GIS Orthographic Digitizing of Aerial Photographs by Terrain Modeling

Abstract
Spatial data digitized from individual raw aerial photographs are corrected analytically to update a geographic information system (GIS) database. The collinearity correction model is compiled by applying digital terrain data and a suitable base of horizontal control. This method, photo-digitizing, allows spatial databases to be updated from digitizer workstations without photogrammetric equipment and processing. Data entry staff do not require special photogrammetric training. From testing on surveyed ground targets, the accuracy of photo-digitizing (5.5 ± 3 m) exceeds that achieved with current field data entry procedures. Field staff retain ownership of data and control of the update process. The procedure is not considered to be a replacement for stereoplotting. The advantages and accuracy of photo-digitizing are well suited for many GIS applications.

Background
The Washington State Department of Natural Resources (DNR) has responsibility for the care and husbanding of the state's valuable lands and natural resources. The department functions as land manager, regulator, fire fighter, and conservator. The DNR manages 2 million hectares of forest, agricultural, urban, and aquatic lands to generate income for schools, universities, counties, and other beneficiaries. The DNR enforces laws regulating logging practices, reforestation requirements, petroleum and natural gas exploration, and surface mine reclamation of resource-based industry. Department wildfire protection and suppression programs defend nearly 5 million hectares of state and private forest land. The DNR has a lead role in preserving Washington's natural heritage with a system of Natural Area Preserves and Natural Resource Conservation Areas. Balancing the needs of these sometimes conflicting responsibilities requires an accurate and accessible information system.

In 1981, the DNR completed a requirements analysis for a GIS, and reached several conclusions. The increasing complexities of land management demanded an integrated approach to forest planning. Land managers needed site specific information and direct access to GIS analysis and update functions. The ARC/INFO system from Environmental Systems Research Institute (ESRI) was selected in 1983 to meet these requirements.

Current GIS data layers include public land survey lines, state trust ownership, political and administrative boundaries, land use and vegetative cover for DNR managed parcels, soils for state and commercial forest lands, roads, and surface hydrology. Acquisition of digital terrain models (DTMs) for state and commercial forest lands is under development.

Working with large natural resource data sets requires efficient procedures for maintaining the GIS database. Aerial photographs are an effective source for many of the updates. Feature boundaries on aerial photographs are converted to digital format in one of three ways. For the most accurate collection of data, the central office uses analog and analytical stereoplotters to create new regional planimetry. For updating with intermediate accuracies on smaller projects, the central office transfers planimetry from aerial photography to base maps or orthophotos with a zoom transfer scope, and then digitizes from those into the GIS database. For individual updates having the least accuracy, the field offices visually transfer feature boundaries from aerial photography to orthophotos and maps, often with the aid of stereoscopes, and then digitize. The field office accuracies obtained are highly variable and often fall outside of the 15-metre accuracy guideline established by the DNR for resource data.

The DNR initiated a project in 1989 to replace the field office method with a more accurate yet cost effective data entry procedure. The strategic goal is to manage data close to the source instead of centrally. Purchasing photogrammetric equipment and training staff for its use at the field level was ruled out as a viable alternative because accuracy exceeded department requirements at a much higher cost in equipment and training. Digitizing directly from photographs with existing equipment and little additional training was the most desirable approach.

Introduction
Digitizing directly from vertical aerial photographs is an attractive resource data entry alternative. Photographs provide the best images for interpreting natural resource features. Raw photographs, though, usually have major displacements due to camera tilt and terrain relief. Tilt can be corrected by simple projective techniques, but relief displacement and scale variation cannot. Only geometrical correction utilizing a digital terrain model (DTM) could satisfy the 15-metre DNR accuracy requirement throughout Washington.

