Positional Accuracy in a Natural Resource Database: Comparison of a Single-Photo Resection Versus Affine Registration.

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Forestry

(ABSTRACT)

Positional and area accuracies were calculated for digitized data taken from 1:20,000 scale aerial photographs and United States Geological Survey (USGS) 1:24,000 scale topographic maps. Positional accuracy was determined as the Euclidian distance between the digitized coordinate and the reference ground coordinate collected with global positioning systems (GPS). Area accuracy was the acreage difference between the digitized area and GPS calculated area. Three methods were employed to collect the digitized data: manual digitizing from topographic maps and aerial photographs followed by an affine transformation, and manual digitizing from aerial photographs while applying a single-photo space resection. Two study sites, one in low terrain relief and one in high terrain relief, were used to examine the effects of terrain on positional accuracies.

The single-photo space resection technique provided the most accurate positional data on both study sites. The single-photo space resection produced mean positional accuracies of 5.0 to 6.0 meters. In comparison, the uncorrected digitized photo data produced mean positional accuracies of 7.0 to 26.0 meters. The effects of terrain displacement were evident in these data sets, as the mean positional accuracy at the low-relief study site was 18.96 meters less than the corresponding accuracy at the high-relief study site. The uncorrected digitized photo data set from the high-relief study site provided the highest mean positional accuracy, 25.86 meters. The topographic map digitized data from both study sites provided mean positional accuracies below 12.0 meters, but failed to meet National Map Accuracy Standards (NMAS) for 1:20,000 scale or smaller maps.

The average area accuracy from both study sites proved to be not significantly different, regardless of the digitizing technique or terrain conditions. The average area accuracy between the two study sites differed by at most 0.05 hectares. Average percent area errors ranged from 9.96% to 11.74% on the low-relief study site and from 11.84% to 12.65% on the high-relief study site.

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INTRODUCTION

Geographic information systems (GIS) have become an integral part of many natural resource management organizations. The increased interest in GIS is spurred by improved access to data, greater speed in analytical functions, timely output, and the ability to combine data from many different sources. With this increasing interest in digital spatial data, many natural resource organizations are becoming involved in improving and maintaining the quality of their spatial databases.

Development of spatial data layers for a natural resource GIS often involves a combination of survey, map, photographic, and satellite data. Map and photographic data are generally input in the computer via digitizing or scanning, and often are the source for most spatial data layers in a natural resource GIS. While many maps used by natural resource organizations for data development and update carry a stated accuracy level, aerial photography does not. Aerial photography contains inaccuracies, resulting from tilt and terrain effects, that need to be understood and considered when determining the accuracy of spatial data taken from this source.

The purpose of this research was to compare and evaluate the spatial accuracy of digital data developed using common, inexpensive digitizing techniques available to natural resource management organizations.

The objectives of this study were:

1) To compare the positional and area accuracies when using the affine transformation on map and photo-derived data to accuracies obtained with single-photo space resection results.

2) To analyze the effect that different source media, specifically 1:24,000 scale USGS topographic maps and NAPP aerial photography, have on the accuracy of spatial data collected from these types of sources.

3) To analyze the effect that geometric errors of tilt and terrain displacement have on the accuracy of spatial data collected from aerial photography with varying terrain.

4) To compare GPS generated area accuracies when perimeter data are collected either by continuously walking the area boundary or by collecting data only at corner & intermediate points along the area boundary.

LITERATURE REVIEW

POSITIONAL ACCURACY IN A NATURAL RESOURCE GIS

A natural resource GIS spatial database usually includes a number of individual data layers, with each layer representing a different theme (Burrough, 1986). These layers are used either singly or in combination for spatial analysis. The increased use of GIS by natural resource organizations to support a variety of management tasks has raised concerns about the quality of these spatial databases. The development and upkeep of these spatial data layers has become an important activity for many natural resource management organizations (Bolstad, 1992).

Positional accuracy in a GIS refers to the closeness of an observation (feature position) to the "true" ground or reference value (or one accepted as being true) (Chrisman,1981). Bolstad & Smith (1992), Chrisman (1991), and Blakemore (1984) define positional accuracy as a measure, usually in ground distance, of how well the digital object coordinates in the various spatial data layers correspond to the "true" coordinates of an entity on the ground. Goodchild & Gopal (1989) state that users of GIS should have a greater sensitivity to error in these databases, a greater awareness of the different kinds of errors which can occur, and knowledge of techniques for recognizing and reducing their impact. The level of positional accuracy in a digital spatial database may be considered to be due to two main sources of error, source error and operational error (Walsh *et al*, 1987).

Source error is the error present in the source media. Its influence on the positional accuracy of spatial databases is a function of the source media's scale, resolution, or format. The accuracy of a given media source is controlled by the method with which it was developed. The most common form of accuracy standard is the NMAS, used by the USGS. These standards state that for small scale maps (> 1:20,000 scale) 90% of all well-defined points must be within 1/50 of an inch of their known ground location (Thompson, 1971). The NMAS is the worst case scenario, well-defined points taken from these maps can be better than the standards set forth by the USGS. For example, 90% of the well-defined points on a 1:24,000 scale USGS topographic map must be plotted at a scaled distance which is +/- 12.19 m of their true ground location. However, many points will be better than this level, but a minimum of 90% of them must be equal to or below this level.

Operational errors are a result of manipulation of the database by various GIS analytical functions. Operational errors can be introduced to a digital spatial database during data entry, data manipulation, data extraction, and data comparison (Vitek *et al*, 1984). Data entry, specifically manual digitizing, is the major source of error for spatial databases (Chrisman, 1982).

DIGITIZATION FROM LARGE-SCALE MAPS

Manual digitization is the most common method of GIS coordinate data capture in natural resource organizations (Bolstad *et al*. 1990, Keefer *et al*. 1988). USGS 1:24,000 scale quadrangle maps are a common source of digital data in natural resource management organizations due to their low cost and wide availability. Generally, the data are captured from the quadrangle map via a digitizing tablet and tied to a base map by a well-defined set of ground control points, usually via a 2-dimensional transformation (Burrough, 1986). An affine, or first order, transformation is often used to transform digitized data from digitizer units (cm or in) into projection or real-world units. This transformation allows for translation, rotation, and scale changes during the coordinate conversion (Maling, 1991). The two-dimensional affine transformation requires a minimum of three known ground control points to transform each digitized coordinate pair (x,y) into a Cartesian coordinate pair (X,Y). If more then three control points are available, a least squares fit of an affine transformation will provide residual estimates.

Positional errors resultant from manual digitization are generally a function of source media error, transformation error, equipment limitations, and user error (Walsh *et al*, 1987). User or digitizing error can be broken down into two types: line following or pointing error and line generalization (Keefer *et al*, 1988). Line following error is resultant from the operator's inability to trace the linear or point feature with the digitizing puck. Line generalization refers to the number and location of points sampled with the digitizing puck along a linear feature. Warner and Carson (1991) identified digitizer operator (user) error to be 0.036 mm and 0.034 mm for the x and y directions respectively. This would correspond to ground deviations of 0.86 m in the x-direction and 0.81 m in the y-direction using a 1:24,000 scale map. In addition, Warner and Carson (1991) state that one can expect the standard deviation of recordings at well-defined points to be better than 0.03 mm. In another study, manual digitizing precision of 0.064 mm, twice the observed equipment error, was observed for well-defined points (Bolstad *et al*, 1990). Similarly, Chen and Finn (1994) observed digitized point location errors of 0.050 mm with a standard deviation of 0.076 mm. This translates to 1.25 m and 1.90 m of ground distance respectively on a 1:25,000 scale map.

Digitized linear and areal feature errors may be observed in different ways. Linear features are often depicted on maps with line widths of 0.25 - 1.01 mm (Bolstad & Smith, 1992). This would correspond to a ground distance of between 6 to 24 meters on a 1:24,000 scale map. Vonderhoe and Chrisman (1985) found deviations of up to 6.70 meters for points taken from USGS digital line graph data. Another study observed line locations to be within 0.127 mm on a 1:24,000 scale map, equivalent to 3.04 meters of ground distance (Dunn *et al*, 1990). In addition, they observed 3.0% to 10.0% area boundary uncertainty for areas of 10 - 30 ha in size. Chen and Finn (1994) state that the average digitized area error is low, with it generally underestimating polygon area. They report an overall average error of -10.16 mm on the map for digitized polygon perimeter readings and -5.08 mm^2 for digitized polygon area readings. Prisley (1989) observed mean polygon area error of 8.0% of the true polygon area under moderate assumptions of variability and correlation. Otawa (1987) reported digitized polygon accuracy of +/- 7.0% from the mean area of fourteen trails. Chrisman and Yandell (1988) calculated area errors for USGS digital line graph data of the Public Land Survey System to be less then 1.0% of the area estimate.

In addition to the positional errors introduced during the actual digitizing process, positional accuracy is also affected by control point or coordinate registration. Positional inaccuracies of this type may result from a number of steps: identification of the control points in geographic or digitizer space, obtaining the coordinates of the control points in both coordinate systems, and application of the transformation functions to the digitized data (Bolstad & Smith, 1992). The effects of these types of errors on the positional accuracy of the digitized data is documented. Fernandez *et al.* (1991) documented map derived control errors ranging from 2.13 to 7.62 meters on the ground and points influenced by map exaggeration had deviations of 4.87 to 7.62 meters on the ground. In addition, Bolstad *et al.* (1990) observed map derived control errors ranging from 1.52 to 85.04 meters on the ground.

AERIAL PHOTOGRAPHY/SINGLE-PHOTO SPACE RESECTION

Aerial photographs have long been an important source of spatial data in many natural resource organizations. Their popularity is in part due to their low cost relative to the detail they provide, the control one has over the source, the frequency which with they may be generated, and their ability to show recent landscape change. Photo-based GIS data layers can be produced by several methods, i.e., by redrafting of data onto copies of base maps and digitized, by direct digitization, stereo interpretation, or through analytical photogrammetric techniques (Bolstad, 1992). Whatever the technique used, photographs are not planimetric, and contain geometric errors due to tilt and terrain displacement (Paine, 1981). Map properties do not hold true for photographs and error may introduced into the database if this is assumed. These errors may be quite large if those photos are registered using an affine or other first order transformation, as is commonly done. One study reported average positional errors resultant from not correcting for these geometric errors of 3.96 to 15.84 meters of ground distance over flat terrain and 38.10 to 73.15 meters of ground distance over steep terrain (Bolstad, 1992). Another study reported acreage errors of up to

10.23% for data collected directly from aerial photographs (Wiles, 1988).

In times past, correction of these tilt and terrain caused errors have been technically feasible but monetarily impractical for most natural resource organizations (Warner, 1988). Analytical photogrammetric methods may reduce tilt and terrain errors, but in most cases were considered too costly. These high costs have resulted in many natural resource organizations using less accurate data or collection methods to develop and update their digital spatial databases. However, with digital imagery now easily stored, accessed, and processed in computer environments, many photogrammetric tasks once reserved for highly trained operators and expensive specialized equipment have become available to natural resource personnel. These technological advances have lead to computer-based photogrammetry, which provides a low cost method to remove much of the geometric error in photo-derived spatial data (Warner, 1990).

One promising technique is the use of a single-photo space resection. Relative to direct digitization, this technique only imposes the additional requirement of elevation data for the region of interest. The accuracies of spatial data obtained from single-photo resection results are comparable to those with traditional stereomodel procedures (Carson & Reutebuch, 1994). One study reports data collected using a PC-based analytical stereo-plotter as having mean ground errors of 0.29 m and 0.19 m for 1:12,000 and 1:8,000 scale photographs, respectively (Warner, 1989). Another study, reported measured ground coordinates using a PC-base analytical stereo-plotter to be within 0.50 m from 1:15,000 scale aerial photographs (Carson, 1985). Ran (1992) reports estimated positional ground errors from single-photo space resections of two different mountainous study areas to be 11.39 m and 7.07 m respectively.

Single-photo space resection is accomplished by measuring photo-coordinates, via a digitizing tablet, and applying the collinearity equations to these data to calculate ground coordinates. Collinearity is based on the condition that the exposure station of any photograph, an object point, and its photo image all lie in a straight line (Wolf, 1983). Space resection by collinearity is based on this principle and involves formulating the collinearity equations for four or more control points. These control points must have known X,Y,Z ground coordinates and must appear in the tilted photograph. The linearized forms of the collinearity equations used in a single-photo space resection are (Wolf, 1983):

$$v_{xa} = b_{11}d\omega+b_{12}d\phi+b_{13}d\kappa-b_{14}dX_L-b_{15}dY_L-b_{16}dZ_L+J$$

$$v_{ya} = b_{21}d\omega+b_{22}d\phi+b_{23}d\kappa-b_{24}dX_L-b_{25}dY_L-b_{26}dZ_L+K$$

where:

v_{xa} & v_{ya} - corrections to measured photo coordinates x_a & y_a

b_{1i} & b_{2i} - coefficients equal to the partial derivatives used to linearize the equations

$d\omega$, $d\phi$, $d\kappa$ - corrections applied to ω, ϕ, and κ

dX_L, dY_L, dZ_L - corrections applied to X_L, Y_L, and Z_L

ω, ϕ, κ - three rotation angles omega, phi, and kappa

X_L, Y_L, Z_L - coordinates of the camera perspective center

J and K - residual errors in x and y

In performing the single-photo space resection, an x-equation and a y-equation is developed for each control point. These equations are solved for the six unknown elements of the photo exterior orientation and their corrections are determined. The corrections that are produced from the first solution are used to adjust the initial approximations for the six unknowns. After the first solution, the corrections are added to the initial approximations and new approximations are determined. This process is repeated until the magnitudes of the corrections become insignificant (Wolf, 1983).

The Z or elevation values used to perform a single-photo space resection are generally supplied via a digital elevation model (DEM). Alternatively, in areas of low to moderate terrain (less than 150 m elevational difference), a DEM can be interpolated from the control point elevation values. The quality of the DEM used to supply the elevation values affects the amount of planimetric error introduced to the data collected (Warner *et al.*, 1993). Carson and Reutebuch (1994) state that for any given elevational error and focal length, the planimetric error will increase in proportion to the radial distance from the center of the photo to the image point, regardless of photo scale. They observed average positional errors of 0.027 mm, 0.028 mm , and 0.026 mm from photographs with focal lengths of 153 mm, 208 mm, and 304 mm respectively. In addition, Ran (1992) found the random ground error caused by control points was within 4.0 m and the random ground error caused by DEM data was within 2.0 m for data collected from aerial photography in mountainous terrain.

GLOBAL POSITIONING SYSTEMS IN NATURAL RESOURCES

The positional accuracy of geographic coordinates used as control points or as features in a spatial database may be improved through the use of a GPS. GPS is a satellite-based positioning system, developed by the Department of Defense (DOD), which provides suitably equipped users with highly accurate position, velocity, and time data. The low cost, both economically and practically, make these systems a viable option for use in natural resources management settings. A GPS system can be set up for less than $5,000 and require only a few days of training.

The GPS system consists of three major segments: space, control, and user. The space segment consist of 24 NAVSTAR satellites in semi-synchronous orbits around the earth. The satellites circle the earth at 12,600 nautical miles and complete an orbit in approximately twelve hours. All NAVSTAR satellites are equipped with several high-precision atomic clocks and constantly transmit radio signals unique to each satellite's identifying code. Each satellite transmits two L-band radio signals, L1 at 1575.42 MHz and L2 at 1227.60 MHz. The L1 signal is modulated by the Precision or P-code and the Course/Acquisition Code (C/A code). It is this C/A code that is most often for civilian use. P-code signals are reserved for military use or when highly accurate survey data are needed. The theoretical precision of pseudo-range collected data is 30.0 cm for P-code and 3.0 m for C/A code (Liu, 1993). The control segment consists of one master control station, four ground-based monitoring stations, and three upload stations. The control segment as a whole is responsible for tracking, monitoring, updating, and managing the satellite constellation network. The user segment consist of various military and civilian navigation receivers designed to receive, decode, and process the radio signals emitted by the satellites. When fully developed, GPS will provide all-weather, worldwide, 24-hour positional data.

The GPS system determines positional data by reading the pseudo-random radio signal emitted from the satellites and determining the distance to each satellite. Knowing the distance to each satellite, the receiver can calculate the ground position at that point. When four or more satellite signals are received at the same time, the receiver can generate a 3-dimensional x,y,z ground position.

GPS positional accuracy is affected by many different sources. Satellite or receiver clock errors, ephemeris data errors, atmospheric interference, and selective availability

(SA) all degrade the accuracy of the GPS data. Selective availability, implemented by the DOD, degrades the C/A code emitted by the satellites by introducing errors into the navigational and clock systems of the satellite. Selective availability, when activated, may cause ground-based receivers to miscalculate their position by up to several hundred meters. In addition, GPS use in natural resource management must consider positional errors resultant from multipath effects resulting from vegetation or terrain. One study researched the effects of lodgepole pine (Pinus contorta) on the positional accuracy of data collected with GPS. Gerlach (1989) observed that loss of the satellite radio signal was caused 36.0% of the time by tree foliage and 28.0% of the time by branches. Deckert (1994) studied the effects of different eastern forest canopies on the quality of positional accuracy obtained with GPS. He observed mean positional ground accuracies for 300 position fixes of 3.76 m, 5.20 m, and 2.36 m for deciduous sites, coniferous sites, and open sites respectively. Table 1. shows the expected positional accuracies under normal autonomous conditions (Bolstad, 1993).

