Accuracy of Rectification Using Topographic Map versus GPS Ground Control Points

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Abstract

Reliable assessments of landscapes are needed for natural resource conservation and preservation efforts and for understanding the impacts humans are having upon those resources. Remotely sensed data provide an integrated view of the landscape and are nicely suited for temporal change studies. Reliable interpretation of Earth surface characteristics relies largely on accurate rectification of the remote sensing imagery to a map projection and on subsequent thematic classification. For rectification, we found that control points acquired using the Global Positioning System (GPS) were superior to those acquired from digitized topographic maps. Differentially corrected GPS locations provided for the optimum rectification of SPOT satellite imagery while marginally better rectifications were obtained for Landsat MSS imagery using uncorrected GPS positions. Accuracy of ground control point sources for rectification should match the resolution of the digital image. Shifts in pixel digital number locations following the resampling procedure in rectification indicate a substantial amount of change might erroneously be attributed to change when, in fact, it might simply be due to differing methods of determining cartographic coordinates of ground control points. This has important implications in change detection studies and should be explored further.

Introduction

Biological diversity, or biodiversity, is a key component in assessing ecosystem health. Alteration, degradation, and loss of habitat due to human influence is currently the primary stressor that results in a decrease in biodiversity (Ehrlich, 1988). Current projects envisage human population size moving past nine billion over the next 50 years, and leveling at ten to eleven billion by the end of this century (National Research Council, 1999). With nearly twice as many people on the Earth as there are today, and with consumptive lifestyles enjoyed by many but desired by most, increased pressure on environmental resources is to be expected. Human induced global environmental change has become a major national and international policy issue. Detecting change has been a major research effort among environmental scientists, and predictions of major environmental changes in the future are becoming common (see, for example, Weiner (1990)). Land use and land cover are being suggested as the most relevant indices of environmental quality at the national (and global) level (National Research Council, 2000), and satellite imagery represents the most effective and efficient technology for developing regional, national, or global coverages of land use/land cover and their changes over time. However, satellite imagery always has a certain amount of error associated with it. Sources of error may include, among other things, the classification system used, sensor characteristics, environmental conditions at the time an image was acquired, or rectification accuracy. When coverages of the same area from two different dates of satellite imagery are compared to assess change, an analyst may confuse rectification error as change when, in fact, it is not (Khorram *et al.*, 1999). This paper focuses on the often overlooked issue of how rectification may effect land-use/land-cover change analysis. There are many large scale efforts underway, such as the Environmental Monitoring and Assessment Program (USEPA, 1994) or Gap Analysis (Scott *et al.*, 1993), which rely largely on accurate image rectification to a map projection and subsequent thematic classification so that change can be identified and quantified.

The rectification process entails determination of locations of features that are easily recognized in both a satellite image and a corresponding cartographic coordinate system. The feature's location in the image (column and row), as well as its location in the coordinate system (e.g., latitude and longitude) are determined. These features are referred to as ground control points (GCPs), and an affine transformation can be developed so that, for any given column/row location, its corresponding cartographic coordinate can be estimated (typically from least-squares regression). The most traditional source of GCP cartographic coordinates has been to use topographic maps and a digitizing tablet. However, with the advent of the Global Positioning System (GPS), it is not uncommon to define a GCP's cartographic location in the field using a handheld GPS receiver.

For example, Perry (1992) used GPS measurements for collecting ground control points (GCPs) to rectify airial photography. Perry used a reference receiver located over a National Geodetic Survey (NGS) control point (commonly referred to as a benchmark) and a rover receiver for collecting the GCPs. Positions recorded on the rover were corrected differentially using post-processing procedures. Results indicated accuracy comparable to or better than was achieved by digitizing from U.S. Geological Survey (USGS) 1:24,000-scale topographic maps.

Clavet *et al.* (1993) used a combination of orbital data, digital elevation models (DEMs), and four methods of acquiring GCPs to produce ortho-images from SPOT satellite data for use in updating 1:50,000-scale Canadian National Topographic Maps. The authors wanted to determine the most cost-efficient, yet accurate, method of acquiring GCPs for map production purposes. The best method involved the use of precise autotriangulated data and DEMs. However, when photogrammetric data were either absent or of questionable quality, GPS acquired

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data were sufficient as long as the positions were differentially corrected.

