Accuracy Assessment of Elevation Data Sets Using the Global Positioning System

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Abstract

A field survey using the Global Positioning System (GPS) was performed to evaluate the accuracy of a prototype data set called Tactical Terrain Data (TTD). The horizontal and vertical accuracy of a 1:24,000-scale 7½-minute quadrangle, a 1:50,000-scale 15-minute quadrangle, and two Digital Elevation Models (DEMs) were also assessed. Nineteen road intersections located in the study area were tied to three first-order horizontal control stations using relative GPS static and pseudo-kinematic techniques. The coordinates and elevations of the 19 road intersections obtained from the TTD, DEMs, and topographic map sheets were compared to the GPS data in both an absolute and relative sense. The TTD did not meet stated absolute accuracy requirements, while the relative accuracy was found to be satisfactory. The DEMs and the map sheets were of high vertical quality and met stated vertical accuracy standards.

Background

Slonecker and Hewitt (1991) assessed the accuracy of Geographic Information System (GIS) data using information on road intersection locations determined with the Global Positioning System (GPS). Their field work and network adjustment were performed by the U.S. Geological Survey (USGS) in support of photogrammetric mapping. Slonecker and Hewitt's study included an assessment of the accuracy of GPS pseudo-range horizontal coordinates using the differential correction technique. This technique has reported accuracies on the order of 5 m (Trimble Navigation Limited, 1989). Slonecker and Hewitt found the average absolute error of this technique to be 8.3 m, with a root-mean-square error (RMSE) of 9.5 m to meet a target of 25 m in map interpretation.

Perry (1992) used GPS in a differential mode for locating ground control points (GCPs) for use in an agricultural application. Her results showed that GPS produced offsets from 7 to 32 m with an RMSE of 8.2 m for eight GPS-determined points when compared with USGS 1:24,000-scale topographic maps. Another set of measurements showed an RMSE of 4.9 m for 12 points used to register an aerial photograph.

A new format digital data source called Tactical Terrain Data (TTD) is being produced by the U.S. Army Topographic Engineering Center (TEC). TTD is a prototype data set developed by the Department of Defense and can potentially serve as a valuable input to a GIS used for military and engineering applications. The goal of this work was to assess the absolute and relative horizontal accuracy of the transportation layer of the TTD. Also, the absolute vertical and horizontal accuracy of the elevation layer of the TTD, a USGS Digital Elevation Model (DEM), and two map sheets (a USGS 1:24,000-scale 71/2-minute quadrangle and a Defense Mapping Agency (DMA) 1:50,000-scale 15-minute quadrangle) was determined in this study. The TTD, elevation arrays, and map sheets were compared using a network of road intersection points surveyed using the GPS satellite constellation tied to National Geodetic Survey (NGS) first-order control monuments.

Description of the Data Sets

TTD

The DMA TTD evolved from an initial Army requirement for digital topographic data to support terrain analysis. In 1980 the Army asked DMA to produce a prototype data set for evaluation by the services. After this evaluation, digital topographic data requirements for the Army were developed in 1984.

The data content, format, accuracy, and resolution standards of the TTD were negotiated beginning in 1985. The Army requires that the data be capable of supporting a broad range of land combat functions and systems for the 1990s and beyond (Messmore and Fatale, 1989). The first delivery of prototype data was made in September 1988 for evaluation by the user community. The prototype data covers a 15- by 15-minute area corresponding to the DMA 1:50,000-scale Killeen, Texas topographic map (31° to 31°15'N, 97°30' to 97°45'W) (Figure 1).

The TTD is designed so that users can perform tasks such as terrain visualization, mobility/fire planning, communications planning, navigation, munitions guidance, and site and route selection. The TTD data set is comprised of a Digital Terrain Elevation Data (DTED) level II elevation matrix, an enhanced Tactical Terrain Analysis Data Base, and selected features from the 1:50,000-scale Topographic Line Map and the 1:50,000-scale Army Combat Chart.

The accuracy of the prototype TTD is described in terms of the accuracy of the class 2, 1:50,000-scale topographic line maps. This accuracy states that 90 percent of all planimetric features shall be located within 50 m of their geographic position, referenced to the map projection used.

The resolution of feature information in the TTD is a function of inclusion condition requirements applied as each thematic layer was compiled and of the value ranges associated with each attribute. For example, the minimum area for inclusion in the vegetation layer is 50,000 m² or about 225 by 225 m; any distinct vegetation unit smaller than this area would not be included as a polygon in the data layer.

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The prototype TTD are available in both an integrated and nonintegrated format. The integrated version is comprised of nine files that each cover a 5- by 5-minute area, each with a single topologic layer, requiring 47.4 MBytes in storage. The nonintegrated set is made up of eight topologically separate theme files covering the full 15- by 15-minute quad area, requiring a data volume of 7 to 8 MBytes per theme. The two data sets contain the same information; the principal difference between the two is that the contents of the non-integrated set are in a number of separate files instead of one integrated file.

