PEER-REVIEWED ARTICLE

PRACTICAL PAPER

Relative Accuracy of Monoscopic 35-mm Oblique Photography

Abstract

An innovative method for creating a digital elevation model (DEM) from a small-format stereopair was developed for a digital monoplotter. The monoplotter, Carto MDSD, consisted of a standard two-dimensional digitizing tablet and software based upon space resection solutions. DEMs created from (1) control points, (2) a topographic map, (3) large-format stereomodels, and (4) a 35-mm oblique stereopair were compared to determine the influence of DEM data upon monoscopic measurements. A DEM created from a 35-mm oblique stereopair provided relative point location accuracy of about 3 m for monoscopic measurements from a 1:37,000-scale oblique photograph. Plan-dev/scale ratio for a single 35-mm oblique was 0.10 mm, compared to 0.03 mm for a large-format stereomodel of the same area. Applications for the monoscopic measurement system are suggested.

Introduction

Although many aerial photographers use 35-mm cameras for interpretation, few are exploiting photogrammetry. There are many reasons why, but three basic obstacles come to mind: (1) it is difficult to control *proper* overlap of vertical, stereo photography (resulting in poor spot height accuracy and/or loss of usable area of the model) (Warner, 1989a; Warner, 1989b); (2) there are geometric problems associated with non-metric cameras, especially during interior orientation (Warner and Carson, 1991); and (3) stereo plotters are relatively expensive.

To by-pass these obstacles, Norway's Center for Soil and Environmental Research (JORDFORSK) and Carto Instruments developed an inexpensive digital monoplotter, the MDSD, which consists of a standard digitizing tablet and software based upon space resection solutions. Benchmark tests using large-format photography proved the system's foundation (space-resection solutions) to be robust, and *relative* measurement accuracy of monoscopic and stereo photogrammetry was approximately equal (Warner and Carson, 1992). Although *absolute* accuracy of a single, enlarged 35-mm oblique is about one-tenth that of a large-format stereomodel, a small-format oblique can provide acceptable accuracy if abundant elevation data are known.

The most serious limitation of digital monoplotting, in general, is that it requires an existing digital elevation model (DEM) of the area, which is not always available (Searle, 1984; Bethel, 1987). In addition, the accuracy of planimetric measurements is, in part, a function of the DEM's quality. Although the MDSD can either (1) import an external DEM (generated from digitized maps or stereomodels) or (2) create an internal DEM from control points (used in absolute orientation), problems remain: suitable external DEMs often do not exist, and elevation data from an internal DEM (based upon control points only) is often too crude for many measurements purposes.

To overcome the latter problem, we improved the MDSD's internal DEM method. Namely, from an oriented oblique stereopair, *xyz* coordinates of about 100 parallax-free points were used to improve the internal DEM. Two questions arose from the method: (1) were relative photo measurements significantly improved? and (2) how suitable was this method for practical applications?

This paper examined these questions by detailing the various methods of linking DEMs with 35-mm monoscopic obliques. Specifically, we outline the creation of *external* and *internal* DEMs, explain how an internal DEM can be improved, and discuss influential errors from the perspective of DEM data-*quality* and data-*quantity*. Results are illustrated by plotting the various DEMs and corresponding measurements captured from an oblique 35-mm photograph.

Methodology

The study was based upon hand-held 35-mm, low oblique photography of a 2-square-kilometre rolling agricultural landscape, with a 35-m variation in elevation. Photographs were taken from a Cessna 150 at 780 m (AGL) using a Pentax LX fitted with a 35-mm lens. Shutter priority was set at 1/500 sec. The standard single lens reflex (SLR) camera used Ektachrome ASA 400 (processed commercially).

After viewing the exposed diapositives, we selected two frames with a good base/height ratio (1.68) and suitable angular orientation (Ω about 45 degrees) (Plate 1). The diapositives were enlarged (12×) to an A3 format (approximately 30 by 42 cm) by means of a Canon Colorlaser Copier 200 (CLC-200). Manufacturer specifications state the CLC-200 produces enlargements with a resolution of 64 pixels per cm. Unlike traditional optical enlargement of 35-mm diapositives, this laser-scanning copier did not introduce significant image deformation (Warner and Andersen, 1992).