Cook and Pinder (1996) compared the accuracies of rectifications of Landsat TM, SPOT multispectral, and SPOT panchromatic digital images using GPS data and by digitizing USGS 7.5-minute topographic maps. GPS data were differentially corrected by post-processing with a reference receiver. Accuracy of rectification was determined by comparing frequencies of differences in pixel reassignment, as well as the standard root-mean-square error (RMSE) comparison. Results indicated that pixel reassignment based on map coordinates can displace features up to 30 meters from corresponding positions acquired through GPS. Furthermore, decreasing the number of GCPs in order to lower the RMSE did not reduce the differences in pixel reassignment between the rectifications. This approach, in fact, resulted in greater differences in pixel location assignments even though a smaller RMSE was achieved. The authors concluded that rectification accuracy was improved when acquiring GCPs using GPS receivers.

Kardoulas *et al.* (1996) compared rectification of Landsat MSS, Landsat TM, and SPOT panchromatic satellite imagery using 1:100,000-scale topographic maps with GPS-derived locations. GPS locations were collected in autonomous mode with selective availability (SA) enabled. They concluded that GPS-derived points provided better accuracy for Landsat MSS images, marginal accuracy for Landsat TM images, and that differential correction was needed for use with SPOT imagery. The authors did not directly compare map-derived coordinates with GPS-derived coordinates.

The overall goal of this study was to determine if rectification accuracy, especially in light of the need for change-detection research, is affected by the method by which researchers determine the cartographic locations of the ground control points used for rectification. This determination was made based on traditional root-mean-square error techniques and a novel approach utilizing synthetic image files so that all pixels could be tracked during resampling. Finally, material costs and time of effort for each technique were recorded to lend insight into economic issues related to rectification.

Methods

The images used were in conjunction with a continuing large scale environmental study at Ray Roberts Lake in north-central Texas (IAS, 1995; IAS, 1999). Digital imagery from the French Systeme Probatoire d'Observation de la Terre (SPOT) and Landsat Multispectral Scanner (MSS) were acquired in October 1992. The MSS image was acquired through the North American Land Cover (NALC) program and had been resampled to a spatial resolution of 60 by 60 meters. The SPOT image was acquired as partially processed raw data.

Each image was rectified using affine coordinate transformation (Verbyla, 1995). GCPs were generated using four techniques:

- digitizing 1:24,000-scale USGS topographic maps,
- handheld autonomous mode GPS with Selective Availability enabled,
- post-processing of autonomous data using differential corrections with a base station data, and
- real-time differential correction using broadcast correctional data.

Accuracy was compared using two methods. First, root-mean-square (RMS) error was examined. RMS error is a measure of the average total offset (hypotenuse) distance between all GCPs' final column/row locations (integers) in a rectified image, and their predicted column/row locations (real numbers) based on the affine coordinate transformation model. The units of RMS error are in pixels, and, because an image's spatial resolution is known, it is easy to convert RMS error to units of distance such as meters. Khorram *et al.* (1999) recommend 0.5 pixel RMS error or better for change detection research. It is common to determine which of the GCPs from the total set contributes the most error, eliminate that point, and recompute a new transformation model. In this study, GCPs were eliminated until the RMS error was 0.5 pixels or better, but we never used fewer than ten GCPs to develop a transformation model even if the RMS error was not less than 0.5.