The feature data in the TTD are vector data called Center Line Data. In this format features are defined by strings of *x-y* coordinates. These strings represent line segments and points that correspond with the boundaries or locations of real world features. The data also contain complete feature attribute information, but do not contain any symbolization.

The TTD are structured in a format called Mini-Topo (Minimally Redundant Topology). This format has two overlapping data structures, described as spatial and cartographic. The spatial data provide a means for representing the geometry of a data set, while the cartographic data structure allows for storing attribute and relational information. Feature data structures are generated by connecting spatial data (coordinates) with the associated cartographic data (descriptive attributes and relations). For example, a linear feature such as a road would have inserted nodes when the feature components change (for example, from light duty paved to gravel). At line intersections, nodes are also created even if the feature components do not change on either side of the node.

The attribute information for the TTD are represented with DMA's Feature Attribute Coding Standard (FACS). These codes are five alpha-numeric characters and sometimes have associated sub-attributes. An example of a FACS code is 5C030, which stands for the vegetation feature "deciduous forest." Dubishar (1988) provides a listing of all FACS codes and their feature names.

After initial evaluation by potential users, TEC decided that the Mini-Topo structure was too complex for use as a production format. Therefore, a format called Interim Terrain Data (ITD) was developed and supplied by TEC in a User-oriented Minimum Essential Data Set (UMEDS) for users to evaluate.

UMEDS ITD

TEC contracted with Science Applications International Corporation (SAIC) of McLean, Virginia to develop a distribution format for the TTD, known as ITD. The UMEDS format was created to provide a simpler format for the TTD and ITD.

ITD have been produced by DMA since January 1990. These data are designed to bridge the gap between the nonstandard digital topographic data sets and the future standard TTD. ITD are stored in a vector format. SAIC converted one 15-minute tile of ITD for Killeen, Texas, into the UMEDS format to ensure that this format is flexible enough to describe data sets with differing characteristics.

The spatial constructs (primitives) used to define the features in the ITD include nodes (point construct), edges (linear construct), and faces (areal construct). In this format a point feature is made up of a single feature node. A linear feature is constructed with one or more edges, and an areal feature is made up of one or more faces (Ward and Hawkins, 1990). Figure 2 shows the topological relationships inherent in the UMEDS ITD. The dashed line in the diagram indicates that a feature node is related either to a face or an edge, but not both.

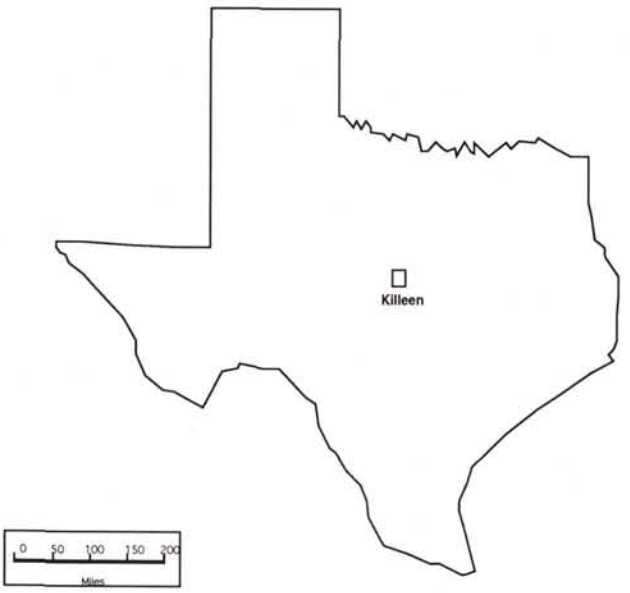

Figure 1. Site location map of Killeen, Texas.

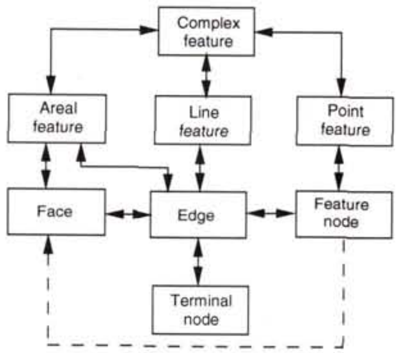

Figure 2. UMEDS ITD topological relationships (after Ward and Hawkins 1990).

The use of spatial constructs removes the need to repeat coordinates, and, thus, reduces the storage requirements of the data and eliminates "slivers and gaps" between features (Ward and Hawkins, 1990). For example, attribute data, which use a certain edge to define part of their boundary, point to the same edge record in the edge file; thus, there will not be two or more stored coordinate strings for the same line.