The photo-digitizing method uses a horizontal base, such as an orthophoto or USGS quad map, to relate ground coordinates to the aerial photograph horizontally, and uses a digital terrain model (DTM) to reference the photograph vertically. From these sets of information, photograph tilt and relief displacement errors are found and eliminated iteratively with collinearity equations. The DNR explored the feasibility of developing this procedure as early as 1980 and reached the conclusion that it was not possible without on-line DTMs, more advanced GIS capabilities, and technical expertise in photogrammetry.

Previously, monoscopic point positioning with DTM

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Gregory S. Tudor
Larry J. Sugarbaker
Land Information Section, Information Management Division,
Washington State Department of Natural Resources,
P.O. Box 47020, Olympia, WA 98504-7020

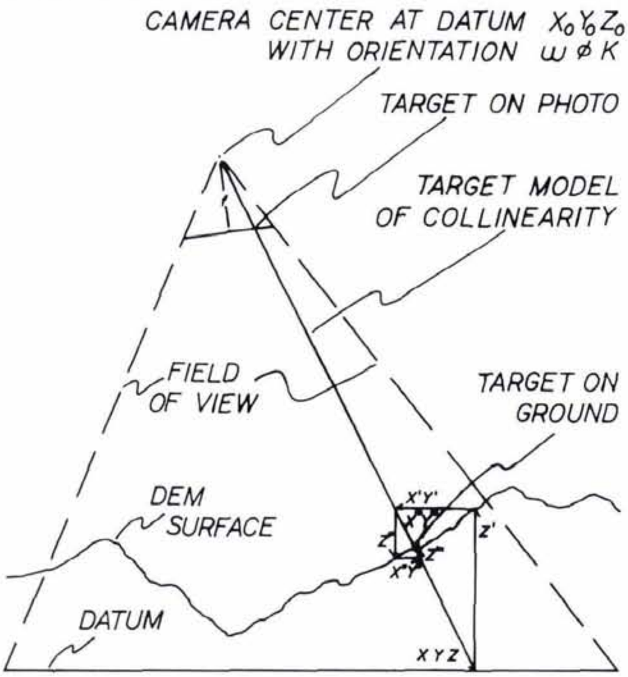

Figure 1. Photo-digitizing schematic of intersection iterations between the collinearity model (horizontal coordinates from an elevation) and the DTM (an elevation from horizontal coordinates).

analysis was reported by the U.S. Air Force for target acquisition using panoramic dynamic photography (Brooks and Sieffert, 1983). Barnes and Vonderohe (1985) researched a more closely related application correcting relief displacement in soil maps compiled from tilt rectified vertical photographs. The University of Montana also developed a system to compute relief and tilt displacement of ground controlled photographs for rectifying scanned interpretive overlays (Martin, 1985).

Operational Procedure

The process of digitizing from vertical photographs involves photograph preparation and photograph digitizing. These procedures are incorporated as interactive programs that are called internally from within the ARC/INFO ArcEdit software. They are written in FORTRAN with subroutine calls to ARC/INFO system routines (ESRI, 1989a).

For photograph preparation, a horizontal base and the aerial photograph are set up at the digitizer. An orthophoto or USGS quadrangle map with ground coordinate tic marks is used for the horizontal base. The tic marks are digitized and their respective ground coordinates are entered to carry out a least-squares solution of the projective transformation from digitizer to ground coordinates. Then the fiducial marks of the vertical aerial photograph are digitized so that the resected collinearity transformation coefficients can be applied later when digitizing photograph features. The photograph is oriented with North at the top so that the fiducial marks are digitized in a consistent pattern.

Finally, the horizontal base and the aerial photograph are spatially related using photocontrol points, well dispersed features that are very distinct and visible on each. Photocontrol points on both the photograph (in digitizer coordinates) and the horizontal base (in projectively transformed ground coordinates) must be chosen to cover the photograph uniformly. About nine points (a minimum of four) should be digitized depending on time and accuracy constraints. The photocontrol ground coordinates are used to obtain elevations from the DTM. The camera location and the orientation, with respect to the ground coordinate system, are found by space resection with a least-squares adjustment. The vertical photograph identification, DTM coverages, fiducial coordinates, focal length, and camera location and orientation are entered in the database.