Second, we examined where specific pixels (or rather, the digital number represented in each pixel) were placed in rectified images. When pixels are resampled from the distorted unrectified image to the undistorted rectified image, they may be shifted by as much (or more) than that indicated by "average" RMS error. This shift has important implications when comparing one image with another, as in a time series study, when change in a characteristic at a pixel location should not be confused with a rectification error. To examine this potential confusion, we produced "synthetic grid files" with the same number of columns and rows contained within each original satellite image of our study area. These synthetic files were created by forming repeating 8 pixel by 8 pixel grids until the desired number of columns and rows were generated. Each of 64 pixels in an individual 8 by 8 grid was assigned a unique digital number ranging from 11 (row 1, column 1) to 88 (row 8, column 8) (Figure 1a). The synthetic files were rectified using affine transformation algorithms generated by four techniques of determining cartographic locations from a predefined set of GCPs (Figure 1b and 1c illustrate two of the four techniques). Finally, each rectified synthetic image (Figures 2a and 2b) was overlaid with the other rectified synthetic images to quantify differences in pixel resampling based only on differences in GCP technique (Figure 2c). This approach provided information not only as to how digital numbers were resampled to a map location between the two GCP techniques, but also as to where and in what directions the differences occurred. This analysis was accomplished using the "MATRIX" procedure in ERDAS Imagine version 8.2 software. MATRIX is a common tool used in change detection, allowing one to examine individual pixels in a time series and determine if its land-cover class (or digital number in raw imagery) has remained unchanged between the two images, or, if it has changed, into what class it changed. Because each pixel's value in our synthetic grid files indicates its original location in the 8 by 8 grid, and because we can rectify the same synthetic grid file using two different transformation models by MATRIXing the two rectified synthetic images, we can determine how much change is due simply to rectification error. Additionally, we can determine directionality of error by examining which cells typically overlay each other in error.

Finally, relative cost of equipment and labor involved in acquiring the different GCPs was compared to provide information for determining the most appropriate method of acquiring GCPs, depending on the level of accuracy required, scale (resolution) of the satellite image, and associated costs. Costs were recorded for two categories: materials (dollars) and labor (time).

Ground control points derived from USGS topographic quadrangle maps were obtained using a large-format CalComp digitizing tablet following standard procedures to ensure accuracy of digitized coordinates (ERDAS, 1990). GPS-derived locations were collected using a Trimble GeoExplorer™ single-frequency ten-channel receiver. Data for both methods were collected as Universal Transverse Mercator (UTM) coordinates based on the 1927 North American Datum (NAD27). Base station data for post-processing differential corrections were obtained through the Texas Department of Transportation which operates Trimble 4000 Community Base Stations™ throughout the state, including one in Arlington, Texas which was used for this research. Real-time differential correction was acquired with an ACCQPOINT DataReceiver™ which receives

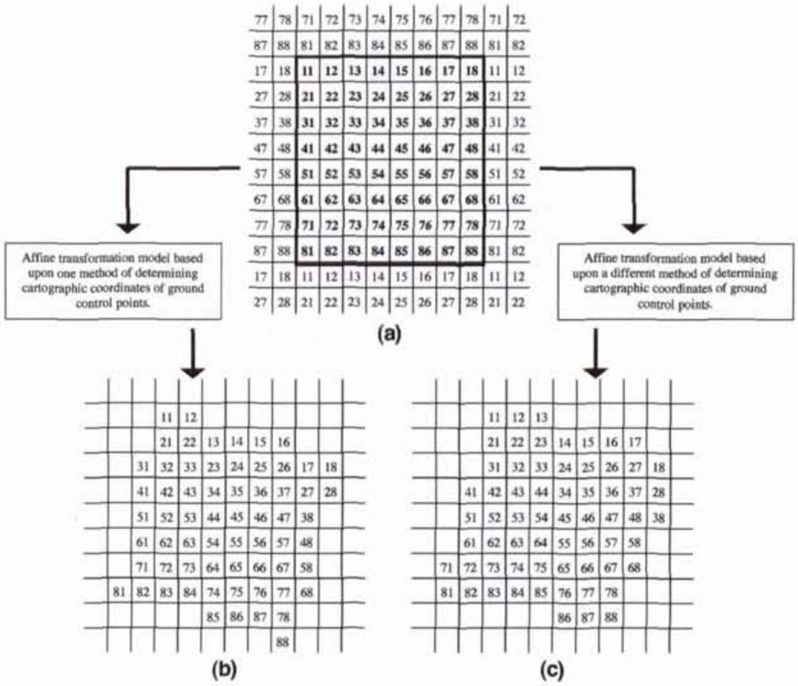

Figure 1. Process of multiple rectifications from one input file. (a) Subset of synthetic grid file, highlighting one 8- by 8-pixel grid pattern which is repeated hundreds of times to produce a synthetic grid file. (b) Results of rectification and resampling from one affine transformation model based upon one method of collecting ground control points (e.g., topographic maps). (c) Results of rectification and resampling from a different method of collecting ground control points (e.g., GPS in autonomous mode).

