using 1:24,000-scale 7.5-minute quadrangle maps and a large-format digitizing tablet. Almost all of these maps complied with the National Map Accuracy Standards. Standard procedures were employed to ensure the accuracy of digitized coordinates (ERDAS, 1990a). Where maps had not been recently revised and did not have UTM coordinates, the Georgia State Plane coordinates were measured and converted to UTM.

The GPS coordinates of each GCP were determined using Trimble Pathfinder Professional Systems. Measures of X, Y, and Z coordinates were recorded at 5-second intervals for ≥ 3 minutes of four-satellite availability at each GCP. Because of vehicle traffic, the coordinates for 54 intersections were calculated by measuring the angle and distance from an antenna position beside the road to the center of the intersection. The GPS position data were corrected by post processing using Trimble Pfinder software version 2.20 (Trimble Navigation, 1991) and base station data collected at 33° 20' 35" N and 81° 44' 3" W. Coordinates from GPS measures were expressed as 1927 North American Datum UTM.

To compare the accuracies of map and GPS methods, coordinates were measured using map and GPS techniques for 20 points of known location. These points were road intersections on the Savannah River Site whose coordinates were available from 1:1200-scale engineering drawings.

First-order affine transformation matrices (Jensen, 1986; ERDAS, 1990b) were computed from map and GPS coordinates and used to rectify scenes. Those GCPs with large apparent errors were deleted (ERDAS, 1990b) to reduce the root-mean-square error (RMSE) to 0.33-, 0.5-, and 1.0-pixel units for Thematic Mapper, SPOT multispectral, and SPOT panchromatic data, respectively. These RMSE values were selected to approximate 10-m accuracy in the images.

To compare the effects of map- and GPS-derived coordinates on rectifications, files (hereafter referred to as grid files) were formed of repeated 8 by 8 grids. Each grid had data values ranging from 11 in the upper left corner to 88 in the lower right corner. The data values were arranged so that the units digit defined the row position and the tens digit defined the column position. Grid files were constructed with the same dimensions as the satellite images, and were rectified using transformation matrices computed from map and GPS coordinates. Nearest-neighbor resampling was used in the rectification procedure. The rectified grid files based on map and GPS coordinates were compared on a pixel-by-pixel basis to measure the frequencies of differences in pixel assignments (ERDAS, 1990c). Because the data values defined row and column positions, the comparisons clearly defined the frequency, direction, and distance of differences in pixel assignments between map based and GPS based rectifications.

Results and Discussion

Comparison of the Accuracy of Map and GPS Coordinates

The positions obtained by GPS were more accurate than those obtained from maps for the 20 intersections with known locations on the Savannah River Site (Figure 1). The errors in map coordinates ranged from 2.2 m to 50.1 m, whereas the errors in GPS coordinates ranged from 0.1 to 9.0 m. The mean distance between map and known positions, 19.4 m, was significantly greater than the mean distance of 4.1 m between the GPS coordinates and known positions (t-test of paired observations; $t = 5.65$; $df = 19$; $P < 0.001$; Steel and Torrie, 1960). Before post processing, the uncorrected GPS coordinates had a mean position error of 23.0 m and were not more accurate than map coordinates. The largest error for the map points was due, in part, to a simplified representation of a complex intersection. All of the position errors for the GPS were ≤ 12 m, whereas only six of the map coordinates had position errors ≤ 12 m. The accuracy of the GPS receivers was similar to that observed by Clavet *et al.* (1993) for comparable GPS receivers and was consistent with the expected accuracy for differentially corrected code phase receivers, which is usually stated as 50 percent of errors being ≤ 5 m (Gilbert, 1993).

Because of the errors in map coordinates (Figure 1), there were often relatively large discrepancies between the coordinates determined by GPS techniques and by map techniques (Figure 2). The mean distance between map and GPS coordinates was 12.5 m and was comparable to that observed by Perry (1992). Most of the discrepancies, 84 of 88, were less than the 30-m dimensions of the Landsat Thematic Mapper pixels, but only 39 of the distances were less than the 10-m pixel size for SPOT panchromatic data.