Table 1: Predicted GPS Accuracy under normal autonomous conditions (meters).

Source of Error	Expected Accuracy (meters)
Satellite Clock Receiver Clock	0.5 - 1.0 1.0 - 1.5
Ephemeris	0.5 - 1.0
Atmosphere	3.0 - 4.0
Selective Availability	5.0 - 100
Accuracy Totals	5.0 -- >100

The accuracy total from Table 1 is the result of differential correction of the data. Differential correction involves the use of two GPS receivers, one over a known location (base station) and another receiver (rover) over unknown locations. The two receivers collect data simultaneously from the same constellation of satellites, thus receiving the same level of errors. Since both receivers collect the same level of data, the base station positions can be compared to the rover positions and the effects of satellite system error, atmospheric interference, and SA are reduced. Evans (1992) studied the navigation ability of GPS to locate forest plot centers and reported average positional accuracy of 2.01 m between GPS position and plot center position. Applying differential correction to the mean of 100 to 300 position fixes resulted in ground accuracies of 2.0 to 3.0 m (August *et al.*, 1994). Liu (1993) reported positional ground accuracies of 4.0 to 4.5 m for 371 position fixes. In addition, Deckert (1994) obtained positional ground accuracies in the 2.0 to 4.0 m range using the same set of protocols.

MATERIALS AND METHODS

This study was designed to compare point positions and areas resultant from various digitizing techniques against "true" ground or reference position values. Different source media and digitizing techniques were used to collect the digitized data, while the reference position was determined chiefly with GPS techniques. While GPS cannot determine exact ground position, it is the best technology available to natural resource organizations, short of precise surveying techniques. The study focused on different physiographic regions in Virginia and Maryland to determined the impact terrain may have on different sources of spatial data, particularly aerial photography.

DATA SOURCES AND STUDY AREA

The data collected for this project came from two different physiographic regions: a low-relief area and a high-relief or mountainous area. The low-relief study site was located in Indian Head, Maryland and includes the Indian Head Naval Surface Warfare Center. It ranged from 77° 07' 30" to 77° 15' of longitude and 38° 30' to 38° 37' 30" of latitude. Vertical terrain varied approximately 45.0 m across this

54 km^2 study area. The low-relief study site was located primarily in an urban residential setting, and was characterized by generally flat to slightly rolling terrain. The high-relief or mountain study site was located in and around Blacksburg, Virginia and had terrain relief of approximately 365.0 m across the 84 km^2 study area. This study site ranged in longitude from 80^0 22' 30" to 80^0 37' 30" and from 37^0 07' 30" to 37^0 22' 30" in latitude. The high-relief study sites were located primarily in deciduous, uneven-aged forests characterized by steep terrain.

Data sources for this study were USGS 1:24,000 scale topographic quadrangle maps, 1:20,000 scale National Aerial Photography Program (NAPP) color-infrared aerial photographs, camera calibration reports for the NAPP photographs, USGS 7.5 minute DEMs, 1:100,000 scale Digital Line Graph (DLG) roads data, analytical photogrammetric survey data of the Indian Head Naval Base, and GPS data collected using a Trimble GeoExplorer portable GPS receiver. The high-relief study site fell within four USGS 7.5 minute topographic quadrangle maps: Blacksburg, Radford North, Newport, and Eggleston. The low-relief study site was covered entirely by the Indian Head, MD-VA 7.5 minute quadrangle map. One 18" X 18" NAPP photograph, taken in April 1988, covered the entire study area for the low-relief site. Similarly, the high-relief study site was covered by one 18" X 18" NAPP photograph taken in March 1991.

DATA COLLECTION

The digital data for this project were collected by either digitizing or gathering GPS readings of selected point and area features. Five data collection methods were used to collect data for each individual test feature. First, C/A code GPS techniques were used to determine the reference ground position. For the low-relief study site, the reference ground position was also determined from the analytical photogrammetric survey. The photogrammetric survey was supplied by the United States Navy and had a reported accuracy of +/- 15.0 cm. Second, the test features were digitized from three sources/set of protocols. These methods were: 1)manual digitizing directly from the topographic quad followed by an affine transformation; 2)manual digitizing directly from the NAPP photographs followed by an affine transformation; and 3)manual digitizing from the NAPP photographs using a single-photo space resection. Lastly, 1:100,000 scale DLG roads data were queried and the resultant feature coordinate values obtained.

POINT FEATURE DATA COLLECTION:

The first step in the point data collection process was to select point features that were easily identifiable in the field and on both the topographic quads and the NAPP photographs. The test points were road intersections, with the exception being remote points only identifiable on the NAPP photographs. The high-relief study site was the only study area that had any remote points. These remote points were point features in steep terrain that were not identifiable on the topo maps (e.g. logging decks, old forest roads, power line crossings). Where possible, the test point was located in the approximate center of the road intersection, although some were near road edges due to heavy traffic. Each road intersection was marked with a small painted X to represent the location of the test point. In the case of the high-relief study site, remote test point locations were marked by driving a colored metal spike into the ground at the test point location. In addition, distance measurements and compass bearings were taken from the test point locations to various reference features (street signs, trees, etc.), ensuring relocation of the test point. The test points were distributed as evenly as possible across the study sites so as to have a representative sample of test points near the photo edges, where the effect of tilt displacement is greatest. The high-relief study area covered the entire NAPP photograph, while the low-relief study area covered the bottom 2/3 of the NAPP photograph. A total of eighty-nine test points were identified on the high-relief study site (Figure 1). Seventy-one test points were identifiable on the topographic quads, forty-three test points were identifiable in the DLG data, and all eighty-nine test points were identifiable on the NAPP photographs. A total of ninety-six test points, covering both the topographic quad and NAPP photograph, were identified on the low-relief study site (Figure 2). Seventy of these test points were identified in the DLG data for the low-relief study site.

Once a test point was identified, the next step taken was to determine the reference ground position for that point. As previously mentioned the "true" ground or reference position was determined using C/A code GPS data. A minimum of three hundred position fixes were collected at each test point location. These position fixes were then differentially corrected to a base-station in close vicinity. The high-relief study site used a base-station less than 15.0 km distant, while the low-relief study site used a base-station approximately 160.0 km distant. The base-station used for the high-relief study site was a Trimble Community Base-

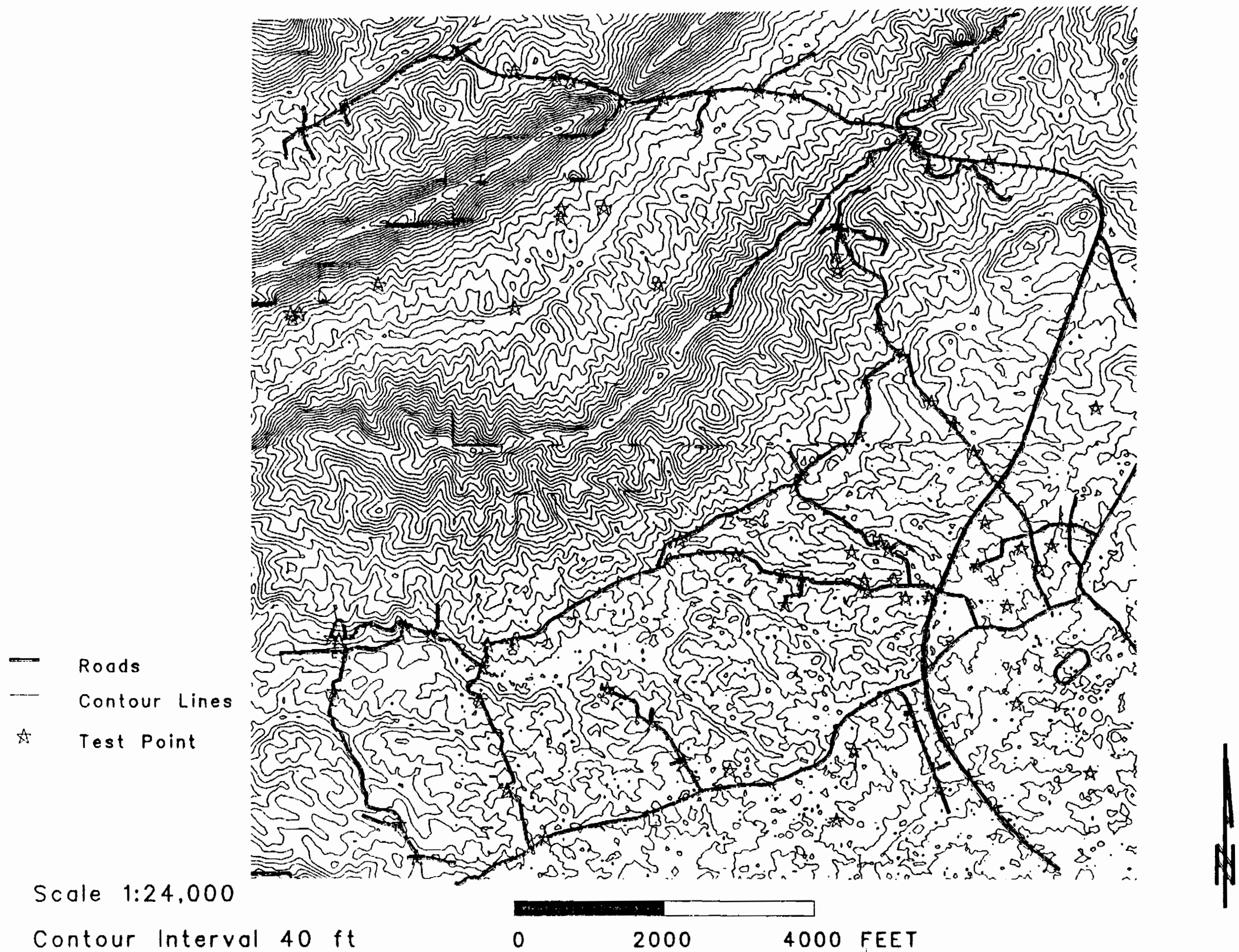

Figure 1: Test Point Distribution on the High-Relief Study Site

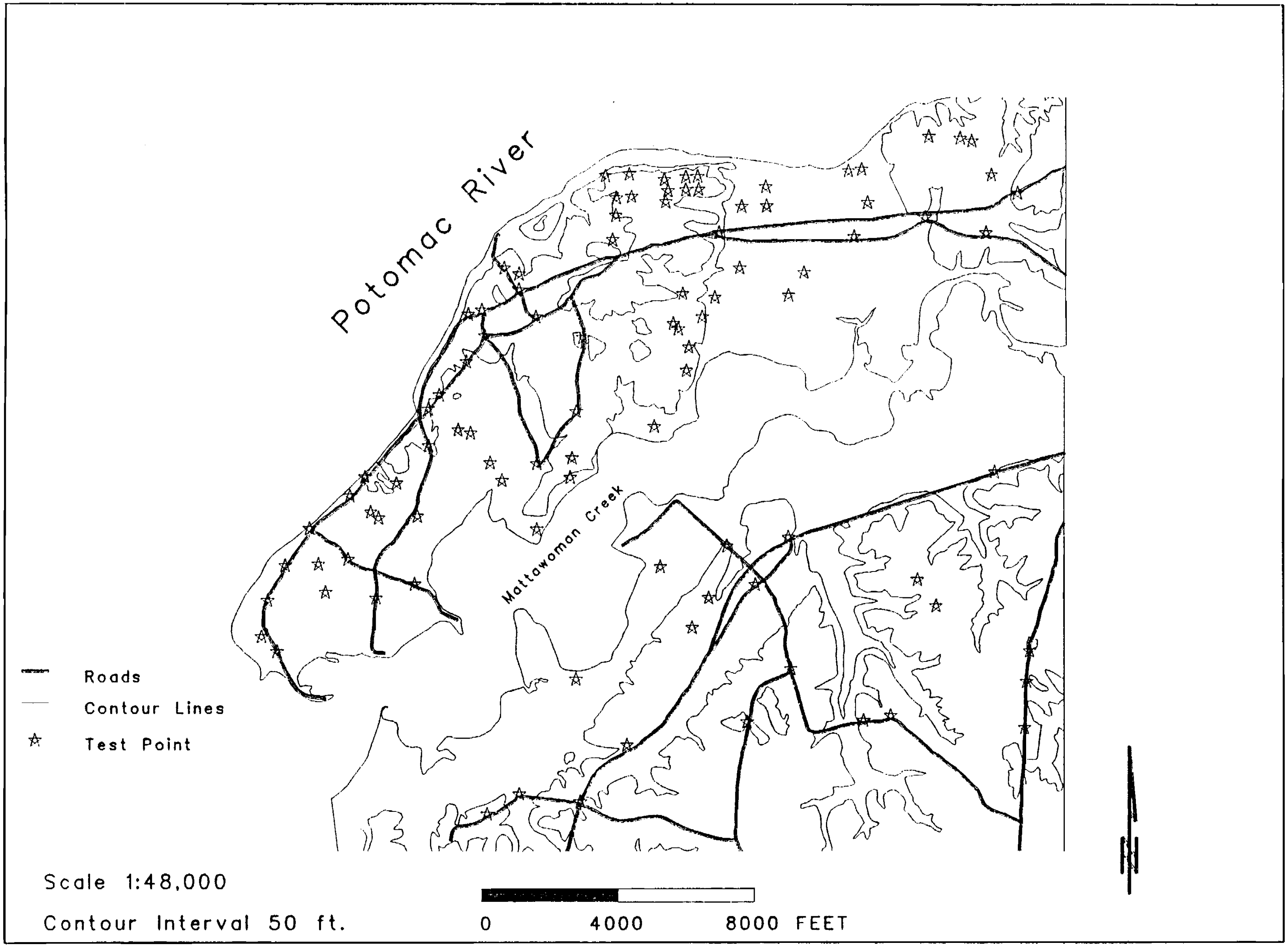

Figure 2: Test Point Distribution on the Low-Relief Study Site

Station (CBS) located atop the College of Forestry and Wildlife Resources building in Blacksburg, Virginia. The base station used for the low-relief study site was a Trimble CBS located atop the U.S. Forest Service office in Harrisonburg, Virginia. Both base-station receivers were 12-channel receivers, set with an elevation mask of 15 degrees above the planar horizon. The base-station and field receiver parameters were identically set to ensure the same constellation of satellites were being tracked by both receivers. The two receivers were set with a positional dilution of precision (PDOP) mask of eight and a minimum signal strength of six. Data were collected in manual 3-D mode at a logging rate of one position fix recorded every second. All positional data were initially collected based on the World Geodetic System of 1984 (WGS-84), and later exported in the appropriate Cartesian coordinate system. The elevational data were collected as the height above the ellipsoid (HAE). Upon differential correction, the position fixes were averaged to determine the mean reference ground position for that test point.

The high-relief study site positional data were exported to the Universal Transverse Mercator (UTM - zone 17), NAD27 grid system. The low-relief study site positional data were exported to the Maryland State Plane Coordinate System

(NAD83 - zone 1900). All GPS data were processed with Trimble's Geo-PC post-processing software (ver 1.0).

The low-relief study site also had reference positions determined by querying the photogrammetric survey data in PC Arc/Info. The photogrammetric survey was initially delivered in an AutoCAD format and converted to PC Arc/Info coverages based on the layers contained in the AutoCAD file. The Arc/Info WHERE command was used to query the roads database and determine the x,y coordinate pair of the road intersections which represented test points.

Once the reference positional data were collected, each test point was manually digitized using three different protocols or techniques. Each manually digitizing technique was repeated five times, resulting in a total of five digitized data sets representing each technique. The source media were removed and then replaced on the digitizing tablet between each of the five digitizing trials. This procedure was done to provide a measure of the amount and variation in registration error introduced during the digitizing process.

First, each test point was digitized from the topographic quad using a Calcomp 9100 digitizer with a stated accuracy of +/- 0.010 inches and a coordinate resolution of 1000 counts per inch. The digitized topographic data were initially collected in digitizer table inches, and an affine transformation was applied to convert the data to a corresponding Cartesian coordinate system. The eight plotted tic marks located on the quadrangle maps were used for coordinate registration and transformation. The digitized data collected from each of the four high-relief study site quadrangle maps were appended after transformation so as to represent the study area as one contiguous unit.

Second, each test point was again manually digitized using a Calcomp 9100, but this time from the NAPP photographs. The uncorrected digitized photo data were initially collected in digitizer table inches, and an affine transformation was applied to convert the data to a corresponding Cartesian coordinate system. The manual digitization from the NAPP photograph used a randomly selected subset of test point features for coordinate registration and transformation. C/A code GPS was used to supply the x,y coordinate ground values for the control points. Twenty-three test points and twenty-two test points were used for coordinate registration from the high-relief and low-relief study sites, respectively.