In the process of photograph digitizing, only the vertical photograph is required at the digitizer. The original fiducial marks and transformation coefficients are recalled from the database. The fiducials are digitized and projectively adjusted by least squares to fit the original digitizer orientation so that the coefficients can be applied. Data points are digitized, projectively transformed to the original digitizer coordinates, and collinearly transformed to the ground coordinate system using initial elevations of zero. From the coordinate values, revised elevations are interpolated from the DTM, and new ground coordinates are recomputed by the collinearity transformation. This iterative process continues until the changes in elevation between each computation become relatively small. The ground coordinates of the data points are then approximately correct (Figure 1).

A check for errors in digitizing tic marks, photocontrol points, and fiducial marks is applied in each least-squares adjustment. This process yields a root-mean-square (RMS) error for each point in digitizer units. The average RMS error is stored in the database for quality verification of the digitizing (Veress, 1974). It should be noted that, for paper photographs such as those used in field operations, it is probably not necessary to correct for errors such as atmospheric refraction, Earth's curvature, or lens distortion unless they are found to be significant by the RMS error check.

For digitizing terrain surface features, photographs overlapping with the digitizing photograph may be used at the digitizer for stereo viewing with a simple stereoscope. However, because DTMs are a fixed sample of elevation values, changes in the ground surface level cannot be measured. Projects that gauge three-dimensional change must measure parallax using stereoplotters.

Digital Terrain Models

Most DTMs are by-products of orthophoto and quad map processing. Both the DNR and the USGS produce DTMs (USGS, 1987). DTM information is converted into ARC/INFO coverage formats using functions to convert from other standard digital formats, contour maps, or point samples. DTMs for collinearity resection and intersection are accessed from ARC/INFO surface modeling modules in either triangulated irregular network (TIN) or lattice/grid formats. DTM coverages must be merged and clipped to a manageable size for photographs that straddle coverages (ESRI, 1989b).

Although digital terrain models have a number of problems with geometry due to their simplified and discontinuous nature, vertical accuracy of the DTM affects the horizontal accuracy of photograph digitizing to a relatively small degree. The horizontal error is proportional with the ratio of the nadir-to-target horizontal distance to the camera height above ground level (refer back to Figure 1).

Transformation Models

Two transformation models are used for photo-digitizing: the projective transformation for changing coordinate systems or orientations and the collinearity transformation for resecting the camera station and intersecting the data points (with the DTM). The polynomial transformation is found to be unsuitable for photo-digitizing. The transformation models are in most photogrammetry references, such as the *Manual of Photogrammetry* (Slama, 1980). For each model, a least-squares adjustment determines an optimal solution of coefficients and analyzes the solution for digitizing errors.

The form of the projective transformation is

$$X = (a_1x + b_1y + c_1)/(a_3x + b_3y + 1)$$
$$Y = (a_2x + b_2y + c_2)/(a_3x + b_3y + 1)$$

where x and y are coordinates of one system, and X and Y are coordinates of a second, perhaps nonparallel, system. For photo- digitizing, tic marks or fiducial marks are used as projection control points.

The collinearity model for resection is

$$x = -f[m_{11}(X - X_0) + m_{12}(Y - Y_0) + m_{13}(Z - Z_0)] / [m_{31}(X - X_0) + m_{32}(Y - Y_0) + m_{33}(Z - Z_0)]$$
$$y = -f[m_{21}(X - X_0) + m_{22}(Y - Y_0) + m_{23}(Z - Z_0)] / [m_{31}(X - X_0) + m_{32}(Y - Y_0) + m_{33}(Z - Z_0)]$$

where x and y are digitized photocontrol photograph coordinates; X_0, Y_0, and Z_0 are camera coordinates in the ground system; and X, Y, and Z are photocontrol ground coordinates. The focal length of the camera is $-f$ for a positive photograph. Components of the matrix (m_{ij}) are functions of omega, phi, and kappa, the rotations about the X, Y, and Z axes. The relief, scale, and tilt corrected ground position of any point on the vertical photograph can then be found by inversing from photograph coordinates iteratively: i.e.,

$$X = X_0 + (Z - Z_0)(m_{11}x + m_{21}y - m_{31}f) / (m_{13}x + m_{23}y - m_{33}f)$$
$$Y = Y_0 + (Z - Z_0)(m_{12}x + m_{22}y - m_{32}f) / (m_{13}x + m_{23}y - m_{33}f)$$