External DEMs

Two external DEMs were created for the study area: one from a map and the other from large-format stereomodels. The *Map DEM* was created by digitizing spot heights and the 5-m interval contours from a 1:5,000-scale map, with the digitizer in continuous mode (2-mm measuring increment, which produced a 10-m ground increment). 3738 points were exported to Golden Software's Surfer program (Version 4) and gridded to 10-m cells. To interpolate elevation—for this and all other

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DEMs—we used the inverse distance method, power of 2 (Figure 1a).

For the *Photo DEM*, we used 1:6,000-scale color infrared stereomodels (paper prints) taken with a Zeiss RMK TOP camera (153.53-mm focal length). An experienced operator used a Carto AP190 stereo digitizer to capture 10,059 points. The Carto AP190 has a point location accuracy better than 20 μm (Carson, 1987). Relative photo measurements from the models were about ±10 cm. The data were exported to the Surfer program and gridded to 7-m cells, and the second external DEM was created (Figure 1b).

Internal DEMs

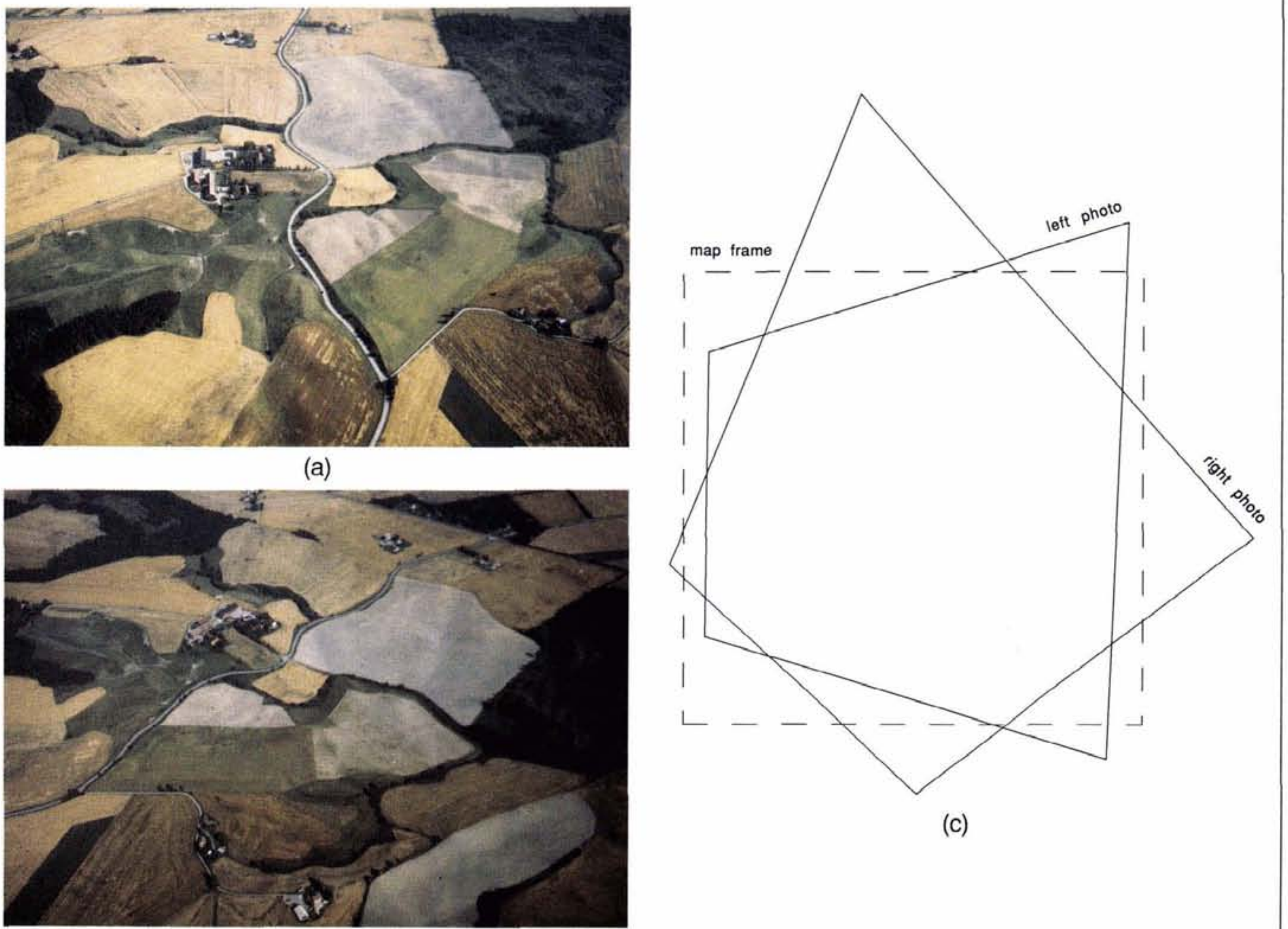
The conventional method for creating an internal DEM is based upon the control points used in the system's absolute orientation program (hence the name, *Internal DEM*). In this case, the coordinates of the 13 control points were digitized from the 1:5,000-scale map. The points were gridded to 10-m cells (which was excessive but compatible), and an internal DEM was created (Figure 1c).