The Accuracy of Pixel Coordinates

The errors involved in measuring pixel coordinates, as determined by comparisons of coordinates between authors, were smaller for the Thematic Mapper and SPOT multispectral images than for the SPOT panchromatic image (Figure 3). The percentages of GCPs where pixel coordinates differed by ≤ 0.5

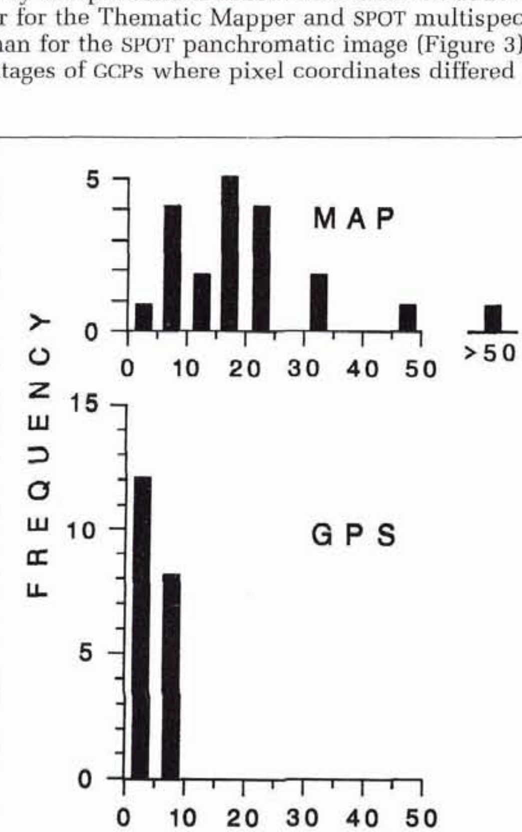

Figure 1. The errors of positions determined by digitizing 7.5-minute quadrangle maps and by GPS for 20 road intersections of known location.

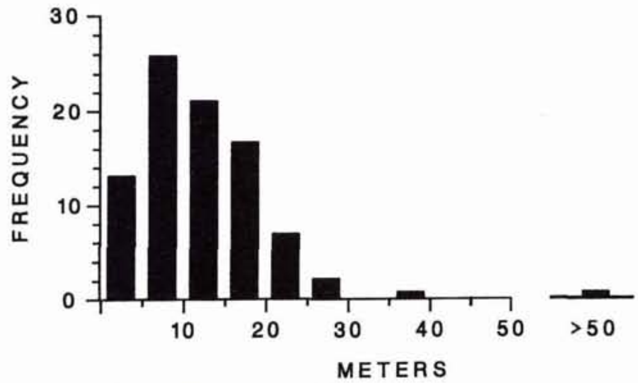

Figure 2. The frequency distribution of the distances between positions determined for ground control points by digitizing 7.5-minute quadrangle maps and by GPS.

pixel units were 73 percent for Thematic Mapper, 78 percent for SPOT multispectral, and 48 percent for SPOT panchromatic. The greater error for the SPOT panchromatic data reflects the difficulty in determining which panchromatic subpixel represented the center of the intersection. These data, as well as the results of Clavet *et al.* (1993), suggest errors of ≥ 4 m in measuring pixel coordinates.

Some large errors of greater than 1 pixel unit occurred due to differences in interpretation of features in the images. These large errors were more numerous for the panchromatic data.

Computation of Transformation Matrices

The GPS method provided more accurate coordinates for the computation of first-order transformation matrices. The initial RMSEs for GPS data were less than those for the map data for all three images (Figure 4), and fewer GCPs had to be deleted from the GPS data than had to be deleted from the map data to achieve relatively small RMSEs. For all three images, more than 70 percent of the GCPs for the GPS data were retained at RMSEs that corresponded to a 10-m accuracy. The large proportion of GCPs retained demonstrates that the differentially corrected GPS data were sufficiently accurate to support rectifications of satellite images at a 10-m resolution. Other studies have demonstrated similar results for GPS data in producing orthoimages (Perry, 1992; Clavet *et al.*, 1993).

The transformation matrices computed from GPS coordinates should be considered to be more accurate than those computed from map coordinates for two reasons. First, the GPS coordinates are more accurate than the map coordinates (Figure 1). Second, a greater proportion of the GCPs are retained from the GPS data than are retained in the map data (Figure 4). Thus, the rectifications performed using GPS data are based on a greater number of GCPs whose coordinates have been determined with greater precision.