Testing Procedure

Vertical photographs with targets having known ground coordinates are used in testing the photo-digitizing prototype. Two sets of positive paper prints and DNR compiled DTMs are used for the test. The photographs, of heavily forested areas, are nine-inch (229-mm) format with four fiducial marks. The first photograph set, 1982, has a focal length of 210 mm, flown at 4880 m above sea level over terrain that ranges in elevation from 760 m to 1370 m. The maximum vertical relief between test targets across any single photograph is 400 m. The second, 1976, has a focal length of 152 mm flown at 3350 m above sea level over terrain that ranges from 60 m to 760 m. The maximum relief between targets across any photograph is 580 m. With the altitude and focal length differences, the average photograph scales were comparable for both, 1:18,000. Overlapping photographs are not necessary for full coverage of the test areas. DNR produced DTMs are used in both TIN and lattice formats.

The digitizer tablet is backlit and has a cursor with a 10-power magnifier. The manufacturer specifies that resolution and accuracy do not exceed 0.001 inches (0.0254 mm) and 0.01 inches (0.254 mm, 4.8 metres at photograph scale), respectively (CALCOMP, 1984).

The first portion of the testing procedure is to register photocontrol and to compute the collinearity coefficients using the resection program. This procedure requires five to ten minutes per photograph. Most of the photographs used in the testing are resected with RMS errors of less than 0.350 mm, but there are some outliers to about 1 mm. In the second portion of the testing procedure, ground controlled targets are digitized and iteratively transformed. A single measurement is taken on each photocontrol point and each target; there are no repetitions. Locations of targets that could not be seen are estimated. Known target coordinates are compared with the photo-digitized values to find horizontal and vertical displacement errors. Means and standard deviations are computed for those errors.

Several different test formats are run on each set of photographs. For 1982, six test formats are tried on combinations of nine photographs: (P), (P4), (P5), (P9), (P9 w/o PI errors), and (P22). For 1976, four test formats are used on combinations of nine photographs: (P4), (P9), (P9 w/o PI errors), and (Q9).

The first format (P) uses the ground controlled targets instead of photocontrol points. The known coordinate values are used to compute the transformation coefficients instead of relying on the orthophoto for those values. Further, the digitizer coordinates used in the transformation are reused to determine the transformed ground coordinates so that digitizing errors do not compound.

The remaining tests use only photocontrol, such as road intersections or other distinctive terrain surface features, for resection. (P4) uses four photocontrol points distributed one in each corner. (P5) uses five photocontrol points distributed one in each corner and one in the center. (P9) format uses nine photocontrol points distributed in three rows of three. In addition, because photograph interpretation (PI) errors are known to be significant in data digitizing (not photograph resection), all points with errors over the mean are examined in 1982 and 1976 (P9) photograph sets. The obvious interpretive errors are eliminated to form new sets designated as (P9 w/o PI Errors). The test format (P22) uses 22 photocontrol points. (Q9) is based on USGS quad maps instead of orthophotos, using nine photocontrol points.

Results and Analysis

The results from each set of test photographs, 1982 and 1976, are in Table 1 and Table 2, respectively. For each test format, the number of photographs used and the number of data points taken are indicated. These are followed by the mean and the standard deviation, "sd," of horizontal and vertical displacement errors between surveyed and digitized ground coordinate positions.