The UMEDS ITD have an efficient two-way topology: the interrelationships between features and spatial constructs are complete in both directions. The feature data point to their associated spatial constructs and the spatial constructs point back to their related feature attributes and to other related constructs. To increase the storage and access efficiency, an

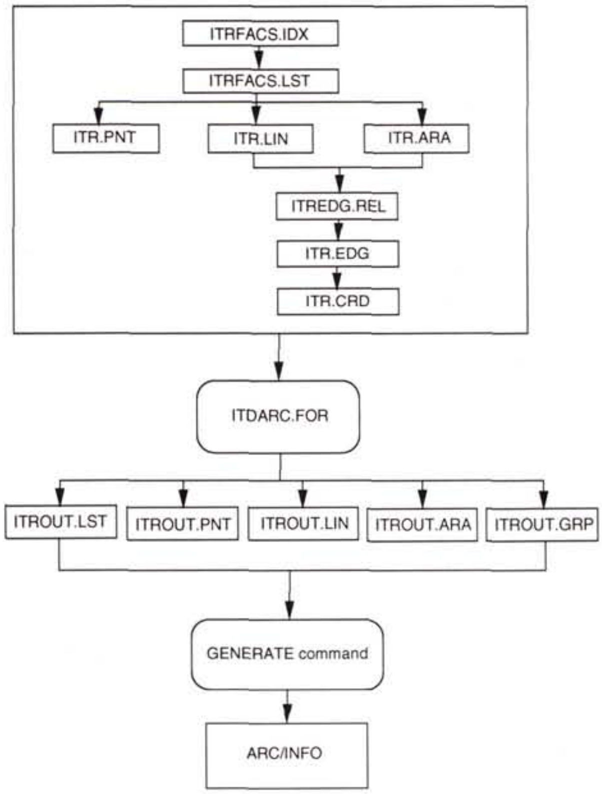

Figure 3. UMEDS ITD files accessed for conversion of ITD into a format readable by ARC/INFO.

indexing method using a pointer file and an ID list are used. The point specifies a block of records in an ID list and the ID list contains the actual feature IDs.

In this way the linear index almost completely removes the need for the computer to search for records, because the pointer allows the computer to access them directly. The UMEDS ITD were stored in standard ASCII format so that data conversion and reading were simplified and so that they could be software and hardware independent.

DTED

The elevation data associated with the TTD (and ITD) are based on the DMA Digital Terrain Elevation Data (DTED) level II. These data are in a raster format with horizontal spacing of one arc-second (nominally 30 m), and are kept separate from the TTD (and ITD) so that functions requiring only elevation information can be performed more easily.

The DTED vertical accuracy is stated as ±20 m linear error, 90 percent probability, mean sea level/National Geodetic Vertical Datum of 1929 (NGVD29), while the horizontal accuracy is ±130 m circular error, 90 percent probability, World Geodetic System of 1972 (WGS72) (Messmore and Fatale, 1989).

USGS Digital Elevation Model (DEM) Data

The National Cartographic Information Center (NCIC) of the USGS provides digital data as part of the National Mapping Program. The elevation data that are provided are in the form of Digital Elevation Models (DEMs), which are sampled arrays of elevations for ground positions at regularly spaced intervals. These arrays of data are provided in quadrangles of 71/2 minutes or 1 degree, providing the same coverage as the standard 1:24,000- and 1:250,000-scale map series quadrangles, respectively. These data are supplied on computer compatible tape (CCT) in ASCII format.

The 71/2-minute DEMs are comprised of a regularly spaced grid of elevations taken at 30-m intervals, and referenced to the Universal Transverse Mercator (UTM) coordinate system based on the North American Datum of 1927 (NAD27). These data are arranged from south to north in profiles that are ordered from west to east.

The 1-degree DEMs consist of an array of elevations taken at 3-arc-second spacings that are referenced horizontally to WGS72 geographic coordinates. The data are recorded from south to north in profiles ordered from west to east. The first and last elevation points in the profile are at the even integer degrees, corresponding to the edges of the quadrangle, resulting in 1201 profiles containing 1201 data points. These 1-degree data are produced by DMA from the 1:250,000-scale map series. The elevations are given in metres above mean sea level, referenced to NGVD29.

The horizontal accuracy of the 1-degree DEM data is dependent upon the horizontal spacing of the elevation array (for the 1-degree data, elevations are collected at 80 to 100 percent of the final point spacing). The elevations are then weighted with additional information such as drainage features, ridges, and other spot elevations. The terrain features are generalized by reduction to grid nodes, which reduces the ability to recover positions of specific terrain features that fall short of the spacing interval. This process results in a type of filtering of the surface.

Vertical accuracy of the DEM data is dependent upon the horizontal grid spacing, collection methods, digitizing systems, and the quality of the source data. Each processing step must satisfy accuracy requirements customarily applied to each system because of the compounding effect in the data compilation.