In contrast to the first two sets of data collected, the third set of digitized data was derived from a single-photo space resection applied during digitizing from the NAPP photographs. The same set of ground control points used to collect the uncorrected photo data was used with the single-photo resection technique. The single-photo resection was accomplished using the **M**ono-**D**igitizing **S**tero-**D**igitizing (MDSD) software. MDSD is specifically designed software that performs a space resection either monoscopically or stereoscopically. The single-photo resection required a camera calibration report, a digital elevation model, and the digitized coordinate pairs. The space resection procedure involved registering the photo coordinate system, registering the ground control coordinate system, and manually collecting (digitizing) the test feature coordinates. The resultant output was adjusted for tilt and terrain effects and automatically transformed to a Cartesian coordinate system. The high-relief study site used four USGS 7.5 minute DEMs to supply the elevation values necessary to perform the space resection. The high-relief study site used a DEM combined from the Blacksburg, Eggleston, Newport, and Radford North quadrangles. In contrast, the low-relief study site used an internally generated DEM, interpolated from the ground control point elevation values, to supply the necessary elevation values.

The USGS DEM format was modified with a utility program (IMPRTDEM), to make it compatible with the MDSD system. Upon collection the single-photo resection data were exported to a PC Arc/Info format.

All digitized data sets from the topographic quads and the NAPP photographs for the high-relief study site were transformed to the Universal Transverse Mercator (UTM - zone 17) NAD27 grid system. In contrast, the low-relief study site digitized data sets were transformed to the Maryland State Plane Coordinate System (NAD83 - zone 1900). The manually digitized data sets from the topographic quads and the NAPP photographs for both study sites were collected and stored using PC Arc/Info ver. 3.4D^{+} software.

The final set of point data collected were derived from USGS 1:100,000 DLG roads data, which is delivered in UTM - NAD27 datum. The DLG roads data were read directly off of a CD-Rom and converted into a PC Arc/Info arc coverage format. This Arc/Info coverage was then queried using the WHERE command to determine the coordinate values for the road intersections that represented test points. To ensure an accurate conversion of the low-relief study site DLG-derived point data to the NAD83 datum, CORPSCON, a coordinate conversion software package produced by the National

Geodetic Survey, was used to determine the latitude and longitude shifts necessary to project the test points from the NAD27 datum to the NAD83 datum. A shift of + 84.76' E and a shift of + 44.30' N was applied to project the low-relief study site DLG-derived point data to the NAD83 datum.

AREA FEATURE DATA COLLECTION:

The first step in the area data collection process was to locate area features identifiable on the NAPP photographs and the ground. In contrast to the point data, area data were not collected from the topographic quads. The construction of the topographic maps does not provide sufficient detail to show area boundaries. Thus, only areas that were identifiable on the NAPP photographs and on the ground were used as test areas. Clearcuts, small fields, and parking lots were the type of area features chosen for testing. The high-relief study site had fourteen test areas identified (Figure 3), while the low-relief study site had fifteen test areas identified (Figure 4).

C/A code GPS data were collected to determine the "true" ground or reference area (in hectares) for the two study sites. Two different methods of collecting the GPS boundary data were employed for each individual test area. Method 1

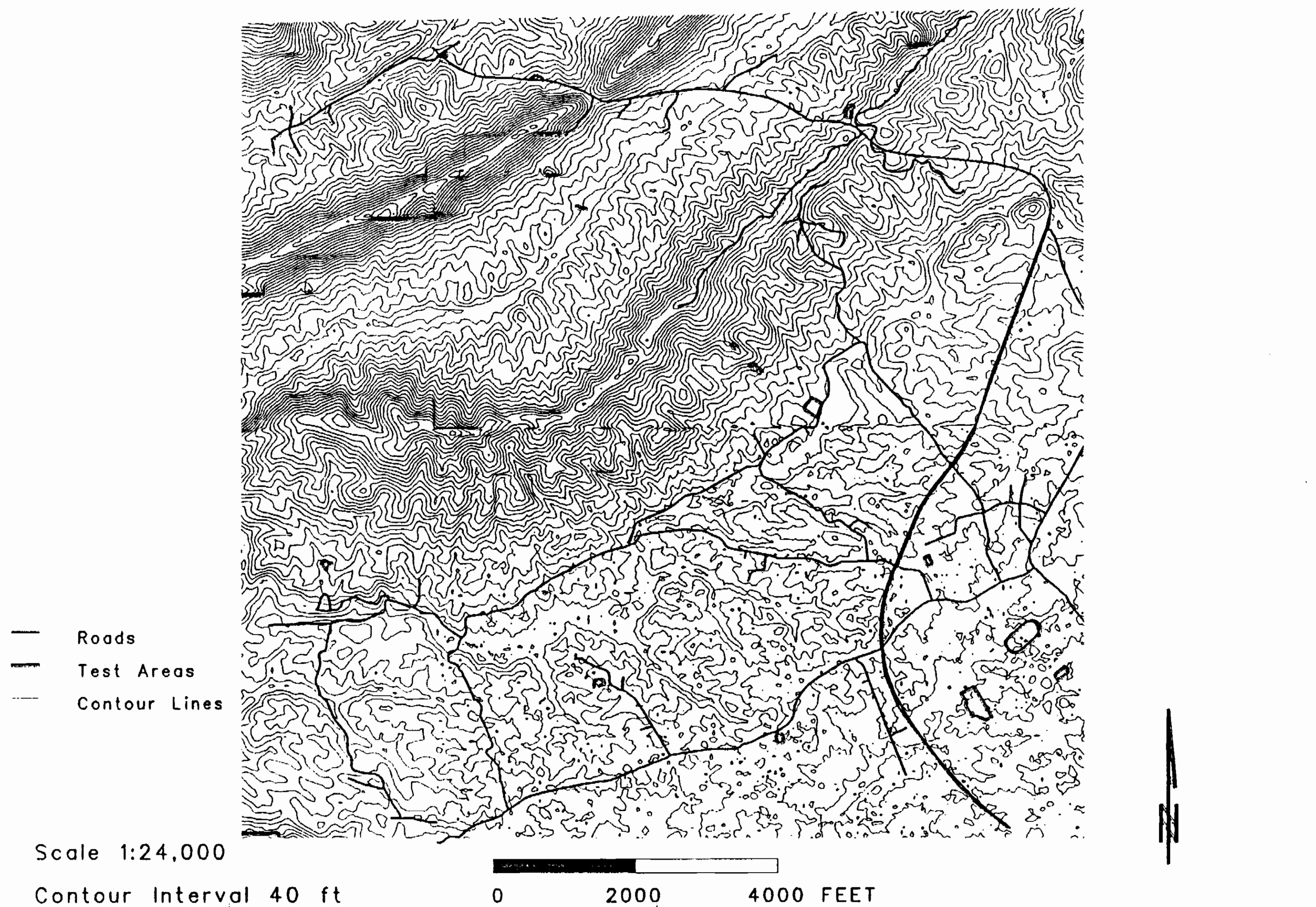

Figure 3: Test Area Distribution on the High-Relief Study Site

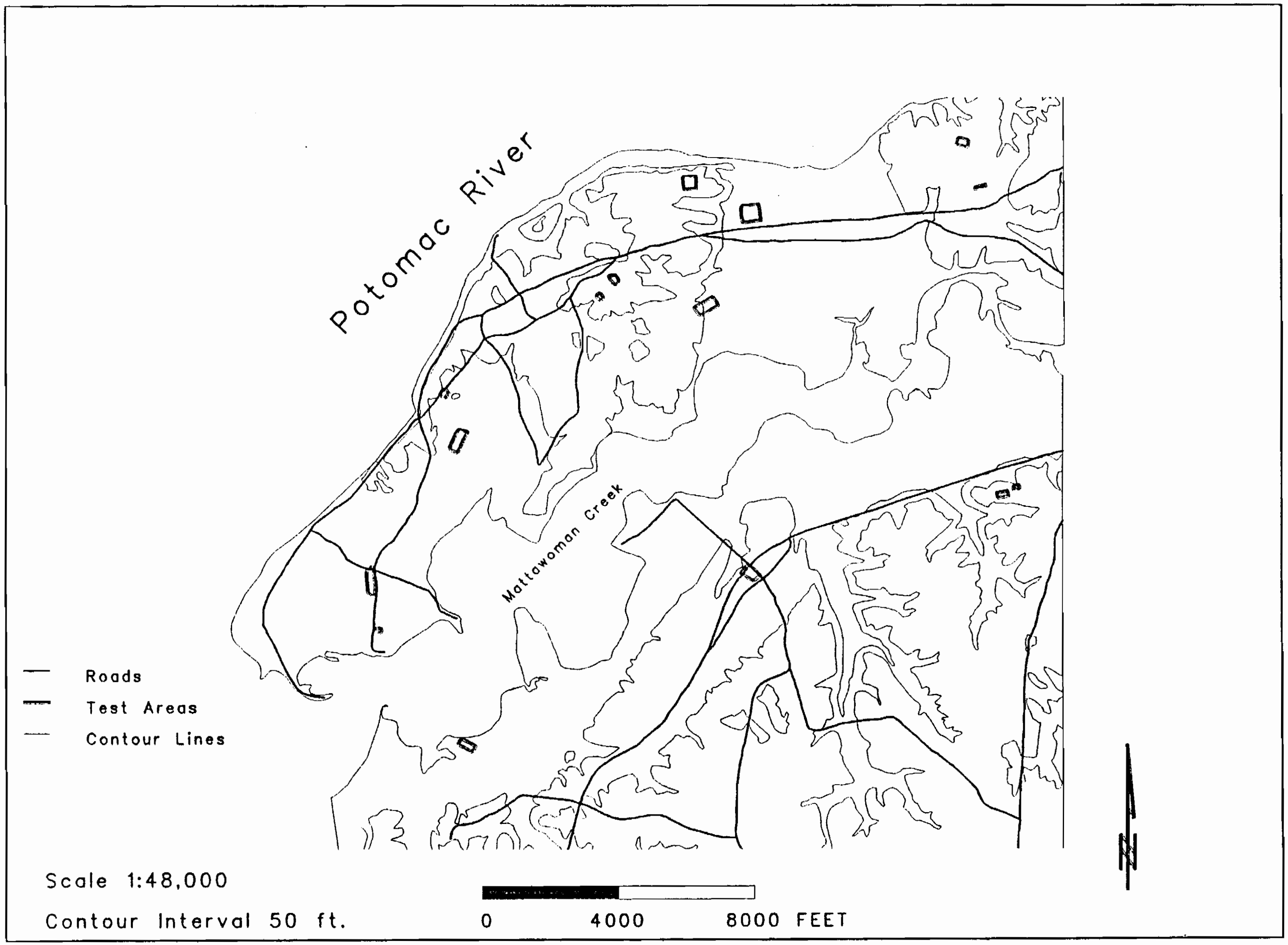

Figure. 4: Test Area Distribution on the Low-Relief Study Site

involved continuously walking the perimeter of each test area while collecting GPS data. Data were collected at a logging rate of one position fix recorded every second during this phase. Method 2 involved following the perimeter of each test area, but this time only collecting GPS data at corners or intermediate points along the area boundary. Corner points were determined as those points along the area boundary where a sharp change in direction was clearly evident. An intermediate point was placed on the area boundary if more than six perpendicular feet was bypassed along an irregular shape in the boundary perimeter. For the second method, two hundred position fixes were collected at each corner point and sixty position fixes were collected at intermediate points. Again, a logging rate of one position fix recorded every second was used to collect the data. A time break of sixty seconds between corner and intermediate points was used to allow for separation of these points during post-processing. The GPS data were differentially corrected using the base-stations previously described. Also similar to the point feature processing, the multiple position fixes collected for the corner and intermediate points were respectively averaged to determine a mean positional value. During data collection the field receiver was set with an elevation mask of fifteen degrees, a PDOP mask of eight, and a minimum signal strength mask of six. All coordinate boundary data were initially collected in the WGS-84 datum and then exported into the respective Cartesian coordinate system outlined above. The vertical data for each boundary point were measured as the height above the ellipsoid.

Once the reference ground area data were collected, digitized estimates of the area boundary were obtained. Area data were collected either by standard digitizing followed by an affine transformation or by applying a single-photo space resection during digitization. The same set of ground control points used during the point feature data collection from the NAPP photographs was used for ground registration and transformation.

First, each test area was manually digitized from the NAPP photographs using a Calcomp 9100 digitizing tablet. The digitized data were initially collected in digitizer table inches and later transformed to the same Cartesian coordinate systems used for the point data. PC Arc/Info was used to collect and process the data for this step. The second set of digitized data were collected by performing a single-photo space resection while digitizing on the NAPP photographs. The single-photo resection was performed using the MDSD software, and followed the same procedure as when collecting the test point data. The same DEMs used to collect the test point data sets were used to collect the test area data. Upon collection, the space resection test area data were exported to a PC Arc/Info format for analysis. Both digitized data sets had polygon topology created using the CLEAN command in PC Arc/Info. A fuzzy tolerance of 0.3 meters and a dangle length of 10.0 meters were used during this operation.

ACCURACY ANALYSIS

Positional Accuracy:

Positional accuracies were determined by comparing digitized locations to the reference positions. In the high-relief study site, this is the difference between the digitized coordinates and the corrected GPS coordinates. In the low-relief study site, it is the difference between the digitized coordinates and corrected GPS or photogrammetric survey coordinates. Determining point feature accuracy involved four different comparisons among the various data sets. The resultant accuracy for each point feature was determined by computing the distance from the x,y coordinates for the digitized data to the x,y coordinates for the GPS or photogrammetric survey data. Euclidian distance was used:

$$\text{distance} = \text{SQRT}(\{X_2 - X_1\}^2 + \{Y_2 - Y_1\}^2)$$

where: X_2, Y_2 = GPS or photogrammetric survey ground positions

X_1, Y_1 = digitized and transformed ground positions

Summary statistics including the mean positional accuracy, maximum positional accuracy, minimum positional accuracy, and standard deviation of the positional accuracies were computed for each of the five data sets from each data collection technique. In addition, these same summary statistics were computed across the five data sets for each of the different data collection techniques. Upon calculation of the summary statistics, separate-variance t-tests were performed to compare the mean positional accuracies between the various data sets. The separate-variance t-test is based upon three assumptions: independent samples, normal distribution, and unequal population variances. The normal distribution assumption was meet based on the Central Limit Theorem and combined independent samples greater than 30. The t-tests were performed at the alpha = 0.05 level. The following formula was used to compute the test statistic for the t-test:

$$t' = (y_1 - y_2) / \mathrm{sqrt}\left(s^2_1 / n_1 + s^2_2 / n_2\right)$$

where: y_1 = sample mean for data set # 1
y_2 = sample mean for data set # 2
s^2_1 = sample variance for data set # 1
s^2_2 = sample variance for data set # 2
n_1 & n_2 = sample size for data set # 1 & # 2

Area Accuracy:

Area accuracies were determined for the high-relief and low-relief study sites by comparing the manually digitized data against the C/A code GPS data. In addition, the two GPS data sets were compared on each study site to determine the amount of variation between the GPS data collection methods. The accuracy of the area features was determined as the difference in hectares between the digitized area data and the GPS area data. The acreage totals for the GPS data sets were determined by using Trimble Inc. Geo-PC ver 1.0 software. The digitized data set acreage values were calculated in DBASE IV and based on the area values stored by PC Arc/Info. Summary statistics including the average area accuracy, maximum area accuracy, minimum area accuracy, and standard deviation of the area accuracies were calculated for both digitized data sets when compared to the two GPS collection methods. Separate-variance t-tests were performed to compare the different means between the digitized data and between the GPS data collection methods. Again, an alpha level = 0.05 was used in the t-tests for the area comparisons. In addition to the area accuracy calculations, the percent area error was calculated for all digitized data sets:

$$\%\ \text{area error} = \frac{\text{acreage difference from reference}}{\text{total GPS acreage}} \times 100$$

<u>Measurement Error Calculation:</u>

In addition to the positional accuracy reported for the test features, the amount of human error introduced during the data collection process was also reported. In particular, the digitizer operator measurement (pointing) error was calculated and reported. The operator measurement error was determined by randomly selecting a subset of twenty points from both the topographic quad and the NAPP photograph data sets for the high-relief study site. Each point was repeatedly digitized ten times, with the operator looking away before each data collection. The standard deviation between the ten readings was calculated for each point, and then the average deviation for the x and y direction was calculated for all twenty points. This process was done on both the topographic quads and the photographs to calculate the amount of measurement error introduced, depending on the source media being used.