The largest initial RMSE for GPS data occurred for the SPOT panchromatic image. A larger RMSE for the panchromatic data was expected because the pixel size is similar to the errors observed in measuring coordinates with GPS (Figure 1). There were, however, indications that errors involved in measuring pixel coordinates also contributed to the larger RMSE. Ten of the 11 GCPs that were deleted from the GPS data to achieve an RMSE of 1.0 pixel were also deleted from the map data. This large proportion of GCPs deleted from both map and GPS data indicates that errors in determining pixel coordinates were responsible for, or at least contributed to, the inaccuracies of the points.

Because the road intersections selected as GCPs had to occur on 7.5-minute quadrangle maps, they were often large enough to encompass several panchromatic pixels. This produced inaccurate measures of pixel coordinates. Smaller and more distinct intersections occurred in the image but not on the maps. If only GPS data were to be used, the GCP selection could have included these more distinct features whose pixel coordinates could have been measured with greater precision. In addition to the greater accuracy of GPS, its use can also contribute to more accurate rectifications by increasing the number, variety, and clarity of features that may be used as GCPs.

The Effect of Map and GPS Accuracy on Rectified Grid Files

Table 1 summarizes comparisons of grid files rectified using map and GPS data for different values of RMSE with different numbers of GCPs retained. The percentage of pixels showing different assigned grid values between map and GPS rectifications ranged from 17.1 percent to 47.7 percent. These differences in assigned values occurred because of small differences in the alignments of map and GPS rectifications. These differences in alignments resulted in a proportion of the pixel assignments to be shifted to neighboring pixel locations. These shifts in assignment were dispersed throughout the files. The direction of the shift often changed as the RMSE was reduced (Table 1).

Reductions in RMSE did not reduce the misalignment between map and GPS rectifications (Table 1). As successive, relatively inaccurate GCPs were deleted, the differences between map and GPS rectifications increased. Thus, the map and GPS rectifications did not converge to similar grid structures as accuracy standards increased. The lack of convergence indicates that rectifications based on map data cannot

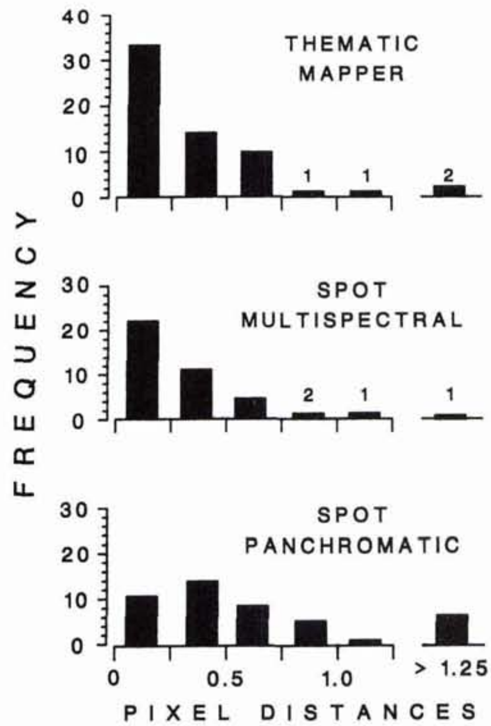

Figure 3. The frequency distributions of the distances between pixel coordinates for ground control points determined by each author for Landsat Thematic Mapper, SPOT multispectral, and SPOT panchromatic images.