The accuracy for the 1-degree data is an absolute horizontal error of ±130 m circular error, 90 percent probability and an absolute vertical accuracy of ±30 m linear error, 90 percent probability. These are absolute accuracy standards; the relative accuracy among points inside the DEMs is often better. More detailed information on USGS DEMs can be found in U.S. Geological Survey (1987).

Approach

Methods, which are outlined in the following sections, were developed to transform the digital data sets into a common coordinate system.

ITD Conversion to ARC/INFO

The documentation supplied with the UMEDS format ITD describes each of the files that constitute an ITD theme layer (Figure 2). Included in the documentation were the file names, the ASCII format fields for each file, and directions on how the UMEDS pointer system operates to give the two-way relations between the spatial data and the attribute data.

For this study many of the supplied files could be omitted because they were used for relating spatial data back to the attributes; but, because the attributes would be needed for other applications, the spatial information was converted and attached to the attributes or FACS codes. Figure 3 shows

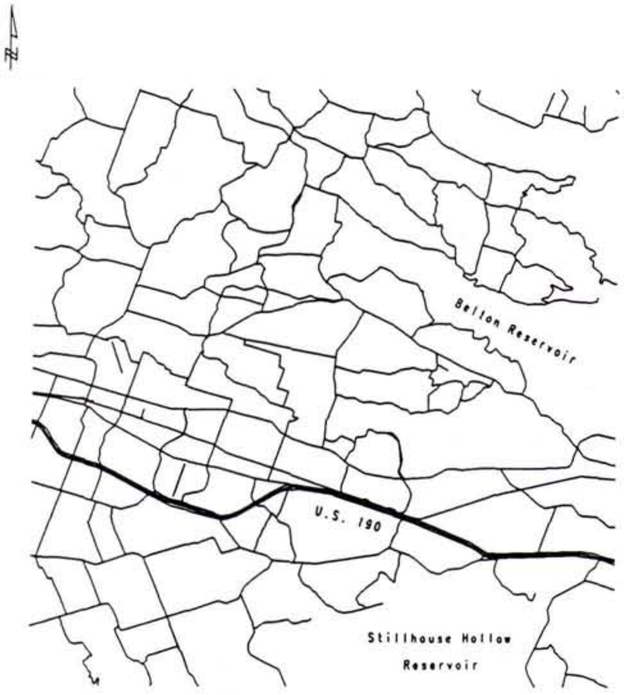

Figure 4. ITD transportation layer.

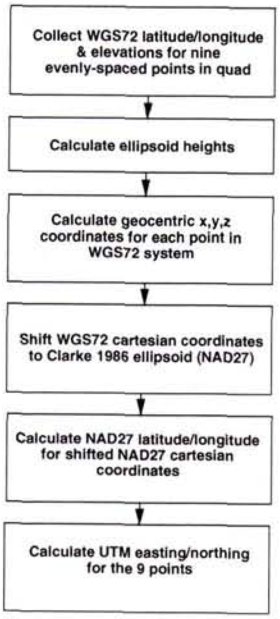

Figure 5. Steps for transforming both elevation arrays to UTM-referenced arrays.

the files that were used and the route taken to access each file (detailed computer code can be found in Adkins, 1991).

A FORTRAN computer program was coded using the documentation supplied by SAIC and follows the program flow shown in Figure 3. Data files were produced by this program that were imported into ARC/INFO using the "generate" command. These included ITROUT.LST that contains the header information about the transportation layer including the ID number for each FACS code; ITROUT.PNT that contains the IDs (or attribute number) and coordinates for point information; ITROUT.LIN that contains the IDs and coordinate strings for linear features; ITROUT.ARA that contains the IDs and coordinate strings for area features; and ITROUT.GRP that contains the IDs for areas connected to a coordinate pair located at the geographic reference point (geographic center) of an area. The topology for the data layer is then created using the "clean" and "build" routines in ARC/INFO. The resulting ITD transportation layer is shown in Figure 4.

Correction of the TTD and ITD Skew

The UMEDS ITD were created from the original TTD source maps, but in this study we found that the coordinates differed.

The original TTD (and thus the ITD) were transformed from the source datum NAD27 to the TTD datum (WGS84) by TEC. During this transformation, an offset and a small rotation and distortion were introduced into the data that resulted in the TTD not being properly registered to the WGS84 datum. Therefore, to place the TTD and ITD accurately onto the WGS84 datum, a data transformation had to be performed. The transformation process was performed with the ARC/INFO routine "transform" that uses a bilinear transformation function.