Registration/Transformation Error Determination:

The amount of ground control point registration and transformation error in the data was determined from the transformation root mean square error (RMSE). RMSE is a common approach to statistically qualify the level of error in geographic control point data (Bolstad & Smith, 1992). The RMSE for each transformation process was determined from the residual values of the fit between each control point and its reference ground value. RMSE values for each digitized data set were calculated and reported as a measure of the amount of registration error in the data set.

RESULTS AND DISCUSSION

The results from this study are divided into two main sections: positional accuracy and area accuracy. The accuracy results for each study site will be discussed first, and then accuracy differences between the two study sites will be discussed. In addition, the amount of measurement error and transformation/registration error introduced during the data collection will be addressed.

MEASUREMENT/OPERATOR ERROR

Measurement (pointing) error and test point placement on the source media was consistent throughout the study. The operator measurement (pointing) error was determined for both the topographic map and the NAPP aerial photographs. The operator measurement error for the NAPP photograph was calculated to be 0.001871 inches in the x-direction and 0.002501 in the y-direction, corresponding to a distance of 0.95 meters and 1.26 meters, respectively, on the ground. The operator measurement error for the topo map was calculated to be 0.001888 inches in the x-direction and 0.001931 inches in the y-direction, corresponding to a distance of 1.15 meters and 1.17 meters, respectively, on the ground.

POSITIONAL ACCURACY

Low-Relief Study Site:

The results from the low-relief study site indicate that the single-photo space resection method provided the greatest positional accuracy of the data collection methods tested. The space resection method had a mean positional ground accuracy of 5.64 meters with a standard deviation of 3.80 meters across the five data sets (Table 2). In contrast, the uncorrected digitized photo, topographic map, and DLG-derived data sets had mean positional accuracies of 7.14 meters, 11.64 meters, and 29.38 meters, respectively. The average positional accuracy results from each of the five data sets for each digitizing technique are found in Appendix B.

Results from separate-variance t-tests indicate that the space resection and uncorrected digitized photo mean positional accuracies are not significantly different. However, the topographic map mean positional accuracy was statistically different from both the space resection and

Table 2: Mean positional accuracy for the low-relief study site point data sets, results in meters.

Data Set	Mean	Maximum	Minimum	Standard Dev.
Space Resection	5.64	19.79	0.50	3.80
Photo	7.14	24.36	0.99	4.35
Topo Map	11.64	40.64	0.79	6.58
DLG	29.38	60.60	2.85	12.64

uncorrected digitized photo data (Table 3). In addition, the mean positional accuracy for the DLG-derived point data was found to be statistically poorer then all three manually digitizing techniques (Table 4). The single-photo space resection method takes into account the geometric errors of tilt and terrain displacement present in the NAPP photograph. However, the tilt and terrain effects are not removed during an affine transformation, thus a higher average mean positional accuracy would be obtained using this technique. The space resection method provided mean positional accuracies 1.50 meters more accurate than the uncorrected digitized photographic data. While this difference may be expected to be greater, the use of near-vertical photography (less than 3° tilt) helped to reduce the tilt displacement influences in the uncorrected photo data set. This, in combination with the low terrain relief resulted in lower positional accuracy. Bolstad (1992) achieved similar results for positional data collected directly from aerial photography in low terrain relief with tilts less then 3.0 degrees.

The topographic map data set contained three extreme data points (outliers) with mean positional accuracies of 57.00 meters, 169.01 meters, and 73.05 meters. These points were determined to be blunders, mislocated test points on the

Table 3: Results of Separate-Variance t-tests comparing the manually digitized point data sets for the low-relief study site, $\alpha = 0.05$.

	Resection vs. Photo	Resection vs. Topo Map	Photo vs. Topo Map
Test Statistic	-1.96	-7.52	-5.84
P-Value	0.05	0.00	0.00
DF	145	150	155

Table 4: Results of Separate-Variance t-tests comparing the manually digitized point data to the DLG-derived data for the low-relief study site, $\alpha = 0.05$.

	Resection vs. DLG	Photo vs. DLG	Topo Map vs. DLG
Test Statistic	-14.33	-13.54	-10.33
P-Value	0.00	0.00	0.00
DF	78	79	92

topo map, and thus were removed from any positional accuracy analysis.

The topographic map data set mean positional accuracy was 6.0 meters greater than the space resection mean positional accuracy. However, looking at the mean positional accuracy distribution (Figure 5) reveals that based upon these results the topographic map data would fail to meet the NMAS set forth by the USGS for a 1:24,000 scale map. The topographic map data set had 39.0% of the test points above 12.19 m in mean positional accuracy. Hence, the topographic map data would not meet NMAS since more than 10.0% of well-defined points would be greater than 12.19 meters away from the reference positions. The 1:100,000 DLG-derived data were 23.0 meters greater in mean positional accuracy than the space resection data but would still meet NMAS. The NMAS for a 1:100,000 scale map requires that 90.0% of all well-defined points be within +/- 50.0 meters of their ground location. The DLG-derived data had 90.0% of the test points within 50.0 meters of the reference positions. In contrast, the space resection and uncorrected digitized photo data sets have 85.0% and 79.0%, respectively, of their test points below 9.0 m of mean positional ground accuracy.

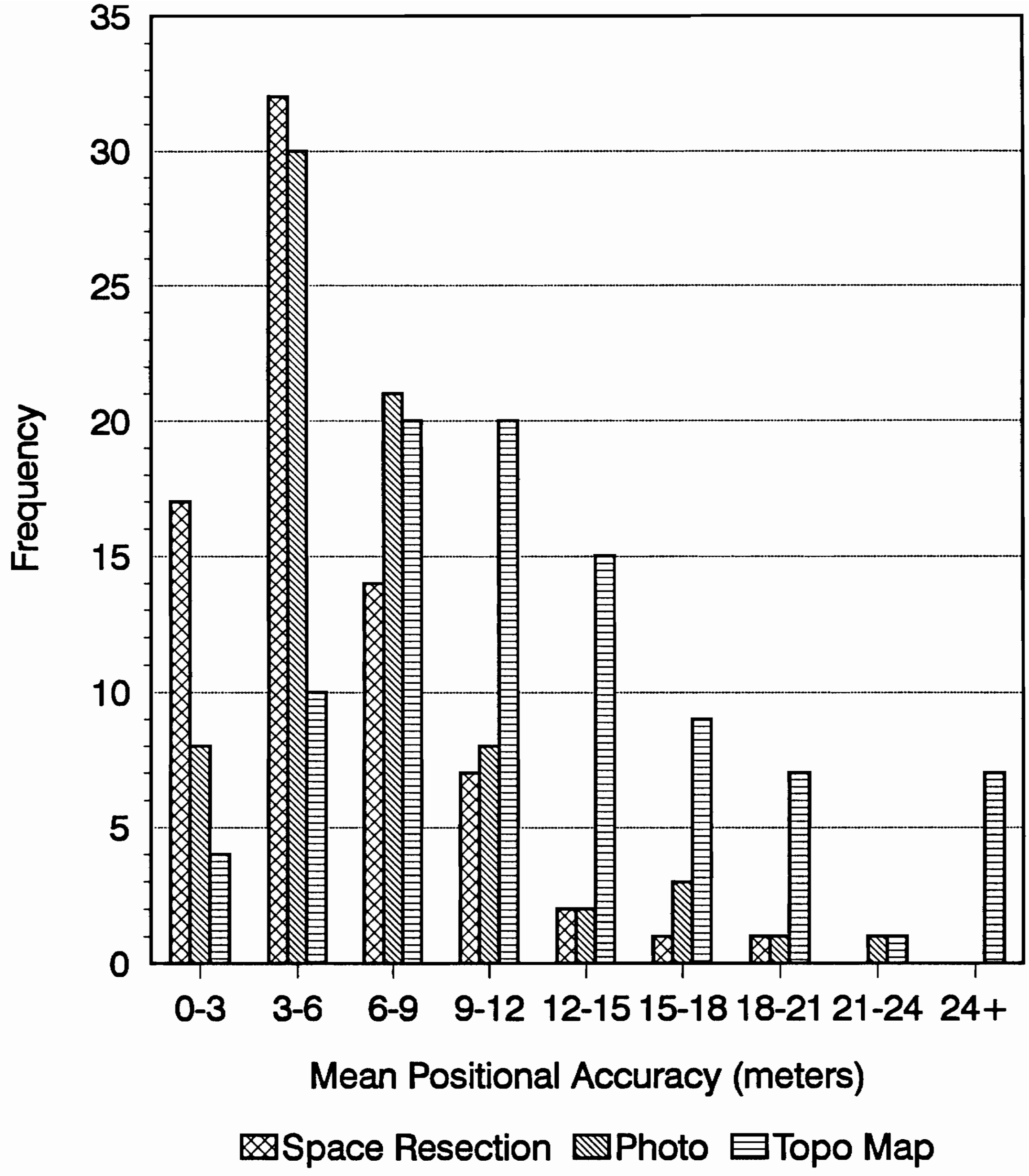

Figure 5: Distribution of mean positional accuracy for test points on the low-relief study site.

Positional accuracy on the low-relief study site was also determined when using the photogrammetric survey as ground reference. Results when using the photogrammetric survey as ground reference are shown in Table 5. Analysis of separate-variance t-test comparisons between Table 2 and Table 5 data sets show that the means for the topographic map or DLG-derived data were not significantly different. However, the means for the space resection and uncorrected digitized photo data sets were found to be statistically different (Table 6). The space resection mean positional accuracy from the photo survey comparison was 3.85 meters higher than the corresponding space resection data from Table 2. The uncorrected digitized photo, topographic map, and DLG-derived data sets have means that were slightly lower than the corresponding means from Table 2. This is because the photogrammetric survey offers more accurate ground control, thus reducing the error introduced during transformation and registration. The mean positional accuracy distributions with the photogrammetric survey ground reference are shown in Figure 6. Based on these results, the topographic map data would fail to meet NMAS. The topographic map data had 32.7% of the test points greater than 12.19 meters from the reference positions. In contrast, the space resection and uncorrected photo data sets have the majority of their test points below

Table 5: Mean positional accuracy for the low-relief study site with the photogrammetric survey as ground reference, results in meters.

Data Set	Mean	Maximum	Minimum	Standard Deviation
Space Resection	9.49	21.67	1.29	5.83
Photo	4.76	12.91	0.57	3.12
Topo Map	10.72	35.10	2.02	6.43
DLG	28.31	53.69	6.71	10.54

Table 6: Results of Separate-Variance t-tests comparing the manually digitized point data sets from the GPS based results against the photogrammetric survey based results for the low-relief study site, $\alpha = 0.05$.

	Space Resection	Uncorrected Photo	DLG	Topo Map
Test Statistic	-4.20	3.24	0.74	1.09
P-Value	0.0001	0.0016	0.46	0.28
DF	56	101	100	115

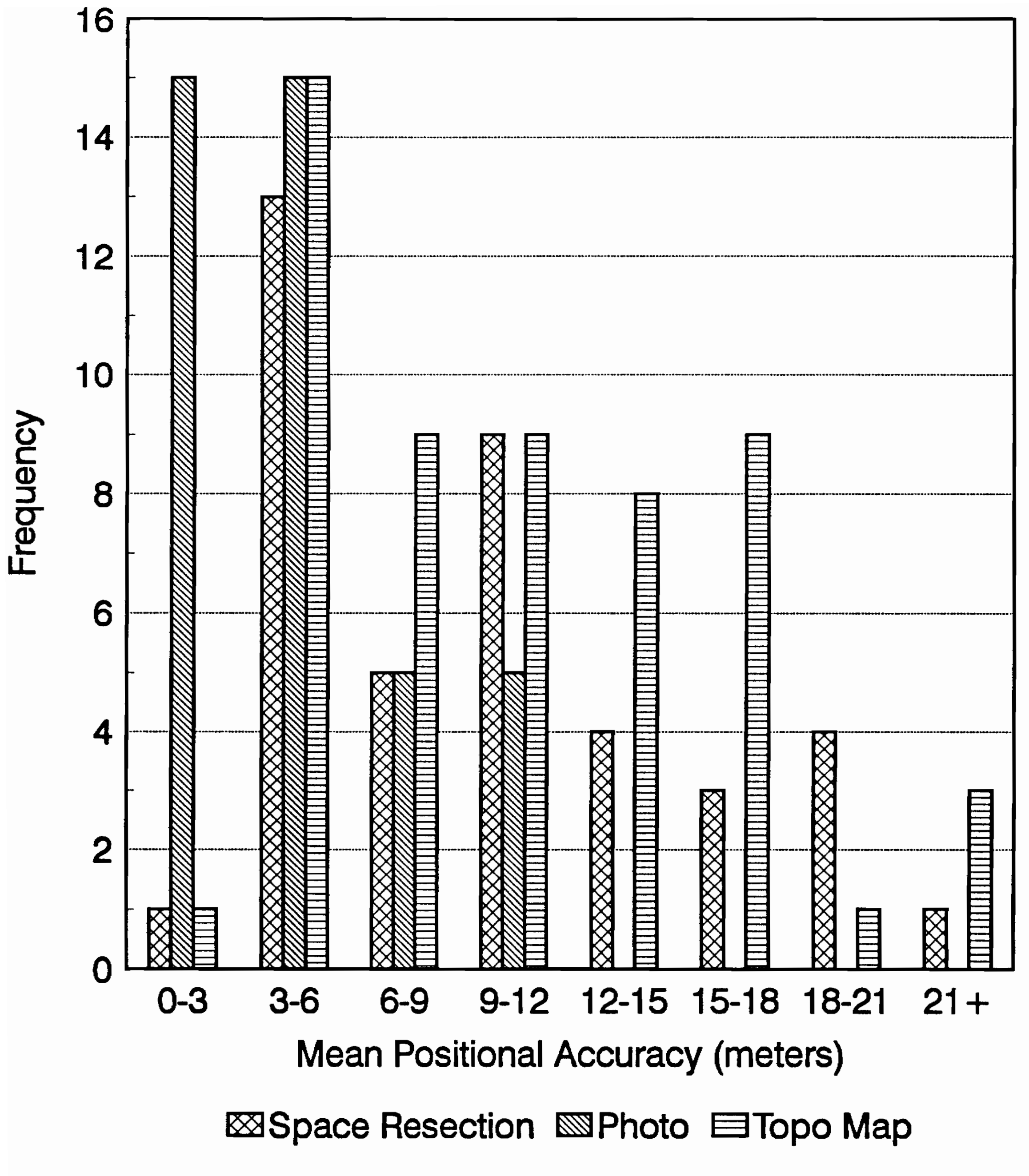

Figure 6: Distribution of mean positional accuracy for test points using the photogrammetric survey as ground reference on the low-relief study site.

10.0 meters in mean positional accuracy. The DLG-derived data would meet NMAS as 95.0% of the DLG-derived points were less than 50.0 meters from the reference positions.

High-Relief Study Site:

Similar to the low-relief site when using the GPS based results, the space resection method exhibited the greatest positional accuracy. The space resection method had a mean positional accuracy of 6.27 meters and a standard deviation of 3.51 meters. In contrast, the uncorrected digitized photo, topographic map, and DLG-derived data sets had mean positional accuracies of 25.86 meters, 11.20 meters, and 17.61 meters respectively. The average positional accuracy results for the five digitized data sets are found in Appendix B. Mean positional accuracy results for all of the point data for the high-relief study site are shown in Table 7.

In contrast to the low-relief study site, separate-variance t-test results reveal that all of the digitized data sets were statistically different (Table 8). Similarly, the mean positional accuracy for the DLG-derived point data was found to be statistically different from all three manually digitizing techniques (Table 9). The space resection method

Table 7: Mean positional accuracy for the high-relief study site point data sets, results in meters.

Data Set	Mean	Maximum	Minimum	Standard Deviation
Space Resection	6.27	16.32	0.73	3.51
Photo	25.86	90.43	5.41	18.87
Topo Map	11.20	65.95	1.19	10.72
DLG	17.61	41.64	1.86	10.71

Table 8: Results of Separate-Variance t-tests comparing the manually digitized point data sets for the high-relief study site, $\alpha = 0.05$.

	Resection vs. Photo	Resection vs. Topo Map	Photo vs. Topo Map
Test Statistic	-8.06	-3.62	5.40
P-Value	0.00	0.0005	0.00
DF	65	81	95

Table 9: Results of Separate-Variance t-tests comparing the manually digitized point data sets to the DLG-derived data for the high-relief study site, $\alpha = 0.05$.

	Resection vs. DLG	Photo Data vs. DLG	Topo Map vs. DLG
Test Statistic	-6.48	2.82	-3.01
P-Value	0.00	0.005	0.003
DF	44	100	83

was 19.59 meters more accurate than the uncorrected digitized photo data, 4.93 meters more accurate than the topographic map data, and 11.34 meters more accurate in ground distance than the DLG-derived data. Contrary to the low-relief site, terrain displacement does have a strong influence on this study site. This is evident by the large mean positional accuracy obtained for the uncorrected digitized photo data set. Reducing the effects of tilt and particularly terrain from the data collected from the NAPP photographs improved the mean positional accuracy of the resultant point data by 19.59 meters.