The improved method for creating an internal DEM used the 13 control points plus 96 parallax-free points, referred to as the *Enhanced-109-Internal DEM*. (The numerical prefix of all enhanced DEMs indicates the number of points used to create them.) Because this new method was the heart of the study, operating procedures are detailed.

(1) *Interior Orientation*. First, the two 35-mm enlargements were taped on a standard digitizing table, and the four corners of each enlargement were digitized. These photo coordinates were matched to camera coordinates to compute an interior fit: left photo 41 μm, right 36 μm (at original diapositive scale). The camera's frame edge corners and focal length were previously calibrated using a convergent photography system developed at the Dept. of Photogrammetry and Land Surveying, the Norwegian Agricultural University.

(2) *Relative Orientation*. The operator registered the 13 control points by first digitizing a control point on the left photo, then the right photo, followed by entering the point's identification number. Relative orientation residuals (standard deviation produced by the Schut's (1965) method) were ±30 μm at original diapositive scale, or 1.11 m on the ground.

(3) *Absolute Orientation*. The 13 control points were used for a standard conformal scaling and leveling of the



(a)

(b)

(c)

Plate 1. 35-mm oblique photographs and photo/map overlay. (a) left photo, (b) right photo, (c) photo/map overlay.

model. The mathematical formulation is detailed by Carson (1985). Expected ground accuracy for the stereopair was 3.75 m in the X direction, 2.58 m in Y, and 2.02 m in Z.

(4) *Point Collection.* After leveling and scaling the photograph to the ground (step 3), 109 points were identified on both photographs and annotated on acetate overlays. The points were well-distributed across the image and represented different elevations. Then the operator registered each point by first entering a point's identification number, followed by digitizing the point on the left then the right photo. The dual photo-measurements (parallax-free points) were exported to Surfer, gridded to 10 m, and a DEM was issued (Figure 1d).

Plotting Relative Accuracy

To illustrate the influence of each DEM on planimetric measurements, the left oblique photograph was controlled by a DEM and a series of measurements were made (Figure 2). Specifically, in each of the four cases, the 109 points were digitized and stored in a data file; then six line-lengths (roads and ravines) and four polygons (field boundaries)