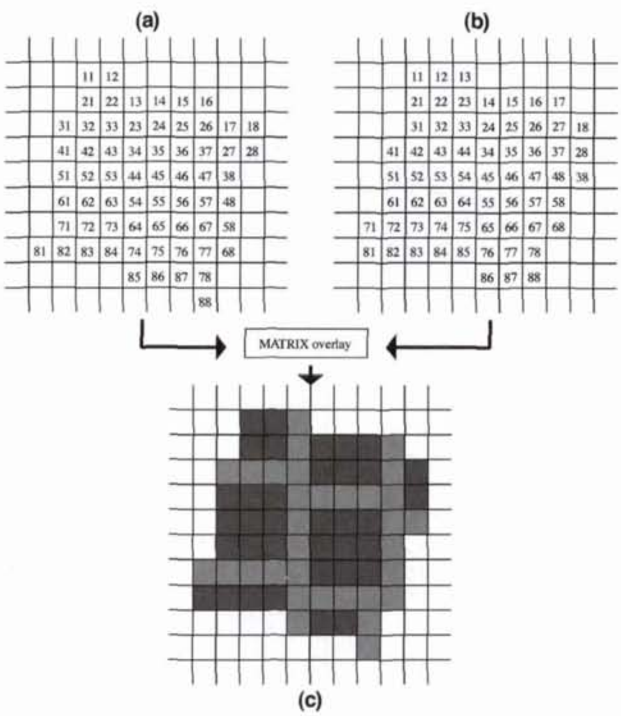

Figure 2. Process of overlaying rectified images. (a) Rectified image from one method of collecting ground control points (e.g., topographic maps). (b) Rectified image from a different method of collecting ground control points (e.g., GPS in autonomous mode). (c) Resultant overlay showing pixels which have different values in the two images (in lighter hash marks) and pixels which have the same values in the two images (in darker hash marks).

Table 1. Descriptive Statistics of Various Methods of Determining Cartographic Locations of Benchmarks in the Study Area

	MASCH benchmark			SALEM2 benchmark		
	n	UTM average coordinate (meters)	average difference between truth and coordinate (standard deviation)	*n*	UTM average coordinate (meters)	average difference between truth and coordinate (standard deviation)
Northing						
NGS (true)	1	3682806.74		1	3714735.24	
USGS topographic map	40	3682798.76	7.98 (2.79)	40	3714732.53	2.71 (3.06)
GPS autonomous	123	3682880.86	75.11 (23.75)	123	3714731.38	3.06 (7.04)
GPS post processing	47	3682807.50	1.75 (0.27)	123	3714735.52	1.09 (0.31)
GPS real time correct	125	3682808.40	2.66 (0.90)	122	3714735.83	1.40 (0.77)
Easting						
NGS (true)	1	667591.57		1	687286.03	
USGS topographic map	40	667586.01	5.56 (0.03)	40	687284.15	1.88 (1.622)
GPS auto	123	667598.01	7.83 (6.08)	123	687346.32	61.54 (16.59)
GPS post processing	47	667591.22	1.03 (0.34)	123	687285.76	1.28 (0.67)
GPS real time correct	125	667591.33	1.15 (0.33)	122	687285.94	1.45 (0.33)
Average Total Offset (hypotenuse)						
NGS (true)						
USGS topographic map			9.69			3.30
GPS auto			75.52			61.62
GPS post processing			2.03			1.68
GPS real time correct			2.90			2.02

differential GPS data carried by frequency modulation (FM) signals. Confirmation of accuracy in the field was attained by obtaining GPS locations at National Geodetic Survey (NGS) first- or second-order triangulation benchmarks within the study area. Benchmark positional data were collected based on the 1983 North American Datum (NAD83) for comparison to published coordinates. Rectifications were conducted using ERDAS Imagine version 8.2. Each image was rectified using a first-order affine transformation process with nearest-neighbor resampling. This process stream ensures the integrity of the original digital number when pixels are reassigned positions during rectification.