Conversion of the Elevation Data to UTM Coordinates

To assess the accuracy of the 1-arc-second DTED and the 3-arc-second USGS DEM, orthometric heights were included in the GPS survey. Both elevation arrays, the GPS survey, and the area maps are referenced vertically to NGVD29. The DEM and DTED elevation arrays are referenced horizontally to WGS72. The horizontal information on the 1:50,000-scale DMA maps and the USGS 1:24,000-scale 7½-minute quadrangles is referenced to NAD27, while the TTD and ITD are referenced horizontally to the WGS84 datum (same as NAD83). Data from the GPS survey were processed to yield both NAD27 and NAD83 values.

We decided that the two elevation arrays would have their horizontal coordinates transformed to the NAD27 datum to make correlations with the map sheets easier, since the GPS survey had coordinates for both datums.

The steps used for the transformation of both elevation arrays to UTM-referenced arrays are shown in Figure 5 and described in detail in Adkins (1991). The datum transformation was performed using a six-step process that converted the data to UTM coordinates. This process included a datum shift and transformation of Cartesian coordinates to geodetic coordinates. The total RMSE for the DEM rectification was 0.136 pixels (approximately 12 m) while the total RMSE for the DTED rectification was 0.403 pixels (also approximately 12 m).

Global Positioning System Survey

To assess the accuracy of the data layers, an independent field survey was performed at the study site in Fort Hood, Texas (Figure 6). The survey was performed using GPS in a differential surveying mode. The GPS survey used both static and pseudo-kinematic techniques to tie 19 road intersection

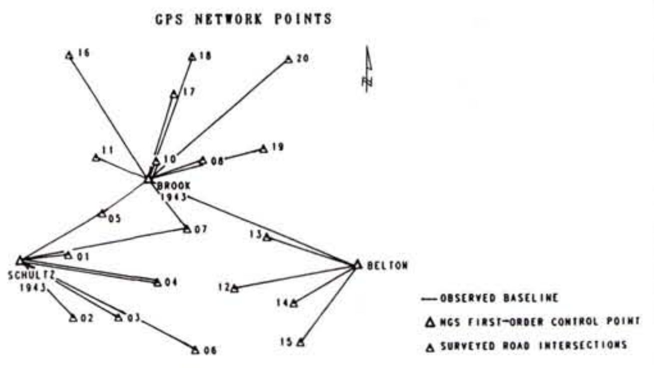

Figure 6. GPS network diagram.

stations to three first-order National Geodetic Survey horizontal control monuments (stations: Belton, Brook 1943, and Schultz 1943). The NGS NAD27 and NAD83 published latitudes, longitudes, and computed UTM zone 14 coordinates for the control stations were used. In addition, a first-order orthometric height (elevation) was used from the Belton station to determine elevations throughout the network.

A pre-survey reconnaissance was performed in which each proposed survey point was assessed for suitability of occupation by a GPS survey receiver. National High Altitude Program (NHAP) photography taken in 1981 was acquired for the study area, and the techniques described by Adkins and Lyon (1991) were used to perform the reconnaissance. This helped to expedite the survey procedure.

The 19 new stations surveyed were all road intersections, with each chosen so that the points were evenly distributed throughout the quadrangle. The road intersections were also selected because of their ease of definition and location in the TTD and ITD.

There were 25 baselines observed in the network, with eight of these lines surveyed using the pseudo-kinematic technique and 17 measured using standard static methods.

GPS Field Operations and Techniques

The field operation was conducted during December 1990. The best GPS observation window was from approximately 2230 to 0600 local time. Thus, all observations were taken at night, using a minimum of three satellites and a maximum of six. The average number of satellites observed during a session was five. For the static baselines, data were acquired for an average of 45 minutes. The pseudo-kinematic field methods were modeled after those presented by Ewing (1990). The stations at the ends of pseudo-kinematic lines were occupied for two simultaneous 10- to 12-minute sessions, which were separated by at least one hour.

All lines observed in the network were radial: one receiver was always on a first-order horizontal control station (Figure 6). While this did not provide the strongest geometric solution for the network, it removed the need for one receiver to travel between points during a session and provided accuracies sufficient for the application.

The raw GPS phase data were processed to solve for the three baseline components (Δx, Δy, and Δz) for each line. The program (TRIMBL, available from Trimble Navigation) uses a least-squares triple-difference solution for an initial value for the components, and then calculates a "best" value for the baselines using a least-squares double-difference solution with fixed integers, where appropriate.

The final value for the components of each baseline, along with their variances and correlations, was then input into the network adjustment program (TURBO-NET®). Unconstrained adjustments were run on the network on both the NAD27 and NAD83 datums, with the latitude, longitude, and ellipsoid height held fixed at station Belton.

To check the consistency of the GPS data, the baseline lengths (from the unconstrained adjustment coordinates) between the three NGS first-order horizontal control stations were compared to the baseline lengths calculated from the published coordinates. Table 1 shows that no GPS baseline differs from the published coordinate baselines by more than 2.02 parts per million (ppm).