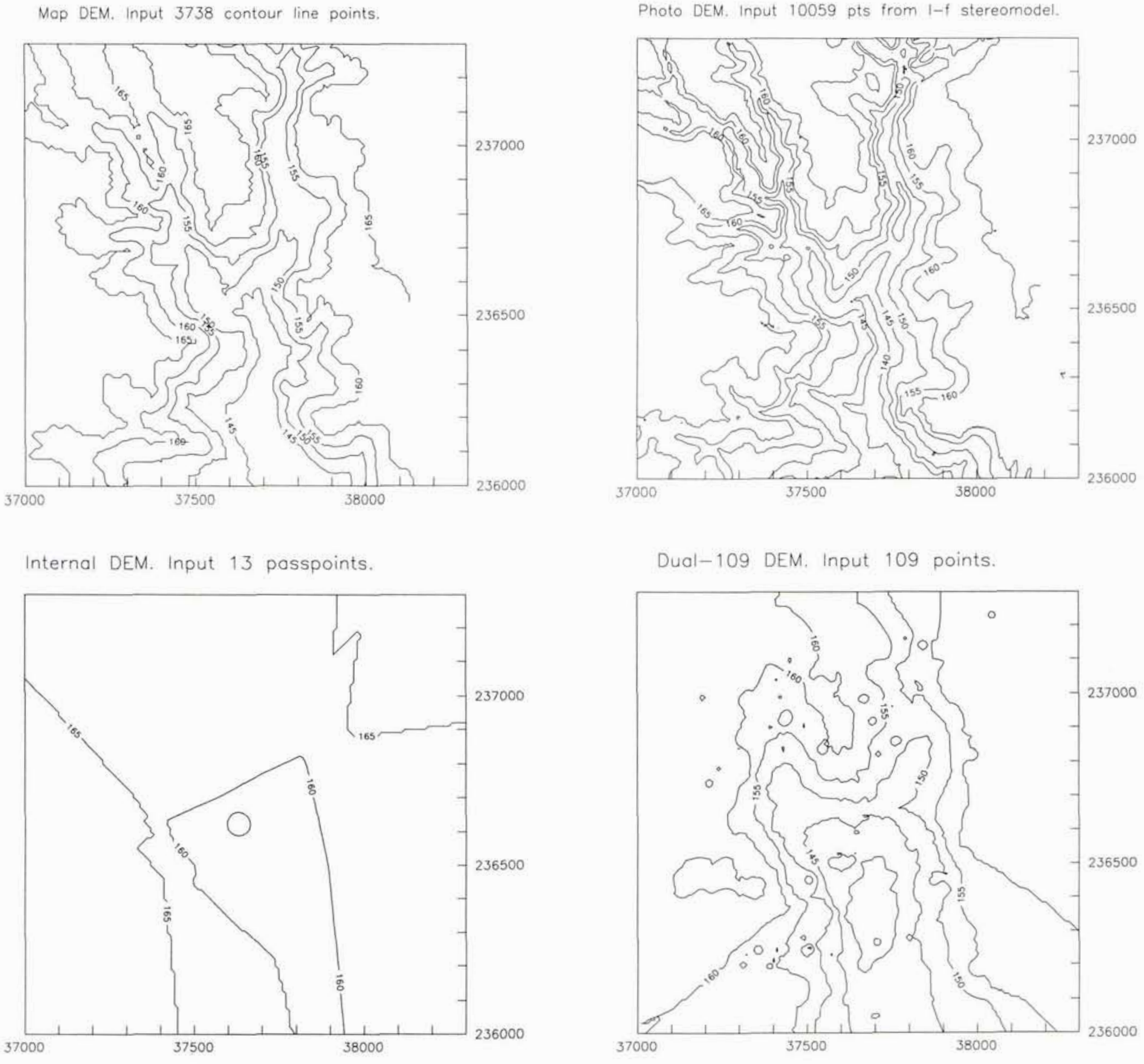


Fig. 1. External and internal DEM-based contour maps. (a) Map- DEM, (b) Photo-DEM, (c) Internal-DEM, (d) Enhanced-109-Internal DEM.

were measured. Lastly, a straight line (in photo) composed of ten points at different elevations was registered.

Results

When comparing measurement accuracies based upon different DEM-controlled images, several considerations come to mind: (1) the influence of the operator on repeated measurements of the same point; (2) the quality of each DEM, and the quantity of data used for creating an *Enhanced-Internal DEM;* and (3) the overall accuracy one can expect from the media, measurements and method.