Results and Discussion

To check the relative accuracy of positional data collected in the field, a search was conducted for first- and second-order National Geodetic Survey (NGS) benchmarks in the study area. These are locations that have been accurately surveyed using a matrix of dual-frequency GPS units collecting data simultaneously at multiple benchmarks in an area over three eight-hour periods for three days. The stated accuracy of the benchmarks on maps meeting National Mapping Standards is ±0.005 mm at publication scale. At a scale of 1:24,000, the accuracy of benchmark locations is within 0.12 meters (4.7 inches) of their actual locations on the ground. Two benchmarks were located in the study area, referred to as Masch and Salem2. Masch is a first-order benchmark located in the southwest corner and Salem2 is a second-order station located in the mid-northern section of the study area.

Table 1 provides average locations and differences from true (published NGS) locations using three modes of GPS-derived locations (*n* ranges from 40 to 125). These locations were collected using the North American Datum of 1983 (NAD83), NGS's datum of choice. The map projection used for the study was Universal Transverse Mercator, north of the equator, Zone 14 (NUTM14). As expected, there were notable differences between a benchmark's true location and that benchmark's position determined using GPS in autonomous mode with Selective Availability (SA) enabled (less than 1 to over 100 meters). SA, an intentional clock and ephemeris error introduced by the Department of Defense, was in effect at the time of this study. Dferences between a benchmark's true location and that benchmark's GPS location determined with post-processing as well

Table 2. Comparison[1] of Best Rectification Transformation (Lowest RMS Error) Using a Minimum of Ten Ground Control Points for the MSS and SPOT 1992 Images

Method	MSS	SPOT
Topo Map	0.64(38.4)	0.35(7.0)
GPS-Auto	0.39(23.4)	0.52(10.4)
GPS-Post	0.52(31.2)	0.09(1.8)
GPS-RT	0.52(31.2)	0.14(2.8)

[1]Values are reported in pixel units and meters (in parentheses).

as real time corrected data were often less than 1 meter and always less than 4 meters. UTM coordinates in Table 1 are based on North American Datum of 1927 (NAD27).

For image rectification, an initial group of 26 GCPs was selected by identifying prominent surface features such as road and highway intersections that were common to both satellite images and that could also be located on USGS topographic maps. GCPs were fairly evenly distributed throughout the study area. Care was taken to avoid multiple GCPs along major linear features such as Interstate Highway 35. Table 2 summarizes the best RMS error for each method and satellite image.

For our study, the best rectification accuracy for the MSS scene was unexpectedly provided by GCPs collected with the GPS in autonomous mode. This method resulted in an accuracy of 0.39 pixel, or 23.4 meters. Both the GPS post-processing and real-time differential corrections resulted in accuracies of 0.52 pixels, or 31.2 meters. The least accurate of GCP sources were those digitized from topographic maps (0.64 pixels). Because all GPS sources provided RMS accuracies better than those digitized from topographic maps, we concluded that GPS-based GCPs were preferred in our study area. However, differential corrections of GPS data are not necessary for accurate rectification of MSS imagery.

The best rectification accuracy for the SPOT scene was provided by GCPs collected with GPS when the data were post-processed with base station data. This method resulted in an accuracy of 0.09 pixels, or 1.8 meters. GPS real-time differential corrections had an accuracy of 0.14 pixels, or 2.8 meters. Both of these methods would therefore result in highly accurate rectifications as reported using RMS error. For this imagery, how-

TABLE 3. COMPARISON OF PIXEL REASSIGNMENT AND DIRECTION OF SHIFT OF PIXELS ASSIGNED DIFFERENT LOCATIONS FOR THE SYNTHETIC MSS AND SPOT GRID FILES

	MSS Synthetic Grid File		SPOT Synthetic Grid File	
	Percent of pixels assigned same location	Predominate direction of shift along axis	Percent of pixels assigned same location	Predominate direction of shift along axis
GPS-Autonomous vs. GPS-Post Processing	38.7	WNW-ESE	18.8	E-W, WSW-ENE
GPS-Autonomous vs. Topographic Map	29.8	WNW-ESE	17.9	SW-NE, WSE-ENE
GPS-Autonomous vs. GPS-Real Time Correction	39.1	WNW-ESE	11.7	SW-NE, WSE-ENE
GPS-Post Processing vs. Topographic Map	59.0	all directions equally	55.1	E-W, N-S
GPS-Post Processing vs. GPS-Real Time Correction	97.4	N-S	65.3	N-S
GPS-Real Time Correction vs. Topographic Map	58.7	N-S	1.5	all directions equally

ever, digitizing topographic maps yielded better results than did the GPS in autonomous mode.