Constrained adjustments were then run on the network on both datums, with all three control stations held fixed horizontally and the ellipsoid height at station Belton fixed vertically (to remove scale errors due to offset from the ellipsoidal surface). Final geodetic and UTM coordinates from the constrained adjustments with their associated standard deviations for all road intersection stations were calculated. UTM coordinates were computed in the adjustment to simplify the positional difference computations.

For the constrained adjustment on the NAD83 datum, the stations were coordinated with a standard deviation of <0.13 m, while the ellipsoidal height uncertainties were <0.42 m. On the NAD27 datum the horizontal errors were <0.47 m, while the ellipsoidal height errors were <1.63 m. The NAD27 discrepancies are greater due to the lower internal consistency of the NAD27 network and the subsequent "warping" of the GPS survey to fit the control.

Digitized Map Coordinates

Coordinates for the road intersections stations were digitized from both the 1:50,000- and 1:24,000-scale maps. This was done to assess the absolute horizontal and vertical accuracy of the map sheets. The maps were referenced to the NAD27 datum, so UTM coordinates derived from this datum were used to reference the maps on the digitizing table. Coordinates were digitized from each map in three trials, with a new map setup on the digitizing table performed before each trial.

The road intersection coordinates for the TTD and ITD were collected using the "Arcedit" function in ARC/INFO. The cursor was directed to each of the road intersection nodes and the displayed node coordinates were recorded. This was performed on both the skew uncorrected and corrected TTD; coordinates were captured only from the corrected data for the ITD. The TTD original coordinates were given to 0.0001 arc-second, which corresponds to approximately 3 mm on the ground. Studying the TTD original coordinates provides an idea of the internal consistency or relative accuracy of the data, before it is warped by the skew and offset correction.

The ITD coordinates were given to 0.001 arc-minute, which corresponds to approximately 1.7 m on the ground.

TABLE 1. COMPARISON OF BASELINE LENGTHS BETWEEN THE GPS NETWORK (L_{GPS}) AND THE PUBLISHED NGS FIRST-ORDER COORDINATES (L_{Pub}).

Station Pair	L_{GPS} (m)	L_{Pub} (m)	ΔL (m)	ppm
Schultz-Brook	13,778.509	13,778.482	0.027	1.96
Brook-Belton	20,329.913	20,329.872	0.041	2.02
Belton Schultz	30,349.849	30,349.806	0.043	1.42

Because the ITD contain less feature information than the TTD, not all of the road intersection stations were present in the data (five stations were omitted).

Elevation Data Value

The UTM coordinates acquired from the transformation of the elevation data were used to determine elevation values at each of the surveyed stations. The elevation values at each station were recorded from the DTED 1-arc-second and the USGS 3-arc-second elevation arrays.

Elevations for each of the survey stations were obtained from the 1:50,000- and 1:24,000-scale maps by contour interpolation or with spot elevations (when present). This was done to check their agreement with the elevation array and the "true elevation" as determined through the GPS survey.

Results and Discussion

Digitized Map Coordinate Accuracy

The map digitized UTM northings and eastings for the survey stations were differenced with the GPS survey-derived UTM coordinates to determine the accuracies associated with the map sheets. The top half of Table 2 shows the average errors in UTM northing (ΔN) and easting (ΔE) and their associated standard deviations (σ) for each of the three digitization trials. The bottom half of Table 2 shows the average error in northing and easting for all three trials, as well as the average total horizontal error (ΔD).

The 1:24,000-scale USGS quads need to comply with National Map Accuracy Standards, which state that 90 percent of well-defined test points shall be in error by no more than 1/50 of an inch (12.2 m at this scale). For three digitization trials (54 coordinate pairs, 18 points), only nine pairs (16.7 percent) meet the linear error tolerance. The average linear error is 15.2 m. Thus, National Map Accuracy Standards were not met; however, the determined accuracy would be sufficient for most GIS applications.

The accuracy requirements for the 1:50,000-scale map state that 90 percent of well-defined features shall be within 50 m of their true location, as referenced to the map projection. In this study (57 coordinate pairs, 19 points) 45 coordinate pairs (78.9 percent) from the 1:50,000-scale map meet the accuracy tolerance. Thus, the stated accuracy objectives are not met at the 90 percent confidence level.

Accuracy of TTD and ITD Transportation Layers

The errors for the ITD and TTD transportation layers in both the absolute and relative sense were analyzed with the independent GPS survey data. Table 3 shows the average absolute error for all of the survey stations in the easting (ΔE) and northing (ΔN) directions, as well as the average total horizontal distance (ΔD) between the data layer coordinates and the GPS coordinates. Also presented are the associated standard deviations, σ, for each of the error values.