Operator Influence

To begin with, we determined the operator's precision in measuring 93 of 109 points six separate times. Sixteen blunders were eliminated from all of the compared data sets, which consisted of 654 points. Thus, about 2 percent of all measured points were blunders. The overall standard deviation of 93 *x,y* photo coordinates was approximately 132 μm at enlarged photo scale, or 44 cm at ground scale, which was less than a 0.1 mm line width at 1:5,000 map scale. Because manufacturer specifications state the digitizing tablet, GTCO Digi-Pad L-Series (DP5A), has a resolution of 25 μm and an accuracy of 100 μm, we can assume the operator's precision did, to a limited degree, influence comparative measurements.

DEM Quality

First, we examined DEM elevations. Points captured from the large-format stereomodels were compared with the corresponding elevations interpolated from the DEMs. To do this we used *X Y Z* values for 3,895 points (from the file that built the *Photo-DEM);* then for all planimetric locations (*X* and *Y*) we queried each DEM for the *Z* values. Each *Z* value was compared against the original and gaps and standard deviations were computed (Table 1). Although the standard deviation of the *Enhanced-109-Internal DEM* was 2.5 times greater than the *Map DEM*—and some measurements (gaps) were three times the standard deviation—keep in mind the *Map DEM* was based upon 35 times more raw data points.

TABLE 1. COMPARISON OF 3895 ELEVATION VALUES WITH DEMs.

DEM	Stand. Dev. *Z* (metres)	Gap (min.)	max.
Internal	8.65	−6.39	24.64
Enhanced-109	5.01	−17.92	13.49
Map	1.99	−7.45	7.69
Photo	0.57	−4.72	2.80

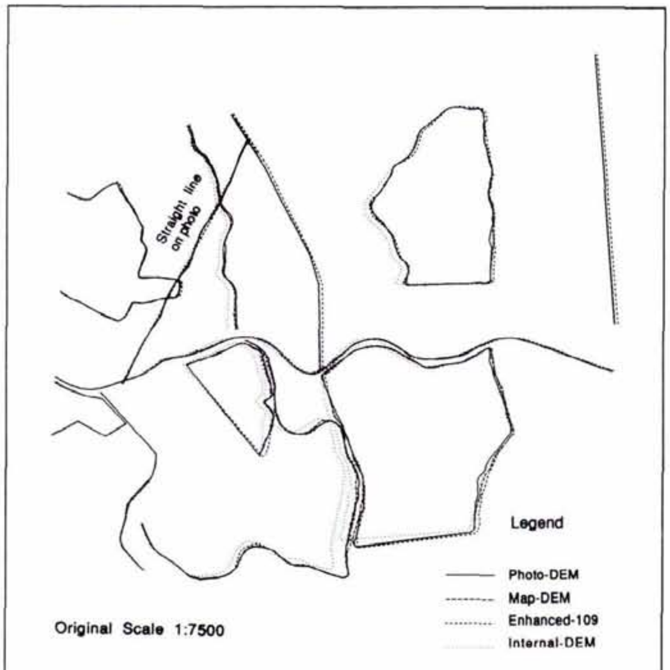


Fig. 2. Planimetric map of photo features based upon control from external and internal DEMs.

Second, we compared the 93 planimetric object locations (*X,Y* ground coordinates) digitized from each DEM-controlled image (Table 2). Because we did not know the "true" ground coordinates of each point, we juxtaposed the best DEM (*Photo-DEM*) with each of the other three DEMs.). Results suggest that, although the parallax-free points increased the precision of an internal DEM by a factor of 4, planimetric measurements controlled by the *Enhanced-109-Internal-DEM* were less accurate than those controlled by the *Map-DEM:* deviations of 24 cm in *X* and 63 cm in *Y*. An explanation for *Y*'s greater error is given later.

Before examining the issue of data quantity, a final comment about quality. We recognized that the data's origin was not the only quality issue. The method of interpolating DEM elevations from random *X,Y,Z* data might influence relative measurements. That is, had we used the kriging method, or a higher power for inverse distance interpolation, or a different grid size, relative measurements might have been different. These considerations were not, however, within the scope of this study.