Table 3 lists the six possible combinations of overlaying the four rectified synthetic grid files (representing both MSS- and SPOT-sized images) using the MATRIX procedure. The higher the percentage of pixels assigned the same location between the two GCP collection methods, the greater the agreement. The two methods corresponding best (97.4 percent agreement) were the GPS post-processing and real-time differential corrections for the MSS-sized synthetic image. The predominate shift of pixels that were not assigned the same location between the two sources of GCPs was north-south, or one pixel up or down. The worst agreement (1.5 percent) was between the topographic map and GPS in autonomous mode for the SPOT-sized synthetic image. The predominate shift in this case was back and forth along a west northwest line, or two pixels to the left and one pixel up. The best SPOT-sized agreement was approximately 65 percent, while the worst MSS-sized agreement was just approximately 30 percent. It is important to note that not all pixel shifts are shifted in the same direction, but that a central pivot point or multiple pivot points seem to occur.

Figure 3 provides a visual representation of the spatial distribution of the agreement and/or disagreement of pixel reassignments that the tabular data could not provide. This represents the worst case for the SPOT-sized synthetic image. The figure depicts two classes of pixels; those assigned the same locations are shaded dark gray and pixels assigned different locations are shaded light gray.

Relative costs of acquiring positional data used for rectifying satellite digital imagery are listed in Table 4. These comparisons do not include typical basic equipment (i.e., computers and digitizing tablets) in addition to appropriate software. The least expensive source of collecting GCPs from both a material cost and time of effort was from USGS topographic maps. Time of effort was nearly the same with all modes of collecting data using the GPS, with post-processing of positional data requiring slightly more time at a computer. The greatest cost of materials was for post-processing, because this method required two GPS receivers, one configured as a base station over a known location, and the other used as a roving unit. If one had access to base station data (such as Texas Department of Transportation sites) within their study area, equipment cost would be equal to GPS in autonomous mode. Real-time differential correction equipment added approximately five-hundred dollars to the cost of the GPS unit and reduced the time of effort by two hours (13 percent).

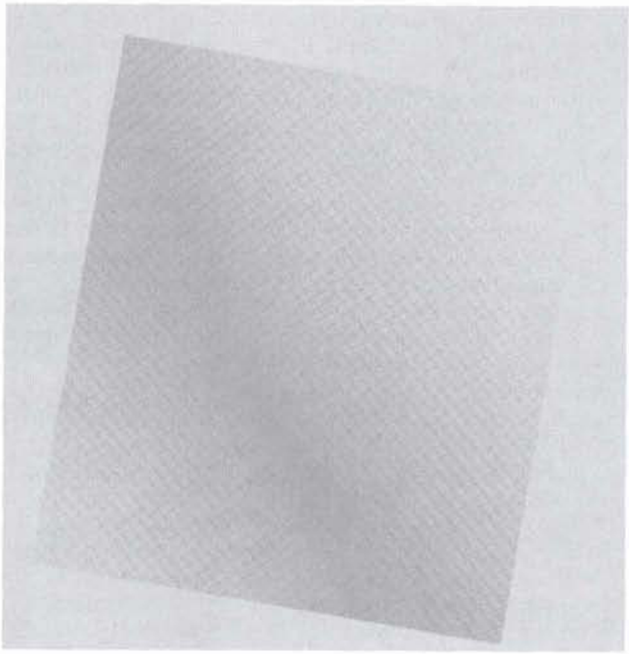

Figure 3. Image of matrix results comparing synthetic SPOT grid files rectified with GCPs differentially corrected in real-time with topographic-map-derived GCPs. Pixels shaded dark gray are those assigned the same location; light gray indicates pixels assigned to different locations during the resampling process.