The stated horizontal accuracy for the TTD and ITD is ±50 m circular error, 90 percent probability (same as the 1:50,000-scale topographic map). This accuracy allows for an error of 36 m in both directions, if ΔE and ΔN are approximately equal. From Table 3, the easting errors (ΔE) are close to this accuracy, but the northing errors (ΔN) were approximately triple the allowable error. Because the horizontal accuracy of the map from which these data were captured (the 1:50,000 scale) was very close to its accuracy tolerance, errors must have been introduced into the data either during data capture, in the datum transformations, or both. The absolute horizontal accuracies of both the TTD and ITD did not meet their design specifications, probably because of less than optimal transformation parameters used to convert the data from their source datum (NAD27) to their operational datum (WGS84). Absolute errors averaged 120.9 m for the TTD and 144.5 m for the ITD. Data capture probably added some small scale-dependent errors to the data, while the transformation process added most of the error. This is fairly obvious due to the systematic negative offset of the northings, as originally calculated.

For the relative accuracy assessment, the computed distances of selected baselines in the TTD and ITD were compared to the GPS-derived distances for the same baselines. The average relative baseline errors (ΔL) and their standard deviations for the uncorrected TTD, corrected TTD, and corrected ITD errors for all of the selected baselines are presented in Table 4. The relative accuracies for the TTD and ITD were reasonable (average relative error for the uncorrected TTD was 24.9 m, average relative error for the ITD was 32.7 m) for this type of data and showed that the internal consistency was fairly good. This gave another indication that the

TABLE 2. DIGITIZED MAP COORDINATE ERRORS. STANDARD DEVIATIONS SHOWN AS σ.

	1:24,000			1:50,000		
	Trial 1	Trial 2	Trial 3	Trial 1	Trial 2	Trial 3
ΔE (m)	13.0	10.9	11.9	24.0	21.5	22.2
$\sigma_{\Delta E}$ (m)	11.4	10.9	9.4	17.6	13.3	16.2
ΔN (m)	16.4	15.7	15.7	19.6	17.4	19.4
$\sigma_{\Delta N}$ (m)	9.7	9.3	9.3	22.0	19.9	19.9
		Average			Average	
ΔE (m)		11.9			22.6	
$\sigma_{\Delta E}$ (m)		10.4			15.5	
ΔN (m)		15.8			18.8	
$\sigma_{\Delta N}$ (m)		9.5			20.0	
ΔD (m)		15.2			27.6	
$\sigma_{\Delta D}$ (m)		10.0			17.1	

TABLE 3. TTD AND ITD AVERAGE ABSOLUTE ERRORS AND THEIR ASSOCIATED STANDARD DEVIATIONS.

Data	ΔE (m)	$\sigma_{\Delta E}$ (m)	ΔN (m)	$\sigma_{\Delta N}$ (m)	ΔD (m)	$\sigma_{\Delta D}$ (m)
TTD	39.1	31.2	109.6	38.6	120.9	36.3
ITD	17.8	10.5	143.0	23.0	144.5	22.8

TABLE 4. TTD AND ITD AVERAGE RELATIVE ERRORS (ΔL_{ave}), as Determined by Comparison to Selected Baselines.

Data Source	ΔL_{ave} (m)	σ (m)
TTD (uncorrected)	24.9	18.9
TTD (corrected)	41.8	22.2
ITD (corrected)	32.7	22.0

TABLE 5. AVERAGE ELEVATION DIFFERENCES FOR THE DTED, DEM, AND SCALED MAP ELEVATIONS.

Data Source	ΔH_{ave} (m)	σ (m)	ΔH_{max} (m)
DTED	1.5	1.2	3.8
USGS DEM	6.9	6.1	23.3
1:24,000 map	1.5	1.4	5.4
1:50,000 map	1.7	1.0	4.0

TABLE 6. ORTHOMETRIC HEIGHTS (H) AND THEIR ERRORS (ΔH) FROM THE GPS SURVEY, DTED (1") AND USGS DEM (3") ELEVATION ARRAYS, AND THE 1:24,000 (24) AND 1:50,000 (50) SCALE MAPS.