Outlier (blunder) points were again identified in the data sets. The space resection data set and the uncorrected digitized photo data set had two blunder points identified. These were points that were mislocated on the photograph and thus were not used in any accuracy analysis. The outliers had mean positional accuracy of 189.38 meters and 75.64 meters in the space resection data and 322.44 meters and 146.76 meters in the uncorrected digitized photo data. The topographic map data also had two blunder points identified, with mean positional accuracies of 212.10 meters and 137.56 meters.

The mean positional accuracy distributions for the test point data are shown in Figure 7. The distribution of mean positional accuracies show how terrain affects spatial data from this site. For example, the uncorrected digitized photo data set had 69.0% of the test points more than 15.0 meters from the reference positions. In contrast, the space resection data set had 88.0% of the test points less than 10.0 meters distant from the reference positions. The topographic map data had 21.0% of the test points greater than 12.19 meters from the reference positions. Based on these findings, the topographic map data would again fail to meet NMAS for a 1:24,000 scale map. The DLG-derived data again met NMAS, as it had 96.0% of the test points less than 50.0 meters distant from the reference positions.

Positional Accuracy Comparisons Between Study Sites:

The difference in positional accuracy between the two study sites was due largely to terrain effects. The source media was of the same scale and production on both sites. With measurement error consistent on both source media, terrain displacement remains the variable differing most between the two study sites.

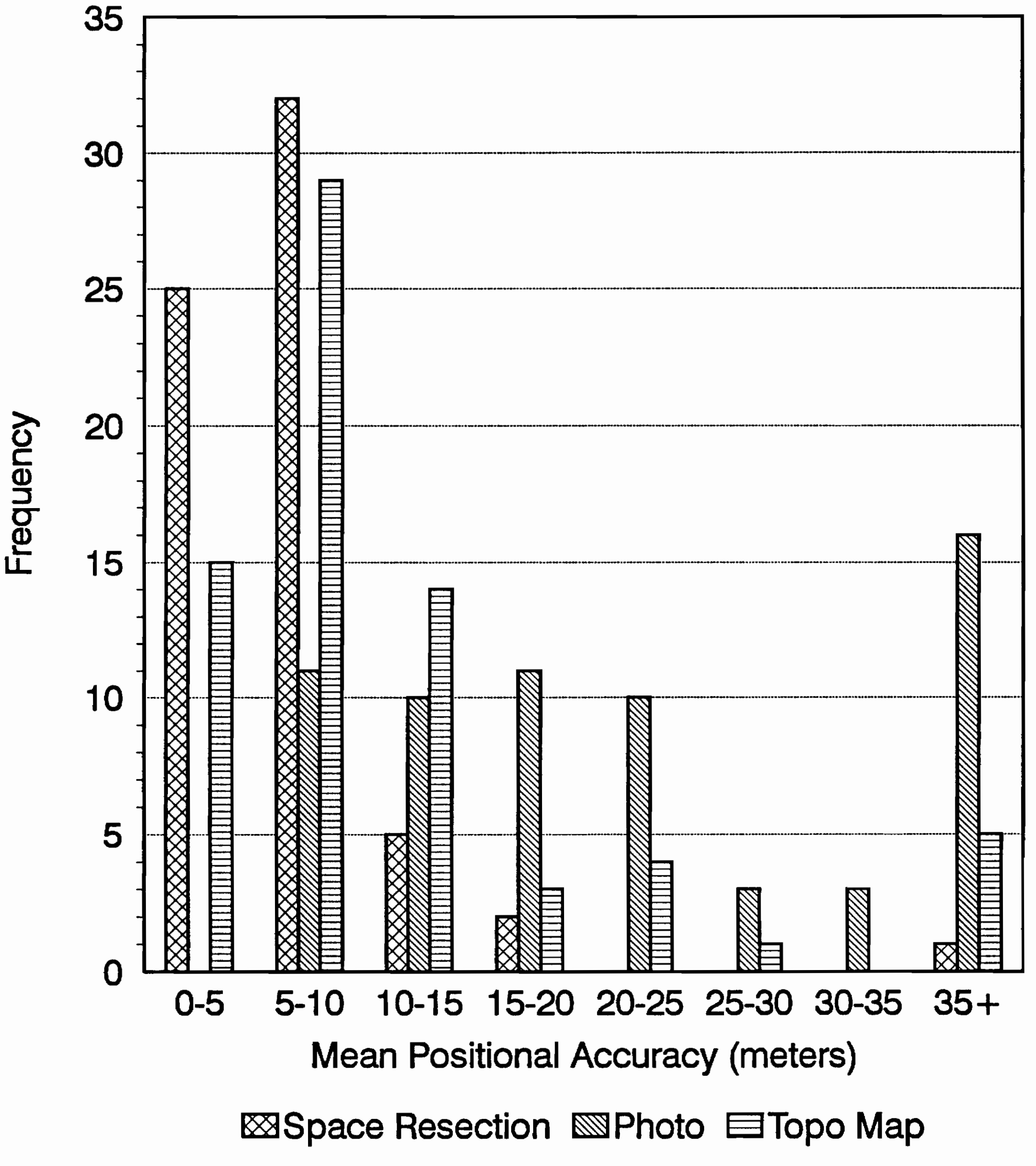

Figure 7: Distribution of mean positional accuracy for test points on the high-relief study site.

Analysis of separate-variance t-test results show that the space resection data and topographic map data from both study sites were not significantly different. However, mean positional accuracies for the uncorrected digitized photo and DLG-derived data sets were statistically different (Table 10). Referring back to Tables 2 and 7, the mean positional accuracies for each study site are shown. Mean positional accuracies between the space resection data sets differ by only 0.63 meters. This is expected, as space resection reduces photo tilt and terrain displacement effects. Thus, the greatest remaining influence on the accuracy of space resection-derived data are the scale, resolution, and format of the photography. Warner (1990) states that photo scale has the greatest single influence on object definition and consequently on photo-derived accuracy. Hence, since the NAPP photographs were of the same scale, resolution, and format the resultant mean positional accuracies from the space resection method were similar.

Even less difference is found, 0.24 meters, between the mean positional accuracies of the topographic map data. The topographic quadrangle maps were produced based on NMAS, thus their resultant positional accuracies would be expected to be of the same magnitude. The DLG-derived data differed

Table 10: Results of Separate-Variance t-tests comparing the digitized point data sets between the two study sites, α = 0.05.

	Space Resection	Photo Data Sets	DLG	Topo Map
Test Statistic	-1.13	-7.80	5.26	0.30
P-Value	0.26	0.00	0.00	0.76
DF	135	66	99	104

by 11.77 meters in mean positional accuracy, but both data sets still meet NMAS for a 1:100,000 scale map. The largest difference was between the uncorrected digitized photo data sets from each study site. The high-relief study site uncorrected digitized photo data set had a mean positional accuracy 18.72 meters larger than the low-relief uncorrected digitized photo data set. This difference highlights the effect terrain displacement had on the accuracy of spatial data collected directly from aerial photography in steep terrain. Positional accuracies of these magnitudes are not uncommon for spatial data collected directly from aerial photographs with varying terrain (Bolstad, 1992).

AREA ACCURACY

<u>Low-Relief Study Site:</u>

The results of the area accuracy analysis show that there were no difference statically between the two GPS data collection methods or between the two digitizing techniques (Table 11). The average area accuracy for the two digitizing techniques is found in Table 12.

The means in Table 12 show that each digitizing technique differs by only 0.003 hectares between the two GPS data

Table 11: Results of Separate-Variance t-tests comparing the manually digitized area data sets for the low-relief study site, $\alpha = 0.05$.

	Resection GPS Method 1 vs. 2	Photo GPS Method 1 vs. 2	Resection vs. Photo GPS Method 1	Resection vs. Photo GPS Method 2
Test Statistic	-0.14	0.13	-0.49	-0.08
P-Value	0.89	0.90	0.63	0.93
DF	23	24	27	27

Table 12: Average area accuracy for the low-relief study site, including the two digitizing techniques and the two GPS area collection methods, results in hectares.

GPS Method 1 GPS Method 2	Mean	Maximum	Minimum	Standard Deviation
Space Resection	0.062 0.065	0.15 0.22	0.016 0.007	0.041 0.060
Photo	0.070 0.067	0.16 0.22	0.010 0.008	0.045 0.070

collection methods. The space resection technique provided slightly more accurate average area data for either GPS data collection method. The space resection data was 0.008 ha less for GPS method 1 and 0.002 ha less for GPS method 2. While the variation between the two digitizing techniques would be expected to be greater, these results are not unrealistic. The low variation between the two digitizing techniques may be the result of any number of factors. For instance, the small average size of the test areas (Table 13) allows for increased measurement error during digitization. The effect of digitizing error on area estimates for a given area is amplified as the size of the area decreases. For example, a two meter digitizing error on a 100.0 ha polygon has much less influence on the overall polygon area than it would on a 10.0 ha polygon. In addition, GPS errors, DEM error, and line generalization error could be influencing the digitized area acreage values.

The average percent area error for each digitizing technique follows the same trends as for the average area accuracy (Table 14). The space resection data set had average percent area error of 10.67% and 9.96% for the two GPS data collection methods respectively. The uncorrected digitized photo data set had average percent area error of 11.74% and

Table 13: Acreage values for the low-relief study site from the two GPS methods and the two digitized data sets, area in hectares.

Test Area #	GPS Method 1	GPS Method 2	Space Resection	Uncorr. Photo
1	0.98	0.97	0.93	0.89
2	0.23	0.22	0.22	0.23
3	1.44	1.31	1.53	1.54
4	1.56	1.50	1.68	1.69
5	0.21	0.19	0.37	0.38
6	0.28	0.25	0.23	0.23
7	0.44	0.41	0.48	0.50
8	1.82	1.80	1.85	1.84
9	2.43	2.41	2.49	2.38
10	1.21	1.27	1.28	1.30
11	0.71	0.66	0.68	0.65
12	0.22	0.23	0.20	0.17
13	0.21	0.20	0.17	0.19
14	0.53	0.51	0.48	0.48
15	1.49	1.33	1.35	1.34

Table 14: Percent area error for the low-relief study site, including the two digitizing techniques and the two GPS data collection methods.

Test Area #	Resection GPS Method 1	Resection GPS Method 2	Photo GPS Method 1	Photo GPS Method 2
1	-3.44	-3.44	-8.10	-8.18
2	-7.27	0.59	-1.72	5.17
3	5.78	14.47	6.03	14.69
4	7.19	10.79	7.41	11.00
5	42.39	47.82	43.61	48.93
6	-22.41	-10.34	-20.33	-8.47
7	8.26	15.70	10.48	17.74
8	1.96	2.61	1.31	1.97
9	2.43	3.24	-2.20	-1.35
10	5.06	0.31	7.12	2.47
11	-4.76	2.38	-9.31	-1.86
12	-12.00	-16.00	-27.27	-31.81
13	-18.18	-13.63	-10.63	-6.38
14	-9.16	-6.67	-9.16	-6.68
15	-9.82	2.08	-11.48	0.60
Mean	10.67	9.96	11.74	11.15

11.15% for two GPS data collection methods. Again, these results do not show a large variation between the two digitizing techniques or the two GPS collection methods. In addition, the average percent area error values do not compare favorably to previous studies. Bolstad (1992) observed average percent area error of 0.0% to 3.0% for polygons 40-50 ha in size over moderate to flat terrain and less than 3° of tilt. Wiles (1988) observed average percent area errors of less than 7.0% for polygons digitized from 35 mm aerial photography in moderate terrain.

<u>High-Relief Study Site:</u>

Similar to the low-relief study site, the average area accuracy results show that there were no significant difference statically between the two GPS data collection methods or between the two digitizing techniques (Table 15) for the high-relief study site. The average area accuracy results for both digitizing techniques can be found in Table 16.

The average area accuracy for the space resection technique differs by 0.007 ha for the two GPS data collection methods, while the uncorrected digitized photo data varies by 0.01 ha. The average area accuracy difference between the

Table 15: Results of Separate-Variance t-tests comparing the manually digitized area data sets for the high-relief study site, $\alpha = 0.05$.

	Resection GPS Method 1 vs. 2	Photo GPS Method 1 vs. 2	Resection vs. Photo GPS Method 1	Resection vs. Photo GPS Method 2
Test Statistic	-0.11	0.15	0.07	0.35
P-Value	0.91	0.88	0.94	0.73
DF	25	25	25	25

Table 16: Average area accuracy for the high-relief study site, including the two digitizing techniques and the two GPS area collection methods, results in hectares.

GPS Method 1 GPS Method 2	Mean	Maximum	Minimum	Standard Deviation
Space Resection	0.103 0.110	0.330 0.081	0.016 0.330	0.096 0.010
Photo	0.100 0.090	0.370 0.080	0.012 0.370	0.092 0.020

two digitizing techniques is small, regardless of the GPS collection method. The two digitizing techniques differ at most by 0.01 ha for either GPS data collection method. Again, a larger variation in the average accuracies between the two digitizing techniques would be expected. The effect of terrain displacement on the uncorrected photo data would be expected to have a greater influence than what is reported from these results. Similar to the low-relief study site, the small amount of variation between the two digitizing techniques could result from numerous factors. In particular, the small area size (Table 17) may have contributed to increased digitizing error being introduced into the data.

The percent area errors for each combination of the digitizing technique and GPS methods are found in Table 18. These results again follow the trends of the average area accuracy. There was little variation between the average percent area error for each digitizing technique or either GPS data collection method. The space resection method had average percent area errors of 12.65% and 11.96% for the GPS data collection method 1 and 2, respectively. Likewise, the uncorrected digitized photo data had average percent area errors of 11.84% and 12.10% for the GPS data collection method 1 and 2, respectively. While the average percent

Table 17: Acreage values for the high-relief study site from the two GPS methods and the two digitized data sets, area in hectares.

Test Area #	GPS Method 1	GPS Method 2	Space Resection	Uncorr. Photo
1	1.26	1.27	1.20	1.21
2	8.41	8.53	8.44	8.64
3	7.00	7.02	6.87	7.10
4	0.80	0.84	0.70	0.67
5	0.79	0.77	0.70	0.72
6	0.64	0.69	0.93	0.76
7	0.76	0.81	0.79	0.72
8	2.84	2.88	2.80	2.79
9	0.85	0.84	0.81	0.82
10	0.19	0.20	0.21	0.24
11	0.16	0.16	0.17	0.21
12	0.41	0.43	0.49	0.41
13	0.44	0.44	0.62	0.55
14	0.58	0.59	0.92	0.96

Table 18: Percent area error for the high-relief study site, including the two digitizing techniques and the two GPS data collection methods.

Test Area #	Resection GPS Method 1	Resection GPS Method 2	Photo GPS Method 1	Photo GPS Method 2
1	-5.05	-6.39	-4.34	-5.68
2	0.28	-1.15	2.57	1.17
3	-1.88	-2.11	1.31	1.08
4	-13.79	-19.54	-17.85	-23.80
5	-13.87	-10.40	-10.67	-7.30
6	30.86	25.65	16.31	10.00
7	4.06	-2.03	-5.58	-12.29
8	-1.58	-2.88	-2.02	-3.33
9	-4.97	-3.98	-3.43	-2.45
10	11.11	7.40	20.00	16.66
11	9.09	6.81	23.07	21.15
12	15.57	12.29	-0.98	-4.90
13	28.57	29.22	20.28	21.01
14	36.40	35.96	39.07	38.65
Mean	12.65	11.96	11.84	12.10

area error exhibits little variation between the digitizing techniques, the results again do not compare favorably to previous studies. Average percent area errors of 5.0% to 7.0% were observed for polygons 40-50 ha in size in steep terrain with less than 3° of tilt (Bolstad, 1992). Prisley (1989) observed polygon percent area errors ranging from 5.0% to 15.0%, while Demini (1960) observed area error of 0.7 to 6.2% from tilted photographs. The increased percent area errors are again resultant from the increased digitizing error due to the small test area size.

<u>Area Accuracy Comparison Between Study Sites:</u>

Analysis of separate-variance t-test results for the average area accuracies between the two study sites indicate that there was no significant difference between the average area accuracy for the two sites (Table 19). The high-relief study site had slightly larger average area accuracies for the two digitizing techniques regardless of the GPS method tested. The high-relief site accuracy was at most 0.05 hectares greater than the low-relief study site. This would translate to 0.09 of an acre, an error amount that could be influenced by digitizing error, transformation error, GPS error, or DEM error. The average percent area error difference between the two study sites shows little

Table 19: Results of Separate-Variance t-tests comparing the manually digitized area data sets between the two study sites, $\alpha = 0.05$.

	Resection GPS Method 1	Resection GPS Method 2	Photo Data GPS Method 1	Photo Data GPS Method 2
Test Statistic	1.40	1.35	1.05	0.92
P-Value	0.18	0.19	0.31	0.37
DF	17	24	18	25

difference in the two GPS data collection methods or digitizing techniques. The space resection data sets in combination with GPS method 1 differ by 1.98% between the two study sites. Likewise, the uncorrected photo data sets combined with GPS method 1 have a percent area error difference of 2.00% between the study sites. In contrast, the same data sets when combined with GPS method 2 have percent area error differences of only 0.10% and 0.85% for the space resection and uncorrected photo data respectively.