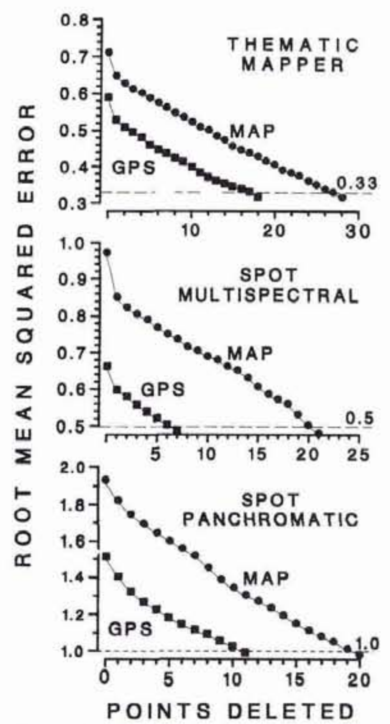

Figure 4. The initial root-mean-square errors (RMSE) expressed in units of pixels and the reduction in RMSE with the deletion of successive ground control points to obtain RMSE of ≤ 0.33 for Thematic Mapper, ≤ 0.5 for SPOT multispectral, and ≤ 1.0 for SPOT panchromatic images. Computations were performed using the COORDN procedure of ERDAS (1990b).

TABLE 1. THE PERCENTAGE OF PIXELS WITH DIFFERENT ASSIGNED VALUES BETWEEN GRID FILES RECTIFIED USING COORDINATES DETERMINED FROM 7.5-MINUTE MAPS AND GPS.

Image Type	RMSE	Number of GCP Retained		Percent Different	Direction of Spatial Shifts
		Map	GPS		
Thematic Mapper	Initial	64	64	17.1	South
	0.50	52	61	24.2	North
	0.33	36	46	23.4	East
SPOT Multispectral	Initial	40	40	25.2	South
	0.75	33	40	44.4	South
	0.625	25	39	47.7	South
	0.50	19	33	42.4	South
SPOT Panchromatic	Initial	46	46	38.7	South
	1.5	36	45	42.0	South
	1.0	26	35	46.9	North

be made as accurate as rectifications based on GPS data by simply imposing a small RMSE on a large number of GCPs.

Large differences between map and GPS rectifications occurred for the SPOT panchromatic image. Almost one-half the pixels in the rectified files had different assigned values. A large difference was expected for the panchromatic image due to the small pixel sizes and the RMSE of 1.0, and the results of this study are consistent with those of Clavet *et al.* (1993) who concluded that cartographically derived coordinates were not sufficiently accurate to produce acceptable rectifications of SPOT panchromatic data.

The differences between map and GPS rectifications for the Thematic Mapper and SPOT multispectral images were also large. The differences for the SPOT multispectral data were as large as those for the panchromatic data. Differences > 20 percent occurred for the relatively large Thematic Mapper pixels. The differences for the Thematic Mapper image imply that more than 20 percent of the features in the data rectified by the map coordinates are displaced 30 m from their corresponding positions in the data rectified by the GPS coordinates. This amount of displacement is not consistent with current map accuracy standards.

The large differences between map and GPS rectifications for Thematic Mapper, SPOT multispectral, and SPOT panchromatic data in Table 1 indicate the increases in accuracy that may be expected from using coordinates measured by GPS. Whether the benefits of this increased accuracy warrant the use of GPS depends on (1) the accuracy required and (2) the costs of measuring GPS coordinates. In addition to the cost of obtaining the GPS receivers, the major expenses associated with GPS measurements are the time and travel costs involved in visiting the GCPs. The costs of visiting the GCPs is largely dependent on the size, location, and terrain of the area being rectified (see Clavet *et al.* (1993) for an example of cost analysis computations).

Other types of GPS receivers are available that can provide more accurate position coordinates than code phase receivers. Systems employing p-code receivers can achieve nominal accuracies of ≤ 0.1 m, but their use for rectifying satellite images may not be warranted due to the time and cost required to obtain GCP coordinates (Clavet *et al.*, 1993). Moreover, accuracies as small as 0.1 m are not required when the errors involved in measuring pixel coordinates are ≥ 4 m. Although the use of p-code receivers may not be warranted, the recent development of GPS receivers that can rapidly measure positions with nominal accuracies of ≤ 2 m (Gilbert, 1993) should prove useful in further increasing the accuracy of satellite image rectifications.

Conclusion

These comparisons illustrate that using GPS and map coordinates can produce rectified files that differ in more than 40 percent of their pixel assignments. These differences involve generally small spatial shifts, but they can result in more than 20 percent of the features in the rectified images being displaced by 30 m. Where position accuracy in the rectified data is required, the use of GPS may be warranted for even relatively large pixels.

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