The digitizing test results follow expectations, but accuracy is better than anticipated. Original error analyses indicated that horizontal accuracy would be from 15 to 30 metres, though some factors are not certain. The horizontal data are assumed to be distributed normally, but are skewed.

The 1982 (P) ground controlled photographs have nearly half the error of the photocontrolled photographs, i.e., 3.07 m. The results of this test indicate the absolute limits of accuracy for photo-digitizing. This minimum error is the product of the accuracy of the digitizer at photograph scale and the DTM accuracy. Using photocontrol and compounding of errors cause further inaccuracy.

Tests on different numbers of photocontrol points are not as conclusive. (P22) is not representative because it is a single photograph. Because (P4) and (P5) are much the same format, the two are used together for comparison with the (P9) tests. There is only slight improvement using nine, versus four or five photocontrol points. Nonetheless, some weight may be given for using more photocontrol points.

Results for using USGS quad maps (Q9) are better than the corresponding orthophoto format (P9). Photocontrol selection is more difficult, though, taking greater time and care. Thus, (Q9) has fairly good accuracy (7.19 ± 7.47 m).

TABLE 1. DESCRIPTIONS AND RESULTS OF 1982 TEST FORMATS.

1982 test formats	number of photos	number of points	positional error of digitized ground coordinates (metres)			
			horizontal error		vertical error	
			mean	sd	mean	sd
P	9	240	3.07	2.47	−5.50	5.49
P4,P5	7	193	5.97	3.68	−5.70	5.65
P9	9	240	5.90	3.09	−5.25	
P9 w/o PI error	9	223	5.43	2.58		
P22	1	22	4.25	2.04	−4.53	

TABLE 2. DESCRIPTIONS AND RESULTS OF 1976 TEST FORMATS.

1976 test formats	number of photos	number of points	positional error of digitized ground coordinates (metres)			
			horizontal error		vertical error	
			mean	sd	mean	sd
P4	4	178	9.75	10.49	−5.42	8.73
P9	9	428	9.27	8.94	−5.73	
P9 w/o PI error	9	328	5.67	3.12		
Q9	2	89	7.19	7.47	−6.77	

The systematically negative vertical error is an effect of iterative relief displacement corrections obtained from the DTM. The error alternates between negative and positive values through odd and even number iterations of the intersection routine (see Figure 1). Only three iterations are necessary, giving a negative vertical error. Additional iterations yield only slight improvement. Generally, DTM elevations are within 5 to 10 metres of surveyed ground control. One exceptional error is located right at the edge of a cliff where the DTM does not match horizontally.

Comparing the two photograph sets, 1982 has much better means and standard deviations than 1976, (5.90 ± 3.09 m) versus (9.27 ± 8.94 m) in the (P9) format. The two sets vary significantly in photographic quality. 1982 has clearly visible ground targets in almost all cases, and images are very sharp with fairly high contrast. However, 1976 is overexposed, making target identification difficult. Also, because 1976 has greater relief and is photographed at a lower relative height with a shorter focal length, many targets are obscured, making photograph interpretation a serious concern. DTM errors have more effect too.

In order to gain a better comparison between the two photograph sets, 1982 and 1976, all of the (P9) data points with errors greater than the mean are examined closely, and causes of error are identified (see Table 3). Of the total number of horizontal displacement errors over the mean, different types of errors are broken down into a rough classification scheme: target identification, target visibility, target image distortion, DTM displacements, errors of unknown cause over one standard deviation from the mean, and errors of unknown cause within one standard deviation of the mean. The first three groups of errors are collectively termed PI errors. Means and standard deviations of the horizontal errors are recomputed for the (P9) format without the PI errors (refer back to Tables 1 and 2). The accuracy of (P9 w/o PI errors) is much better than (P9) for 1976 (5.67 ± 3.12 m), although there is not much change for 1982 (5.43 ± 2.58 m). The two sets compare quite favorably without the PI errors.