Station	H_{GPS} (m)	H - 1" (m)	H - 3" (m)	ΔH - 1" (m)	ΔH - 3" (m)	H - 24 (m)	H - 50 (m)	ΔH - 24 (m)	ΔH - 50 (m)
1	278.4	275	278	−3.4	−0.4	276	276	−2.4	−2.4
2	274.5	274	261	−0.5	−13.5	275	272	+0.5	−2.5
3	251.1	251	257	−0.1	+5.9	252	251	+0.9	−0.1
4	236.8	238	237	+1.2	+0.2	238	237	+1.2	+0.2
5	245.7	248	257	+2.3	+11.3	**	248	**	+2.3
6	219.2	*	*	*	*	219	219	−0.2	−0.2
7	234.2	238	233	+3.8	−1.2	237	235	+2.8	+0.8
8	248.6	251	251	+2.4	+2.4	254	251	+5.4	+2.4
10	267.6	265	275	−2.6	+7.4	268	269	+0.4	+1.4
11	272.0	271	282	−1.0	+10.0	273	274	+1.0	+2.0
12	235.1	236	243	+0.9	+7.9	235	237	−0.1	+1.9
13	202.7	201	213	−1.7	+10.3	201	200	−1.7	−2.7
14	215.2	216	213	+0.8	−2.2	215	215	−0.2	−0.2
15	195.0	196	182	+1.0	−13.0	194	191	−1.0	−4.0
16	254.7	255	278	+0.3	+23.3	253	256	−1.7	+1.3
17	210.0	209	219	−1.0	+9.0	210	208	0.0	−2.0
18	223.3	224	227	+0.7	+3.7	225	222	+1.7	−1.3
19	245.1	245	243	−0.1	−2.1	248	247	+2.9	+1.9
20	212.2	209	213	−3.2	+0.8	209	210	−3.2	−2.2

* Station 6 not in elevations arrays, ** Station 5 not on 1:24,000 scale map.

datum transformations were less than optimal. Considering that for the optimistic case of a single variable difference, the standard deviation for the difference σ is given by

$$\sigma_{x2-x1} = \sqrt{2}\sigma_x$$

For the 1:50,000-scale maps, σ_x would be 50 m, and the error in a coordinate difference would be 70.7 m. None of the baseline errors are greater than 70.7 m in the uncorrected TTD and the ITD, while for the corrected TTD only two baselines exceeded this optimistic tolerance. The skew and rotation correction obviously reduces the internal consistency of the TTD, as is evident in the increase in the average error for the corrected TTD (Table 4).

Accuracy of the Elevation Data and Map Sheets

The DTED and USGS DEM elevation accuracies were assessed by comparing the elevation array values at the survey stations to elevations calculated from the independent GPS survey. The accuracies of elevations scaled from 1:50,000- and 1:24,000-scale map sheets were also studied. Table 5 presents the average elevation error (ΔH_{ave}) for each of these elevation sources, along with the associated standard deviations and maximum elevation difference (ΔH_{max}). The elevations at each station from all of the tested sources along with the associated errors can be found in Table 6.

The DTED vertical error is stated as ±20 m linear error at a 90 percent probability, while the USGS DEM vertical error is ±30 m linear error at 90 percent probability. All of the elevation array sample points for both the DTED and DEM fall within the accuracy tolerances as stated above (Table 6). These digital elevation data sources are of high quality and easily meet their accuracy standards.

The vertical accuracy of the DTED and DEM data was high, with all points falling within the specified tolerances (±20 m at 90 percent confidence for the DTED and ±30 m at 90 percent confidence for the DEM). The average error for the DTED was 1.5 m, while for the DEM it was 6.9 m.

The minimum vertical accuracy standard for the 1:50,000-scale map is ±1 contour interval (10 m) at a 90 percent probability. For the 1:24,000-scale maps, it is also ±1 contour interval, where a contour interval is 20 ft (6.1 m). Again, all points checked fall within their accuracy allowances (Table 6). Thus, both the 1:50,000- and 1:24,000-scale maps meet their accuracy standards.

The vertical and horizontal accuracy of the 1:50,000- and 1:24,000-scale maps was also evaluated. The 1:50,000-scale map had an average vertical error of 1.7 m (tolerance value is 10 m), while the average error for the 1:24,000-scale map was 1.5 m (tolerance value is 6.1 m). No test elevations exceeded the stated tolerances; thus, both maps met their stated vertical accuracy requirements.

The 1:24,000-scale horizontal accuracies need to comply with National Map Accuracy Standards; only 16.7 percent of the test points were within the absolute accuracy tolerance of 12.2 m. The average horizontal linear error was determined to be 15.2 m. The 1:50,000-scale map also did not meet its 50 m circular error at 90 percent confidence; only 78.9 percent of the test points were within the tolerance. The average horizontal linear error for the 1:50,000-scale map was 27.6 m.

In summary, the elevation arrays and scaled map elevations were well within their accuracy standards, with no test points falling outside of the stated tolerances. The absolute horizontal accuracy of the 1:50,000- and 1:24,000-scale maps did not meet their stated horizontal standards. The relative errors of the TTD were reasonable for this type of data, while the absolute horizontal accuracy of these data did not meet their stated requirements. This was most likely due to errors in the transformation process as the data were converted from the map source datum (NAD27) to the operational datum, WGS84.

Conclusions

The work presented in this study can be used as an aid in understanding the errors associated with standard digital cartographic data sets. An idea of the errors associated with data input into a GIS is required so that the limits of a GIS and its products can be determined. In this way GIS data can be used for military and engineering analyses in a precise, meaningful and accurate manner.

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