TRANSFORMATION/REGISTRATION ERROR

The amount of transformation and registration error introduced into the data during the data collection and transformation process was determined from the RMS error. The RMS error was used as a measure of how well the digitized control point coordinates fit their corresponding ground coordinates. Hence, the RMS error was an indication of how accurate the resultant spatial data will be once it was transformed into Cartesian ground coordinates.

LOW-RELIEF STUDY SITE:

The affine transformation RMS errors for the uncorrected digitized photo and topographic map test point data sets for the low-relief study site are shown in Table 20. In addition, the affine transformation RMS error values for the uncorrected digitized photo data when using the photogrammetric survey as control are included in Table 20. Residual values for the individual control points from each affine transformation for the test point data sets can be found in Appendix C.

The RMS error for the affine transformation on the uncorrected digitized photo data was consistent, ranging from 6.55 meters to 7.04 meters of ground distance for the GPS based results. This was also true when the photogrammetric survey was used as reference, with residual errors ranging from 4.62 meters to 5.33 meters of ground distance. The RMS errors for the uncorrected digitized photo data with the photogrammetric control are generally 1-2 meters in ground distance lower than the GPS based photo data. This registration improvement is the result of having more accurate ground coordinates for the control points. The RMS errors from the affine transformations for the digitized topographic map data ranged from 1.50 meters to 2.14 meters of ground distance. The ground transformation and fiducial registration RMS errors from the space resection test point data sets are found in Table 21. Also, the space resection ground transformation and fiducial

Table 20: Affine transformation RMS error values for the five point data sets on the low-relief study site (meters).

Method	Data Set # 1	Data Set # 2	Data Set # 3	Data Set # 4	Data Set # 5
Photo - GPS Based	7.04	6.87	6.61	6.55	6.90
Photo - Survey Based	4.94	4.69	4.62	4.64	5.33
Topo Map	1.71	1.72	1.50	1.52	2.14

registration RMS errors when using the photogrammetric survey as control are included in Table 21. The RMS errors when using the photogrammetric survey as control are again lower then when using the GPS based coordinates for control. The same fiducial registration was used in both of the space resection cases. The residual values of the individual control points from the ground transformation process for the space resection data are found in Appendix C.

The affine transformation RMS error for the uncorrected digitized photo test area data was 6.96 meters. The RMS error for the single-photo space resection ground transformation of the test area data was 1.15 meters. The residual values for the individual control points from both transformation processes of the test area data can be found in Appendix C.

HIGH-RELIEF STUDY SITE:

The affine transformation RMS error values for the uncorrected digitized photo and topographic map test point data sets for the high-relief study site are shown in Table 22. The residual values for the individual control points from each affine transformation for the test point data are found in Appendix C.

Table 21: Transformation RMS error values for the five space resection point data sets on the low-relief study site (meters).

	Data Set # 1	Data Set # 2	Data Set # 3	Data Set # 4	Data Set # 5
Ground-GPS Based	1.15	1.14	1.17	1.09	1.08
Ground-Survey Based	0.94	0.93	0.88	0.96	0.88
Fiducial	0.184	0.185	0.179	0.183	0.162

Table 22: Affine transformation RMS error values for the five point data sets on the high-relief study site (meters).

Method	Data Set # 1	Data Set # 2	Data Set # 3	Data Set # 4	Data Set # 5
Photo	29.05	29.55	29.32	28.88	29.21
Topo Map	2.11-3.23	1.40-2.98	2.28-3.29	1.39-3.17	1.90-3.27

Similar to the low-relief study site, the RMS error values for uncorrected digitized photo data set were consistent, ranging from 28.88 meters to 29.55 meters in ground distance (a change of less than 1 meter). The RMS error values for the topographic map data sets shown in Table 22 represent the range of values from the four different quads that covered the study site. A complete list of the RMS error values for each quadrangle transformation is in Appendix C. The transformation and fiducial registration residuals from the space resection test point data sets are found in Table 23. The residual values from the transformation process for the individual control points are found in Appendix C.

The affine transformation RMS error for the uncorrected digitized photo test area data was 29.05 meters. The RMS error for the single-photo space resection ground transformation of the test area data was 1.05 meters. The residual values for the individual control points from both transformation processes of the test area data can be found in Appendix C. The large RMS error for the uncorrected digitized photo data was a result of the terrain displacement present in the high-relief study site

Table 23: Transformation RMS error values for the five space resection point data sets on the high-relief study site (meters).

	Data Set # 1	Data Set # 2	Data Set # 3	Data Set # 4	Data Set # 5
Ground	1.05	1.12	1.01	1.20	1.03
Fiducial	0.161	0.185	0.181	0.183	0.163

photograph. RMS transformation errors of this magnitude are not uncommon for ground registration from aerial photography in steep terrain (Bolstad, 1992).

CONCLUSIONS

The accuracy of digital spatial data collected by natural resource organizations is affected by the source of the data and the method used to collect the data. As the use of GIS continues to grow in natural resource organizations, the reliability and accuracy of the data used in GIS analysis is becoming increasingly important. The purpose of this research was to compare different digitizing techniques available to natural resource organizations and determine the level of accuracy which could be obtained with the different techniques.

The results of this study show that spatial data collected directly from near-vertical aerial photography using a single-photo space resection with GPS based ground control can provide positional accuracies of 5.0 to 6.0 meters, regardless of the terrain conditions. Spatial data collected by directly digitizing from near-vertical aerial photography, using GPS based ground control, followed by an affine transformation provided mean positional accuracies of 7.0 to 26.0 meters. Spatial point data collected using this approach is affected by the amount of tilt and terrain displacement present in the aerial photography used to collect the data. For this study, the spatial data collected from aerial photography in low terrain relief was approximately three times more accurate than data collected in high terrain relief areas. The two-dimensional affine transformation does not reduce the tilt and terrain displacement influences present in the aerial photography. Hence, use of this technique must take into account these displacement influences and the resultant affect on the accuracy of the spatial data collected in this manner.

Digitizing directly from the topographic maps followed by an affine transformation provided mean positional accuracies from both study sites of less than 12.0 meters. However, the topographic map data from either study site failed to meet USGS NMAS for 1:20,000 and smaller scale maps. In contrast, the 1:100,000 DLG-derived point data provided mean positional accuracies of between 17.0 to 23.0 meters but still met NMAS on both study sites.

The area accuracy results from this study report that there were no statistical differences among the area accuracies from the two study sites. No statistical difference was found between the different digitizing techniques or the GPS data collection methods, regardless of the terrain conditions. The average area accuracies deviated by less than 0.10 hectare among and between the two study areas. The small amount of variation in the average area accuracies between the digitizing techniques is largely the result of the small size of the area features tested. The small average test area size, less than 2.0 ha, increased the influences of digitizing and transformation error; thus, shadowing any possible accuracy differences between the techniques. The average percent area error ranged from 9.96% to 11.74% on the low-relief site and from 11.96% to 12.65% on the high-relief site. These values are large when considering the small area sizes and comparing the results to similar studies (Bolstad 1992).

In conclusion, this study demonstrated that positional accuracies of less than 6.0 meters can be obtained when using GPS based ground control points and applying a single-photo space resection during digitization. Digitizing directly from aerial photography in low terrain relief, with C/A code GPS based ground control, can provide positional accuracies even with single-photo space resection results and better than data derived from topographic maps. However, in areas of steep terrain the single-photo space resection technique is recommended over direct digitization from either aerial photography or topographic maps. As the use of GIS technology continues to expand in natural resource organizations, a single-photo space resection in combination with C/A code GPS offers an alternative technique to standard digitizing, which can provide equal or more accurate spatial data.

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APPENDIX A:

POINT AND AREA VALUES

Table A.1: GPS point values for the low-relief study site, coordinates in Maryland Stateplane feet (NAD83-Zone 1900).

PT #	SPC Northing	SPC Easting	Elevation
1	327570	1253559	32
2	328009	1253107	35
3	329083	1253277	28
5	329323	1254980	45
6	330109	1253785	46
8	330144	1254768	38
9	331202	1254504	52
10	341797	1270719	38
11	330294	1255638	51
12	329148	1256467	56
13	329559	1267613	61
14	329556	1257592	22
15	340721	1267931	61
16	332162	1255687	54
17	331684	1256299	32
18	331511	1256531	49
19	342627	1273944	94
20	332724	1256132	53
21	332537	1257060	34
22	331569	1257674	51
23	341642	1274523	79
24	333641	1258008	40
25	339943	1266518	49
26	338147	1265451	49
27	334727	1257994	54
28	335146	1258312	43
29	334112	1258868	26
30	334016	1259249	41
31	333149	1259824	27
32	332624	1260170	20
33	331185	1261191	40
34	336134	1259116	55
35	337468	1266016	54
36	333124	1261186	41
37	332712	1262163	17
38	333286	1262223	79
39	341277	1267910	35
40	337535	1259165	82
41	337657	1259576	92
42	336889	1259662	67
43	334659	1262344	80
44	334216	1264629	15
45	338900	1260219	86
46	338725	1260658	81
47	338259	1260655	90
48	337449	1261146	75
49	322778	1259750	77
50	323360	1260686	33
51	336852	1262523	93
52	335881	1265571	83
53	336572	1265636	84
54	337101	1265323	65
55	337261	1265182	79

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56	323134	1262461	113
57	324825	1263837	71
58	339734	1263395	90
59	340443	1263489	98
60	340946	1263499	128
61	340980	1263963	139
62	341594	1263183	122
63	341636	1263895	125
64	341479	1264911	121
65	341159	1265016	126
66	340840	1264949	111
67	341558	1265532	130
68	341580	1265883	102
69	341183	1265533	124
70	341198	1265908	98
71	338048	1266400	39
72	338909	1267141	30
73	340708	1267192	56
74	338111	1268574	39
75	338779	1269033	45
76	341751	1270331	47
77	340821	1270894	41
78	339836	1270495	50
79	340394	1272576	30
80	342762	1272688	77
81	342716	1273602	86
82	341107	1275309	124
83	339956	1274366	76
84	332893	1274640	54
85	329709	1272368	138
86	328935	1272904	133
87	327593	1275667	147
88	326691	1275577	153
89	325326	1275513	153
90	325695	1271581	117
91	325547	1270785	105
92	330959	1268580	62
93	327075	1268650	140
94	325507	1267376	151
95	330695	1266774	59
96	329176	1266220	65
97	328291	1265734	69
98	330083	1264804	10
99	326757	1262334	12

Table A.2: GPS point values for the high-relief study site, coordinates in UTM meters (NAD27-Zone 17).

PT #	UTM Northing	UTM Easting	Elevation
1	4121169	550871	630
2	4121647	551213	642
3	4121390	550673	636
4	4121681	550264	632
5	4121193	550181	626
6	4120744	550508	628
7	4118371	548612	619
8	4119150	548809	626
9	4118716	549756	602
10	4119561	549437	624
11	4119665	550613	610
12	4118899	551433	618
13	4120840	549631	636
14	4120831	549379	630
15	4121035	549252	625
16	4121033	548920	614
17	4121345	548780	611
18	4120911	548951	626
19	4120761	548032	607
20	4121046	548219	609
21	4121083	547999	609
22	4121313	547484	602
23	4121474	546860	575
24	4122074	548139	575
25	4122186	548220	586
26	4122653	548866	586
27	4123248	548930	585
28	4123534	549349	592
29	4123870	549092	615
30	4124509	548618	731
31	4124670	548610	737
32	4124929	548667	755
33	4124964	548657	753
34	4125007	548613	761
35	4123010	549667	599
36	4122461	550140	609
37	4122959	551502	663
38	4121415	551002	634
39	4121453	549096	613
40	4121375	549186	615
41	4118924	547420	611
42	4119822	546057	598
43	4119444	546559	612
44	4119027	546907	608
45	4118197	545380	606
46	4118711	544944	619
47	4120064	544667	562
48	4120364	545030	580
49	4120312	544727	580
50	4120409	544099	571
51	4120513	543812	562
52	4119702	544641	605
53	4120385	542975	555
54	4120370	543063	551

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55	4120228	543141	592
56	4119796	543011	587
57	4118324	543746	606
58	4117961	543949	605
59	4125927	549473	757
60	4126504	547728	675
61	4126621	545642	712
62	4126644	545490	704
63	4126714	545013	665
64	4126920	544384	625
65	4126334	543132	644
66	4126068	542664	672
67	4126387	546208	740
68	4126427	546675	710
69	4126488	547209	680
70	4124004	547241	860
71	4125751	548970	800
72	4125996	549373	752
73	4125888	549473	751
74	4127149	550355	795
80	4122767	549909	596
81	4125733	550302	704
82	4126450	548134	681
83	4124074	545029	628
84	4124344	546621	705
85	4125209	546015	641
86	4125093	545541	667
87	4125196	545547	674
89	4125673	549627	742
90	4125456	550325	675
92	4124002	542525	684
93	4123955	542549	679
94	4123998	542626	676
95	4124341	543497	679
96	4126384	549656	810

Table A.3: Photogrammetric survey point coordinates from the low-relief study site, coordinates in Maryland Stateplane feet (NAD83-Zone 1900).

PT #	SPC Northing	SPC Easting
1	327730	1253482
2	328006	1253101
3	329080	1253269
5	329320	1254976
6	330095	1253768
8	330140	1254766
9	331201	1254517
11	330297	1255614
12	329151	1256466
14	329550	1257580
16	332154	1255683
17	331679	1256297
18	331498	1256530
20	332729	1256132
21	332537	1257059
22	331544	1257675
24	333643	1258007
27	334722	1257987
28	335147	1258313
29	334111	1258865
30	334011	1259279
31	333151	1259837
32	332624	1260174
33	331176	1261176
34	336151	1259108
36	333125	1261172
37	332726	1262183
38	333288	1262225
40	337529	1259161
41	337652	1259567
42	336905	1259654
43	334635	1262341
44	334215	1264622
45	338899	1260221
46	338713	1260652
47	338262	1260650
48	337449	1261135
51	336849	1262512
52	335878	1265574
53	336567	1265617
54	337099	1265332
55	337267	1265188
58	339727	1263380
59	340446	1263495
60	340941	1263499
61	340968	1263935
62	341593	1263171
63	341638	1263896
64	341477	1264908

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65	341157	1265012
66	340836	1264946
67	341547	1265512
68	341560	1265886
69	341181	1265525
70	341199	1265902

APPENDIX B:

AVERAGE ACCURACY RESULTS FOR THE FIVE DIGITIZED DATA SETS

Table B.1: Average positional accuracy results for the five space resection data sets from the low-relief study site, results in meters.

Data Set #	Mean	Maximum	Minimum	Standard Deviation
1	5.53	18.91	0.50	3.89
2	5.76	17.88	0.70	3.77
3	5.87	19.51	0.77	3.71
4	5.58	20.56	0.13	3.83
5	5.47	22.09	0.41	3.80

Table B.2: Average positional accuracy results for the five uncorrected digitized photo data sets from the low-relief study site, results in meters.

Data Set #	Mean	Maximum	Minimum	Standard Deviation
1	7.21	21.02	1.23	4.12
2	6.87	19.79	1.49	3.98
3	6.82	21.80	0.53	3.89
4	6.70	19.45	1.11	3.95
5	6.92	20.27	0.60	4.01

Table B.3: Average positional accuracy results for the five digitized topographic map data sets from the low-relief study site, results in meters.

Data Set #	Mean	Maximum	Minimum	Standard Deviation
1	11.71	40.95	0.82	6.42
2	11.64	39.08	0.43	6.50
3	11.72	40.52	1.02	6.63
4	11.87	39.48	1.05	6.58
5	11.28	43.19	0.65	6.79

Table B.4: Average positional accuracy results for the five space resection data sets from the high-relief study site, results in meters.

Data Set #	Mean	Maximum	Minimum	Standard Deviation
1	6.12	15.97	0.92	3.47
2	6.53	17.66	1.63	3.59
3	6.16	16.91	0.09	3.52
4	6.37	16.18	0.68	3.55
5	6.20	14.90	0.33	3.44

Table B.5: Average positional accuracy results for the five uncorrected digitized photo data sets from the high-relief study site, results in meters.

Data Set #	Mean	Maximum	Minimum	Standard Deviation
1	25.53	89.97	5.76	18.28
2	25.80	89.23	5.93	18.86
3	26.05	91.44	6.41	19.09
4	25.89	90.70	4.27	19.01
5	26.06	90.84	4.72	19.14

Table B.6: Average positional accuracy results for the five digitized topographic map data sets from the high-relief study site, results in meters.