TABLE 4. COMPARISON OF EQUIPMENT COSTS AND TIME OF EFFORT EXPENDED TO COLLECT GROUND CONTROL POINTS FOR DIGITAL IMAGE RECTIFICATION

Data Collection Method	Material Cost ($)	Time of Effort (hrs)
Topographical Maps	80.00	4.75
GPS-Autonomous	500.00	14.00
GPS-Post Processing	3000.00	16.00
GPS-Real Time Corrections	1000.00	14.00

Conclusions

The Global Positioning System (GPS) was highly accurate when positional data were differentially corrected. Accuracy was determined by comparing GPS positions to published NGS benchmark locations. There were only small (one meter or less) differences between positional data corrected in real-time and by post-processing. All modes of collecting GPS positional data provided higher rectification accuracy (measured by root-mean-square error) than did topographic-map-derived ground control points (GCPs) when rectifying the Landsat MSS image. The best MSS rectification accuracy (as measured by RMS error) was obtained using the GPS in autonomous mode (with Selective Availability enabled) without differentially correcting the positions. This was an unexpected finding because it is the least accurate of all GPS modes tested. This may potentially be explained because the nominal accuracy for GPS in autonomous mode is 100 meters, depending on satellite geometry, similar to and only somewhat less than the resolution of MSS images. When rectifying the SPOT image with GCPs collected by GPS in the autonomous mode, the 100-meter nominal accuracy of GPS is substantially less than the resolution of the imagery, and produced the worst RMS error of all techniques tested, as was expected. A highly accurate SPOT rectification was obtained using differentially corrected GPS positions either in real-time or post-processed. It appears that the most important criterion in selecting a method of collecting GCPs for image rectification seems to be matching the resolution of the images to the accuracy of the GCP source. Coarse images, such as Landsat MSS, are sufficiently accurately rectified using GCPs of similar accuracy (autonomous mode). Finer resolution images, such as SPOT (and most likely all of the new high resolution systems currently launched or planned) require more accurate GCPs, such as those provided by differentially corrected GPS positions using a base station. Additionally, this study has shown that a large amount of error can be introduced by simply using different techniques to gather GCPs when rectifying images. The synthetic grid image study shows that rectifying a single image twice, using the same GCPs, but determining the cartographic coordinates of those GCPs with two different techniques, can result in over 98 percent of pixels being assigned to different locations in the final rectified image. The implication for change detection research is that a conclusion might be drawn that 98 percent of a study area had changed between the time of two images when, in fact, the two images were identical. This may not be as much of a problem when land cover is relatively homogeneous, but can add to misclassification in landscapes that are highly irregular. The synthetic images in this study represented the most severe of land-cover conditions where every pixel was considered "edge" in that there were no pixels adjacent to like pixels. In such landscapes, rectification accuracy plays a much more important role than with clumped or contiguous landscapes. Thus, an important finding of this research leads to a quality control issue; change detection studies should define a set of GCPs, decide upon a technique for determining the cartographic coordinates of those GCPs, and not waver from that definition for the duration of the change detection study.

There are two concerns that should be pointed out regarding GPS and map accuracy. First, the intentional error (designated as Selective Availability), introduced into the GPS by the Department of Defense for the purpose of degrading signal accuracy, was turned off in early 2000, eliminating the primary source of positional error that requires differential correction. Base station triangulations will still be needed for very high accuracy applications, such as surveying with centimeter accuracy specifications. However, for digital image rectification, a single frequency GPS unit without the differential correction requirement will be all that is needed for one- to two-meter positional accuracy. This effectively renders the discussion of the preferable mode of collecting GPS positions as moot.

Second is the concept of accuracy. According to Thompson (1988),

> "Map accuracy determination is by no means an exact science. Many accuracy specifications and testing procedures cannot be so clear and mathematically incontrovertible that they will give the exact and only answer to the problem of evaluating the accuracy of a given map. There is an area of interpretation, whose existence must be recognized to avoid rigidly applying narrow rules in a way that does not reflect the spirit or intent of the specifications."

In other words, the accuracy of any given map is neither more nor less than that explicitly stated by the map producer. Additionally, the accuracy of any point is only relative to some other point or reference grid. True location is an abstract concept as the Earth's surface is not only spinning and hurtling through space, but is inherently dynamic and thus constantly changing, albeit some areas change at a slower rate than others. The main point here is that, when working with map accuracy, it is important to be explicit and consistent.

Ultimately, we are concerned with the classification accuracy of thematic maps. Inaccurate classification leads to incorrect conclusions and assumptions of landscape conditions which would lead to erroneous management with potentially disastrous results.

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