A number of things could be done to improve accuracy with corresponding increases in time and cost. Repeating measurements could reduce the digitizing errors somewhat, but would take more time and might not eliminate blunders. More stable film bases of larger scale photographs and orthophotos would increase resolution, and reduce interpretation errors. Using an instrument of higher precision, such as a calibrated digitizer (25 micrometres) or a digital monocomparator (1 micrometre), would yield better measurements. Ground control would substantially improve accuracy, although at great expense. However, because DTM accuracy usually cannot be improved, most enhancements are not worthwhile.

Conclusion

Photo-digitizing with tilt and relief displacement corrections using a DTM is a viable alternative for collecting natural resource data for GIS applications. This system of photograph preparation and data digitizing is not a replacement for other photogrammetric techniques that are able to achieve higher levels of accuracy. The method would improve accuracy and replace traditional field digitizing procedures for updating the GIS database. The setup time is about five to ten minutes per photograph, not including data digitizing. For a single update, digitizing takes less time than transferring data to an orthophoto and digitizing. The land manager is able to use the aerial photograph instead of a lower resolution orthophoto or map. The comprehensive photographic record from recent to old can be digitized without ground control coordinate records. Data entry is at the field level, close to the data source.

The accuracy of photo-digitizing is well within the limits of interpretation for many features (5.5 ± 3 m). The method is a good option for planimetric applications not requiring measurement of vertical changes in the terrain. As in any photogrammetric project, terrain, camera geometry, and adjustment must be carefully appraised in planning, design, and preparation.

Important components to facilitating operational use of this application include a GIS with surface modeling software and a staff trained in GIS data entry techniques. Data sets supporting aerial photography must include controlled maps and digital terrain models. The DNR plans to develop this procedure in an operational environment where photocontrol and DTMs are available within the GIS database. User interaction with these supporting data sets will be minimal.

TABLE 3. BREAKDOWN OF IDENTIFIED DATA POINT ERRORS IN (P9) FORMAT PHOTOGRAPHS OF TEST SETS 1982 AND 1976.

Photo set	1982	1976
Number of points in P9 format	240	428
Number of errors over the mean	104	132
photo interpretation errors		
target identification errors	9	66
targets not visible	3	24
targets visibly distorted at photo edges	5	10
digital terrain model errors	2	1
errors of unknown cause		
over 1 standard deviation from the mean	13	5
within 1 standard deviation of the mean	72	26

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References

Barnes, Grenville, and Alan P. Vonderohe, 1985. An Analytical Technique to Account for Photographic Distortions in Natural Resource Records, *URISA Proceedings Volume I: Land Records Systems*, Ottawa, Ontario, pp. 171-180.

Brooks, William F., and James A. Sieffert, 1983. Point Positioning with Monoscopic Digital Imagery and a Digital Terrain Elevation Data Base, *ACSM-ASP Fall Proceedings*: Falls Church, Virginia, pp. 387-395.

CALCOMP, 1984. *CALCOMP 9100 Series Digitizer Operator's Manual*, California Computer Products, Inc., California.

ESRI, 1989a. *ARC/INFO Programmer's Manual*, 3 Volumes, Environmental Systems Research Institute, Inc., Redlands, California.

———, 1989b. *TIN User's Guide: ARC/INFO Surface Modeling and Display*, Environmental Systems Research Institute, Inc., Redlands, California.

Martin, Fred D., 1985. Using a Geographic Information System for Forest Land Mapping and Management, *Photogrammetric Engineering & Remote Sensing*, Vol. 51, pp. 1753-1759.

Slama, Chester C (editor), 1980. *Manual of Photogrammetry, Fourth Edition*, American Society of Photogrammetry, Falls Church, Virginia, 1056 p.

USGS, 1987. *Digital Elevation Models: Data Users Guide*, United States, Department of the Interior, Geological Survey, Reston, Virginia, 40 p.

Veress, Sandor A., 1974. *Adjustment by Least Squares*, American Congress on Surveying and Mapping, Washington D.C., 217 p.

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