Data Set #	Mean	Maximum	Minimum	Standard Deviation
1	11.31	65.24	1.32	10.95
2	11.32	66.40	0.47	10.88
3	11.39	66.61	0.93	10.75
4	11.10	67.60	1.26	10.54
5	10.90	63.92	1.99	10.52

APPENDIX C:

TRANSFORMATION RESIDUALS

HIGH-RELIEF STUDY SITE:

Table C.1: Affine transformation residuals for the Blacksburg topographic quad 1st data set with RMS error = 2.11 m, residuals in meters.

Control point #	X-Residual Error	Y-Residual Error
1	-2.00	-0.85
2	-0.45	2.64
3	-1.27	-0.48
4	0.31	2.01
5	3.22	-0.26
6	-0.84	-1.77
7	1.03	-1.40
8	-1.17	0.11

Table C.2: Affine transformation residuals for the Blacksburg topographic quad 2nd data set with RMS error = 2.21 m, residuals in meters.

Control point #	X-Residual Error	Y-Residual Error
1	-1.43	-2.17
2	2.71	2.32
3	-1.56	-1.73
4	2.70	1.87
5	-0.93	0.74
6	-0.45	-0.88
7	-0.56	-0.58
8	-0.46	0.44

Table C.3: Affine transformation residuals for the Blacksburg topographic quad 3rd data set with RMS error = 2.33 m, residuals in meters.

Control point #	X-Residual Error	Y-Residual Error
1	-2.29	-0.25
2	0.76	3.23
3	-2.41	-0.72
4	0.46	2.24
5	0.70	-1.22
6	0.42	-3.22
7	1.03	0.18
8	1.30	-0.23

Table C.4: Affine transformation residuals for the Blacksburg topographic quad 4th data set with RMS error = 1.89 m, residuals in meters.

Control point #	X-Residual Error	Y-Residual Error
1	-1.74	-1.62
2	0.75	2.11
3	-1.87	-1.24
4	0.39	0.69
5	0.59	0.27
6	-0.08	-1.81
7	-0.96	-0.86
8	0.98	2.45

Table C.5: Affine transformation residuals for the Blacksburg topographic quad 5th data set with RMS error = 2.72 m, residuals in meters.

Control point #	X-Residual Error	Y-Residual Error
1	-3.39	0.08
2	0.84	2.55
3	-3.33	-0.20
4	-0.43	2.25
5	1.54	-1.31
6	-0.18	-1.90
7	1.32	-0.45
8	3.64	-1.02

Table C.6: Affine transformation residuals for the Eggleston topographic quad 1st data set with RMS error = 2.99 m, residuals in meters.

Control point #	X-Residual Error	Y-Residual Error
1	-4.19	-1.04
2	0.58	0.16
3	-2.86	-1.12
4	2.57	0.59
5	4.07	0.10
6	2.88	1.14
7	0.06	0.30
8	-3.11	-0.14

Table C.7: Affine transformation residuals for the Eggleston topographic quad 2nd data set with RMS error = 2.98 m, residuals in meters.

Control point #	X-Residual Error	Y-Residual Error
1	-3.54	-1.59
2	0.95	3.45
3	-3.55	-1.32
4	2.11	2.91
5	1.48	-0.28
6	2.27	-1.83
7	1.49	-1.13
8	-1.22	-0.19

Table C.8: Affine transformation residuals for the Eggleston topographic quad 3rd data set with RMS error = 3.29 m, residuals in meters.

Control point #	X-Residual Error	Y-Residual Error
1	-2.84	0.58
2	-0.15	2.21
3	-2.37	1.00
4	2.78	0.87
5	0.79	-0.87
6	5.65	-2.85
7	-0.65	-2.12
8	-3.21	1.18

Table C.9: Affine transformation residuals for the Eggleston topographic quad 4th data set with RMS error = 3.04 m, residuals in meters.

Control point #	X-Residual Error	Y-Residual Error
1	-4.01	0.26
2	0.26	2.12
3	-2.68	0.80
4	2.08	2.08
5	3.12	-0.95
6	3.79	-0.92
7	-0.88	-2.61
8	-1.68	-0.78

Table C.10: Affine transformation residuals for the Eggleston topographic quad 5th data set with RMS error = 2.64 m, residuals in meters.

Control point #	X-Residual Error	Y-Residual Error
1	-3.21	-0.66
2	1.30	2.72
3	-1.94	-0.18
4	1.96	3.14
5	2.26	-0.53
6	1.59	-0.61
7	-1.56	-1.99
8	-0.39	-1.87

Table C.11: Affine transformation residuals for the Radford North topographic quad 1st data set with RMS error = 2.39 m, residuals in meters.

Control point #	X-Residual Error	Y-Residual Error
1	0.61	0.45
2	-3.15	-0.85
3	-0.53	1.64
4	-2.93	-0.42
5	-0.51	1.72
6	1.67	0.28
7	3.39	-1.83
8	1.00	-1.00

Table C.12: Affine transformation residuals for the Radford North topographic quad 2nd data set with RMS error = 2.30 m, residuals in meters.

Control point #	X-Residual Error	Y-Residual Error
1	1.69	-1.27
2	-2.84	-1.96
3	1.20	-0.89
4	-2.57	-1.53
5	0.24	2.44
6	0.48	1.61
7	1.72	1.30
8	0.23	0.30

Table C.13: Affine transformation residuals for the Radford North topographic quad 3rd data set with RMS error = 2.52 m, residuals in meters.

Control point #	X-Residual Error	Y-Residual Error
1	1.06	1.52
2	-3.72	-1.92
3	0.84	0.68
4	-3.38	-2.03
5	0.82	-1.44
6	1.93	0.89
7	1.50	1.08
8	0.93	1.22

Table C.14: Affine transformation residuals for the Radford North topographic quad 4th data set with RMS error = 3.17 m, residuals in meters.

Control point #	X-Residual Error	Y-Residual Error
1	1.55	-0.15
2	-4.17	-2.90
3	0.58	-1.06
4	-4.02	-2.16
5	-0.23	0.05
6	2.03	2.83
7	2.67	2.77
8	1.59	0.61

Table C.15: Affine transformation residuals for the Radford North topographic quad 5th data set with RMS error = 3.27 m, residuals in meters.

Control point #	X-Residual Error	Y-Residual Error
1	2.62	0.68
2	-4.88	-2.77
3	1.46	0.38
4	-4.37	-1.84
5	-0.43	0.89
6	2.04	1.82
7	3.03	1.79
8	0.52	-0.95

Table C.16: Affine transformation residuals for the Newport topographic quad 1st data set with RMS error = 3.23 m, residuals in meters.

Control point #	X-Residual Error	Y-Residual Error
1	-1.30	4.92
2	-1.23	-1.38
3	-0.97	2.68
4	-1.20	-1.99
5	2.19	-5.48
6	0.70	-0.93
7	1.22	1.23
8	0.59	0.95

Table C.17: Affine transformation residuals for the Newport topographic quad 2nd data set with RMS error = 1.40 m, residuals in meters.

Control point #	X-Residual Error	Y-Residual Error
1	-0.31	-1.45
2	0.24	1.22
3	0.11	-0.93
4	-0.12	2.05
5	1.04	0.86
6	-0.90	0.71
7	-0.27	-0.70
8	0.21	-1.75

Table C.18: Affine transformation residuals for the Newport topographic quad 3rd data set with RMS error = 2.28 m, residuals in meters.

Control point #	X-Residual Error	Y-Residual Error
1	-2.74	1.76
2	-0.69	0.12
3	-2.16	1.54
4	-1.17	0.64
5	3.24	-1.03
6	0.31	-0.54
7	1.49	-0.39
8	1.71	-2.11

Table C.19: Affine transformation residuals for the Newport topographic quad 4th data set with RMS error = 1.39 m, residuals in meters.

Control point #	X-Residual Error	Y-Residual Error
1	-1.39	0.38
2	-0.46	0.92
3	-0.87	0.35
4	-0.08	1.58
5	1.70	-0.56
6	1.05	-0.11
7	0.14	-0.47
8	-0.08	-2.11

Table C.20: Affine transformation residuals for the Newport topographic quad 5th data set with RMS error = 1.90 m, residuals in meters.

Control point #	X-Residual Error	Y-Residual Error
1	-2.68	1.79
2	0.97	-1.64
3	-2.11	1.50
4	0.88	-1.12
5	1.36	-1.03
6	0.83	1.02
7	-0.35	-0.17
8	1.09	-0.39

Table C.21: Affine transformation residuals for the uncorrected digitized photo 1st data set, residuals in meters.

Control Point #	X-Residual Error	Y-Residual Error
2	19.74	-9.02
8	-12.36	-4.00
10	-11.59	-2.56
20	-10.55	-11.19
21	-19.66	-5.70
26	-22.64	-14.29
28	-21.39	-18.81
34	27.44	34.59
38	19.24	-8.21
44	-18.98	10.30
50	19.42	7.57
52	-13.47	5.65
53	41.48	12.51
54	43.71	12.07
57	0.38	17.83
59	50.83	45.78
61	-21.12	8.82
68	-6.24	2.96
69	6.29	-6.54
80	-13.36	-9.43
84	-8.35	-10.74
92	-29.54	-28.34
95	-19.28	-29.22

Table C.22: Affine transformation residuals for the uncorrected digitized photo 2nd data set, residuals in meters.

Control Point #	X-Residual Error	Y-Residual Error
2	21.32	-7.75
8	-11.50	-3.13
10	-8.22	-1.35
20	-13.15	-12.21
21	-21.25	-2.93
26	-21.34	-15.82
28	-22.64	-17.01
34	29.90	34.74
38	16.39	-11.03
44	-22.33	7.01
50	22.74	6.06
52	-14.24	7.84
53	40.60	12.96
54	44.77	11.62
57	2.36	15.66
59	58.26	40.97
61	-23.38	6.57
68	-3.44	3.82
69	1.19	-6.52
80	-16.76	-6.57
84	-10.33	-6.97
92	-28.22	-27.90
95	-20.72	-28.05

Table C.23: Affine transformation residuals for the uncorrected digitized photo 3rd data set, residuals in meters.

Control Point #	X-Residual Error	Y-Residual Error
2	21.80	-5.14
8	-13.82	-4.30
10	-10.31	-4.14
20	-15.01	-11.56
21	-20.93	-3.18
26	-21.28	-18.73
28	-22.96	-19.63
34	30.54	34.81
38	18.43	-8.23
44	-17.27	8.13
50	23.45	7.80
52	-12.27	7.90
53	39.69	13.94
54	42.37	10.89
57	1.70	14.45
59	56.56	42.02
61	-22.52	6.05
68	-3.45	3.88
69	2.41	-7.19
80	-16.12	-5.63
84	-13.57	-8.16
92	-28.69	-27.61
95	-18.72	-26.53

Table C.24: Affine transformation residuals for the uncorrected digitized photo 4th data set, residuals in meters.

Control Point #	X-Residual Error	Y-Residual Error
2	17.58	-5.82
8	-10.48	-3.78
10	-5.28	-2.94
20	-14.39	-11.52
21	-19.63	-2.36
26	-20.01	-15.32
28	-22.60	-16.65
34	31.44	32.01
38	14.58	-9.78
44	-21.69	7.42
50	22.27	9.08
52	-10.98	6.50
53	40.30	13.23
54	43.96	9.92
57	0.29	14.54
59	58.08	41.16
61	-19.34	7.28
68	-3.05	2.54
69	1.21	-6.22
80	-14.42	-7.15
84	-18.81	-8.87
92	-28.63	-27.62
95	-20.39	-25.64

Table C.25: Affine transformation residuals for the uncorrected digitized photo 5th data set, residuals in meters.

Control Point #	X-Residual Error	Y-Residual Error
2	18.33	-6.38
8	-15.27	-3.11
10	-6.43	-4.75
20	-15.08	-13.95
21	-20.63	-3.22
26	-21.60	-15.06
28	-22.85	-18.35
34	30.01	35.25
38	17.25	-9.17
44	-19.44	8.85
50	20.70	7.83
52	-8.04	8.33
53	41.88	13.84
54	43.34	11.02
57	0.72	12.57
59	58.29	39.46
61	-22.33	4.99
68	-2.71	4.18
69	2.88	-7.65
80	-14.12	-4.14
84	-13.51	-6.70
92	-29.62	-26.01
95	-21.76	-27.82

Table C.26: Ground transformation residuals for the space resection 1st data set, residuals in meters.

Control Point #	X-Residual Error	Y-Residual Error	Residual Error Distance
2	2.14	0.44	2.19
8	1.02	-1.48	1.80
10	2.18	2.34	3.20
20	3.88	-4.97	6.31
21	-6.75	-1.58	6.94
26	-0.71	-2.97	3.05
28	-6.57	1.53	6.75
34	-2.28	1.12	2.54
38	4.31	-3.13	5.33
44	-3.51	2.20	4.14
50	8.24	0.23	8.24
52	-2.95	4.24	5.17
53	-3.68	-0.35	3.70
54	0.96	-2.99	3.14
57	4.73	-1.81	5.07
59	1.79	-7.18	7.40
61	-6.18	3.47	7.09
68	2.39	-2.87	3.74
69	2.02	-0.05	2.02
80	-0.71	7.70	7.74
84	-1.18	-1.78	2.13
92	-2.43	4.48	5.09
95	3.28	3.42	4.75

Table C.27: Ground transformation residuals for the space resection 2nd data set, residuals in meters.

Control Point #	X-Residual Error	Y-Residual Error	Residual Error Distance
2	1.98	2.97	3.51
8	1.12	2.91	3.12
10	2.97	4.13	5.09
20	2.22	-7.38	7.71
21	-2.56	1.09	2.79
26	-1.96	-2.78	3.40
28	-6.37	0.71	6.41
34	-2.53	3.02	3.95
38	7.64	-1.98	7.90
44	-3.33	4.62	5.69
50	4.01	-2.67	4.82
52	-7.68	4.97	9.15
53	-2.54	-0.63	2.61
54	-1.00	-5.06	5.16
57	2.43	2.48	3.47
59	5.14	-7.25	8.89
61	-7.73	2.11	8.02
68	0.71	-4.79	4.85
69	6.04	-1.53	6.23
80	1.05	3.35	3.51
84	-0.33	-1.39	1.43
92	-1.56	2.43	2.89
95	2.28	0.66	2.37

Table C.28: Ground transformation residuals for the space resection 3rd data set, residuals in meters.

Control Point #	X-Residual Error	Y-Residual Error	Residual Error Distance
2	1.19	2.22	2.52
8	0.10	0.72	0.73
10	1.08	2.28	2.53
20	2.11	-6.17	6.52
21	-4.56	0.70	4.61
26	-3.27	-2.88	4.36
28	-6.94	1.87	7.19
34	-2.10	1.07	2.36
38	7.34	-2.06	7.63
44	-0.80	1.74	1.92
50	4.16	-0.24	4.16
52	-4.56	4.60	6.48
53	-2.13	0.45	2.18
54	-0.28	-4.30	4.31
57	4.50	-1.07	4.62
59	5.46	-7.68	9.43
61	-5.77	3.96	7.00
68	0.78	-4.95	5.01
69	-0.62	0.46	0.78
80	0.44	4.01	4.03
84	1.98	-0.57	2.06
92	-2.07	4.63	5.07
95	3.95	1.19	4.13

Table C.29: Ground transformation residuals for the space resection 4th data set, residuals in meters.

Control Point #	X-Residual Error	Y-Residual Error	Residual Error Distance
2	2.67	1.03	2.86
8	0.20	0.24	0.31
10	5.18	3.52	6.27
20	3.21	-8.76	9.30
21	-4.52	1.20	4.68
26	-2.85	-2.12	3.55
28	-10.49	2.68	10.83
34	-3.11	3.04	4.35
38	6.15	-2.29	6.57
44	-4.58	2.92	5.43
50	6.30	-1.21	6.41
52	-5.79	5.41	7.92
53	-4.12	-0.65	4.17
54	1.41	-4.93	5.13
57	5.24	0.43	5.26
59	4.45	-9.56	10.54
61	-2.29	2.84	5.39
68	2.71	-1.74	3.22
69	0.10	0.65	0.66
80	0.02	4.18	4.18
84	0.22	-1.64	1.65
92	-3.45	3.74	5.09
95	3.32	0.98	3.47

Table C.30: Ground transformation residuals for the space resection 5th data set, residuals in meters.

Control Point #	X-Residual Error	Y-Residual Error	Residual Error Distance
2	2.83	1.95	3.43
8	-0.06	-0.14	0.16
10	1.14	3.55	3.73
20	1.09	-6.78	6.87
21	-5.00	1.07	5.11
26	-2.08	-2.04	2.99
28	-7.02	1.01	7.09
34	-1.11	1.02	1.51
38	5.81	-1.08	5.91
44	-2.35	1.78	2.95
50	7.69	-1.29	7.80
52	-7.06	3.12	7.72
53	-1.16	2.08	2.39
54	-0.15	-3.63	3.63
57	5.31	-3.36	3.28
59	4.06	-6.72	7.85
61	-2.77	2.64	3.83
68	4.67	-1.36	4.87
69	-0.10	0.65	0.66
80	-1.34	5.20	5.37
84	-2.91	-2.89	4.11
92	-1.80	4.79	5.11
95	2.33	4.42	2.37

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Table C.31: Affine transformation residuals for the Indian Head topographic quad 1st data set, residuals in feet.

Control Point #	X-Residual Error	Y-Residual Error
1	2.63	1.14
2	-2.85	-0.02
3	7.15	1.52
4	0.76	0.31
5	3.08	-0.64
6	5.26	0.23
7	-10.46	-1.77
8	-5.58	-0.78

Table C.32: Affine transformation residuals for the Indian Head topographic quad 2nd data set, residuals in feet.

Control Point #	X-Residual Error	Y-Residual Error
1	2.60	1.10
2	-2.88	-0.03
3	7.17	1.42
4	0.72	0.32
5	3.09	-0.65
6	5.22	0.25
7	-9.95	-1.79
8	-5.60	-0.80

Table C.33: Affine transformation residuals for the Indian Head topographic quad 3rd data set, residuals in feet.

Control Point #	X-Residual Error	Y-Residual Error
1	4.58	0.74
2	-2.28	1.98
3	5.09	-0.83
4	-3.88	4.16
5	3.12	-2.87
6	-6.53	0.76
7	1.62	1.83
8	-1.71	-5.78

Table C.34: Affine transformation residuals for the Indian Head topographic quad 4th data set, residuals in feet.

Control Point #	X-Residual Error	Y-Residual Error
1	0.61	1.63
2	0.85	1.49
3	2.53	-2.34
4	0.43	4.28
5	1.00	-4.73
6	-0.96	0.41
7	-4.76	7.16
8	0.27	-7.92

Table C.35: Affine transformation residuals for the Indian Head topographic quad 5th data set, residuals in feet.

Control Point #	X-Residual Error	Y-Residual Error
1	-0.37	9.53
2	-5.45	-1.04
3	2.36	6.18
4	-4.27	1.35
5	7.78	-8.54
6	1.96	-0.91
7	-0.42	1.51
8	-1.58	-8.08

Table C.36: Affine transformation residuals for the uncorrected digitized photo 1st data set, residuals in feet.

Control Point #	X-Residual Error	Y-Residual Error
3	27.29	12.64
10	-9.35	-0.86
14	-1.29	6.24
15	0.11	-15.92
21	13.01	-1.96
24	10.42	-24.17
28	16.21	-21.46
33	-14.61	-2.55
34	9.32	4.35
37	36.50	14.40
40	-15.58	-16.29
48	-9.32	2.14
49	-44.66	24.88
58	4.36	11.15
62	-25.01	1.14
67	-31.27	3.64
69	-0.01	5.78
79	-2.37	3.50
81	28.04	22.82
84	-0.35	-3.10
87	15.50	-8.98
93	-6.93	-17.38

Table C.37: Affine transformation residuals for the uncorrected digitized photo 2nd data set, residuals in feet.

Control Point #	X-Residual Error	Y-Residual Error
3	26.62	13.25
10	-8.83	1.49
14	-5.96	-6.10
15	-8.92	-8.46
21	13.27	-3.74
24	9.80	-9.28
28	18.38	-26.11
33	-9.15	-7.51
34	10.34	5.54
37	31.54	11.83
40	-14.08	-22.04
48	-18.31	8.26
49	-34.67	28.46
58	6.02	5.62
62	-22.28	7.39
67	-28.07	0.28
69	-5.28	8.97
79	-5.89	6.50
81	44.20	12.11
84	-1.17	-4.96
87	9.68	-8.83
93	-7.21	-12.69

Table C.38: Affine transformation residuals for the uncorrected digitized photo 3rd data set, residuals in feet.

Control Point #	X-Residual Error	Y-Residual Error
3	35.07	14.81
10	-7.11	4.28
14	-4.63	2.14
15	-3.65	-12.15
21	2.35	-6.94
24	5.11	-7.50
28	18.42	-20.57
33	-1.33	-8.17
34	1.75	1.74
37	33.98	17.33
40	-14.72	-21.71
48	-9.54	2.38
49	-34.83	21.38
58	-1.57	7.98
62	-26.39	7.14
67	-26.11	-4.90
69	-2.27	10.56
79	3.96	2.77
81	37.46	14.13
84	-4.90	-0.82
87	8.25	-6.67
93	-9.28	-17.20

Table C.39: Affine transformation residuals for the uncorrected digitized photo 4th data set, residuals in feet.

Control Point #	X-Residual Error	Y-Residual Error
3	24.77	12.85
10	-6.38	1.99
14	-1.24	4.76
15	-4.89	-9.61
21	8.65	-7.51
24	7.07	-17.64
28	19.71	-25.15
33	-3.71	-7.64
34	6.47	2.03
37	34.72	15.18
40	-9.33	-11.71
48	-19.57	2.09
49	-38.83	24.75
58	4.82	4.29
62	-23.20	8.29
67	-28.93	4.38
69	-3.67	9.74
79	1.58	-1.62
81	32.67	13.24
84	-6.10	-0.21
87	13.20	-7.88
93	-7.79	-14.60

Table C.40: Affine transformation residuals for the uncorrected digitized photo 5th data set, residuals in feet.

Control Point #	X-Residual Error	Y-Residual Error
3	39.99	13.57
10	-10.97	5.60
14	-6.30	5.75
15	-8.10	-13.94
21	5.04	-9.61
24	8.08	-13.74
28	13.61	-22.66
33	-14.67	-3.83
34	9.94	0.03
37	32.20	17.71
40	-11.90	-17.89
48	-21.88	-1.22
49	-36.23	22.06
58	9.11	8.04
62	-21.18	10.14
67	-24.52	1.02
69	1.24	6.25
79	-1.27	6.00
81	34.38	13.77
84	0.14	-7.52
87	18.08	-9.10
93	-14.77	-10.45

Table C.41: Ground transformation residuals for the space resection 1st data set, residuals in feet.

Control Point #	X-Residual Error	Y-Residual Error	Residual Error Distance
3	3.70	4.51	5.83
10	-7.03	5.15	8.72
14	-3.23	-5.77	6.61
15	1.95	-8.34	8.57
21	1.15	1.46	1.86
24	10.49	-18.92	21.63
28	22.50	-9.76	24.53
33	-10.71	-13.57	17.29
34	10.84	13.20	17.17
37	37.51	14.51	40.22
40	-9.85	-5.26	11.17
48	-11.92	9.53	15.26
49	-27.10	4.34	27.44
58	6.08	11.09	12.65
62	-9.64	5.14	10.93
67	-22.77	-4.41	23.20
69	1.13	6.43	6.53
79	-1.81	3.31	3.77
81	13.54	1.16	13.59
84	-5.90	-13.74	14.96
87	-7.28	20.99	22.22
93	8.36	-21.18	22.77

Table C.42: Ground transformation residuals for the space resection 2nd data set, residuals in feet.

Control Point #	X-Residual Error	Y-Residual Error	Residual Error Distance
3	8.09	2.71	2.60
10	-10.61	3.89	3.44
14	-8.25	-4.82	2.91
15	2.54	-6.58	2.15
21	-6.06	2.87	2.04
24	3.02	-12.62	3.95
28	15.35	-14.66	6.46
33	-6.49	-12.58	4.31
34	6.31	9.23	3.40
37	36.29	19.66	12.58
40	-7.12	-6.40	2.91
48	-1.91	12.99	4.00
49	-30.31	10.05	9.73
58	9.15	8.19	3.74
62	-11.02	2.39	3.43
67	-22.23	-12.54	7.78
69	2.22	0.13	0.68
79	4.65	8.69	3.00
81	9.05	-0.62	2.76
84	2.44	-13.46	4.17
87	-4.07	24.91	7.69
93	8.96	-21.48	7.09

Table C.43: Ground transformation residuals for the space resection 3rd data set, residuals in feet.

Control Point #	X-Residual Error	Y-Residual Error	Residual Error Distance
3	2.39	-0.94	2.57
10	-12.08	-0.65	12.09
14	-7.47	-1.54	7.63
15	-1.44	-12.91	12.99
21	-4.44	1.86	4.81
24	5.26	-5.41	7.55
28	13.75	-8.96	16.42
33	-12.55	-13.91	18.74
34	5.13	10.95	12.09
37	40.30	22.71	46.26
40	-14.79	-7.01	13.36
48	-0.03	9.83	9.83
49	-26.55	15.27	30.63
58	12.45	1.31	12.52
62	-4.85	-2.16	5.32
67	-18.79	-4.76	19.38
69	-5.89	0.50	5.91
79	2.26	2.16	3.13
81	10.09	5.46	11.48
84	7.85	-8.65	11.68
87	-4.34	25.01	25.38
93	13.75	-28.14	31.32

Table C.44: Ground transformation residuals for the space resection 4th data set, residuals in feet.

Control Point #	X-Residual Error	Y-Residual Error	Residual Error Distance
3	3.86	-3.90	5.49
10	-6.76	0.62	6.79
14	-10.80	-3.63	11.40
15	4.75	-14.68	15.43
21	-7.53	0.34	7.54
24	11.90	-6.49	13.56
28	16.14	-14.74	21.86
33	-8.04	-2.11	8.31
34	8.76	11.96	14.82
37	37.26	22.65	43.61
40	-10.12	-5.91	11.72
48	-0.63	4.68	4.72
49	-22.22	8.44	23.77
58	7.35	7.86	10.76
62	-9.62	0.69	9.64
67	-21.54	-5.13	22.14
69	-4.58	0.22	4.59
79	2.64	-1.70	3.14
81	11.90	10.14	15.64
84	3.48	-3.48	4.92
87	-5.27	20.74	21.39
93	-0.90	-26.59	26.60

Table C.45: Ground transformation residuals for the space resection 5th data set, residuals in feet.

Control Point #	X-Residual Error	Y-Residual Error	Residual Error Distance
3	1.69	9.37	9.52
10	-13.98	4.09	14.57
14	-4.42	-7.03	8.30
15	0.32	-7.60	7.61
21	1.60	0.01	1.60
24	5.63	-13.55	14.67
28	17.28	-15.80	23.42
33	-18.47	-14.42	23.43
34	14.51	12.03	18.85
37	29.48	9.06	30.84
40	-9.36	0.49	9.37
48	1.92	10.57	10.74
49	-23.51	7.84	24.78
58	6.01	11.59	13.05
62	-11.09	4.48	11.96
67	-16.16	-9.71	18.85
69	-2.05	0.74	2.18
79	1.34	3.97	4.19
81	13.38	1.36	13.45
84	1.48	-8.76	9.84
87	-8.48	24.79	26.21
93	9.87	-23.52	25.51

Table C.46: Affine transformation residuals using the photogrammetric survey as ground control for the uncorrected digitized photo 1st data set, residuals in feet.

Control Point #	X-Residual Error	Y-Residual Error
3	11.74	24.57
14	-7.43	10.49
21	-0.47	1.42
24	-1.79	-23.34
28	4.98	-18.79
33	-11.87	-2.74
34	8.11	-9.26
37	7.09	-8.60
40	-19.25	-4.96
48	-3.79	1.85
58	18.98	15.33
62	-11.65	2.30
67	-6.27	9.50
69	11.62	2.23

Table C.47: Affine transformation residuals using the photogrammetric survey as ground control for the uncorrected digitized photo 2nd data set, residuals in feet.

Control Point #	X-Residual Error	Y-Residual Error
3	11.50	25.84
14	-10.79	1.94
21	0.28	0.35
24	-1.95	-7.92
28	7.32	-24.03
33	-4.64	-2.38
34	9.25	-8.90
37	3.76	-6.38
40	-17.96	-12.77
48	-12.52	7.65
58	20.89	9.27
62	-9.15	6.17
67	-2.74	5.74
69	6.75	5.40

Table C.48: Affine transformation residuals using the photogrammetric survey as ground control for the uncorrected digitized photo 3rd data set, residuals in feet.

Control Point #	X-Residual Error	Y-Residual Error
3	20.80	25.28
14	-12.26	6.89
21	-10.21	-4.14
24	-6.10	-7.12
28	8.99	-18.67
33	-1.55	-6.63
34	2.45	-12.53
37	1.94	-3.86
40	-15.55	-11.46
48	-2.64	2.00
58	14.34	12.50
62	-10.26	8.00
67	-0.07	1.76
69	10.13	7.98

Table C.49: Affine transformation residuals using the photogrammetric survey as ground control for the uncorrected digitized photo 4th data set, residuals in feet.

Control Point #	X-Residual Error	Y-Residual Error
3	10.85	25.96
14	-8.04	11.52
21	-3.98	-3.48
24	-4.37	-16.43
28	9.68	-22.87
33	-3.06	-4.92
34	6.41	-12.24
37	3.27	-5.37
40	-11.29	-1.83
48	-13.52	1.17
58	19.59	7.35
62	-8.77	7.20
67	-4.24	8.88
69	7.48	5.07

Table C.50: Affine transformation residuals using the photogrammetric survey as ground control for the uncorrected digitized photo 5th data set, residuals in feet.

Control Point #	X-Residual Error	Y-Residual Error
3	24.44	26.16
14	-10.06	10.34
21	-8.36	-5.82
24	-4.17	-12.58
28	1.55	-19.71
33	-8.35	-3.99
34	7.73	-13.39
37	6.00	-5.34
40	-17.48	-6.37
48	-16.98	-1.44
58	23.05	12.06
62	-9.88	11.19
67	-0.06	6.53
69	12.59	2.39

Table C.51: Ground transformation residuals using the photogrammetric survey as control for the space resection 1st data set, residuals in feet.

Control Point #	X-Residual Error	Y-Residual Error	Residual Error Distance
3	-3.92	9.05	9.86
14	-2.98	3.20	4.37
21	-7.02	3.34	7.77
24	3.29	-19.07	14.35
28	14.67	-10.19	17.86
33	-6.55	-1.57	6.73
34	11.92	-3.56	12.44
37	7.45	3.38	8.19
40	-11.80	-0.25	11.80
48	-7.58	7.60	10.74
58	14.70	12.57	19.36
62	-2.62	-2.26	3.46
67	-10.25	-2.41	10.53
69	0.71	0.18	0.73

Table C.52: Ground transformation residuals using the photogrammetric survey as control for the space resection 2nd data set, residuals in feet.

Control Point #	X-Residual Error	Y-Residual Error	Residual Error Distance
3	4.90	6.56	8.19
14	-7.23	1.78	7.44
21	-12.64	4.35	13.37
24	-3.08	-12.81	13.17
28	8.59	-14.61	16.95
33	-2.18	-2.87	3.60
34	8.09	-6.80	10.54
37	6.41	7.46	9.84
40	-8.27	-0.30	8.28
48	2.28	12.74	12.94
58	17.11	12.91	21.44
62	-4.91	-1.60	5.16
67	-10.33	-5.58	11.75
69	1.28	-1.24	1.78

Table C.53: Ground transformation residuals using the photogrammetric survey as control for the space resection 3rd data set, residuals in feet.

Control Point #	X-Residual Error	Y-Residual Error	Residual Error Distance
3	3.74	4.14	5.58
14	-5.28	4.25	6.78
21	-9.72	2.58	10.05
24	-0.09	-6.63	6.63
28	7.52	-9.97	12.49
33	-8.33	-6.34	10.47
34	7.08	-6.16	9.39
37	10.20	8.36	13.19
40	-15.84	-1.86	15.95
48	3.77	8.61	9.40
58	19.93	5.83	20.76
62	0.67	-5.76	5.79
67	-6.88	3.08	7.54
69	-6.78	-0.15	6.78

Table C.54: Ground transformation residuals using the photogrammetric survey as control for the space resection 4th data set, residuals in feet.

Control Point #	X-Residual Error	Y-Residual Error	Residual Error Distance
3	4.53	4.70	10.23
14	-10.58	2.60	2.37
21	-14.24	1.46	4.93
24	5.20	-7.87	14.67
28	8.85	-15.92	19.47
33	-5.67	3.36	9.42
34	9.90	-5.54	15.95
37	5.85	5.63	3.28
40	-11.68	-0.77	14.20
48	3.01	2.47	11.26
58	16.14	11.46	20.39
62	-2.24	-2.54	6.70
67	-6.54	2.18	7.07
69	-2.53	-1.24	4.73

Table C.55: Ground transformation residuals using the photogrammetric survey as control for the space resection 5th data set, residuals in feet.

Control Point #	X-Residual Error	Y-Residual Error	Residual Error Distance
3	-3.83	9.49	6.53
14	1.03	2.13	10.89
21	-4.92	0.32	14.31
24	-0.32	-14.67	9.44
28	9.38	-17.06	18.21
33	-9.41	0.50	6.59
34	15.11	-5.11	11.35
37	3.16	0.87	8.12
40	-13.11	5.44	11.70
48	5.85	9.62	3.90
58	13.44	15.33	19.79
62	-6.69	-0.18	3.39
67	-5.53	-4.41	6.89
69	-4.15	-2.26	2.82

Vita

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