Data Quantity

Another concern was the number of raw points used to generate a DEM, particularly with the *Enhanced-Internal DEM.* To determine if the number of parallax-free points influenced planimetric measurements, we thinned the data file and repeated measurements as follows. First, every third point was eliminated from the 109 point job file and a new 10-m grid DEM was generated, *Enhanced-74-Internal DEM.* Then we digitized the referenced points, lines, and polygons on the left photo. Second, we thinned every other point from the job file, created another 10-m grid DEM, *Enhanced-55-Internal DEM,* and repeated the measurements.

Comparing the 93 *(X,Y,Z)* ground coordinates from the *Photo-DEM* with those from the *Enhanced-55-*, *Enhanced-74-*, and *Enhanced-109-Internal DEMs* showed that the precision of relative measurements increased with the number of raw data points (Table 3). As expected, increasing the quantity of raw data improved measurement accuracy proportionally. Note that the relative accuracy in the *Y* direction was substantially worse than in *X*. This too can be expected because the *Y*-axis was extended by the oblique angle of the photo.

TABLE 2. RELATIVE PLANIMETRIC ACCURACY ON LEFT PHOTO USING 93 POINTS.

	Relative Accuracy (metres)					
	X			*Y*		
		Gap			Gap	
DEM	Std. Dev.	(min)	max	Std. Dev.	(min)	max
Internal	4.86	−7.13	16.36	12.27	−29.43	8.02
Enhanced-109	1.16	−2.55	4.07	3.47	−11.01	7.43
Map	0.92	−3.10	2.95	2.83	−8.97	10.45

Figure 3a illustrates how an elevation error—determined from the DEM—significantly affects one planimetric location. As Ω decreases, an error in Z determination erodes planimetric measurements (Figure 3b). Also note that ω varies over the photo.

Planimetric Accuracy

The final issue we addressed was this. How did relative measurements off a single 35-mm oblique photograph compare with conventional large-format stereoscopic measurements? The question was answered, in part, by the *plan deviation/scale ratio.* "Plan deviation/scale ratio" is based upon the accepted notion that planimetric accuracy (i.e., deviation) is closely related to the scale of the photography. The ratio is computed by dividing the root-sum-square of the plan deviations by the scale.This ratio indicates the overall accuracy one can expect from the media, measurements, and method.

Plan deviation was based upon the standard deviation of 93 planimetric measurements. Because scale variation was very large in the oblique imagery, and at any given point it was different in all directions, a comment about scale determination is in order. Scale is a changing function, and can be handled either by differential integral calculus (e.g., Katz, 1950) or statistics. In this study we used the latter and defined the scale of an oblique photograph as *that which was determined by a least-squares fit between the photo-coordinates and the planimetric ground coordinates used for control in space resection.* The scale therefore varied with the selection of control points. However, because this selection was dictated by the area of interest (in the photograph), we felt that the average scale produced by this least-squares fit was most relevant.

The plan-dev/scale ratios (Table 4) suggested that, overall, measurements controlled by the *Map-DEM* and *Enhanced-109-Internal DEM* were about the same. However, the overall accuracy of small-format monoscopic oblique measurements were, at best, one-third as good as large-format stereoscopic measurements. Based upon these plan-dev/scale results, we can then estimate the overall accuracy of monoscopic measurements at different photo scales or different flying heights, assuming the camera's angle of depression remains near 45 degrees. For instance, at 1:10,000 photo scale, the oblique imagery controlled by the *Enhanced-109-Internal DEM* would yield a planimetric accuracy of approximately one metre. Flying height, however, would be about 200 m (AGL)—the limit set by most aviation authorities.

A final comment about plan-dev/scale ratios. We know that the accuracy of measured points depends on scale: the larger the scale, the greater the accuracy. In vertical photography, scale variation is caused *only* by topographic relief—the result of variance in object distance due to terrain elevation. In oblique photographs, scale is further affected by the magnitude of angular orientation of the camera. Thus, a photo location error of, say, 0.5 mm in an oblique's background produces a greater object location error than a 0.5-mm error in the foreground; and the difference becomes more critical as Ω decreases.

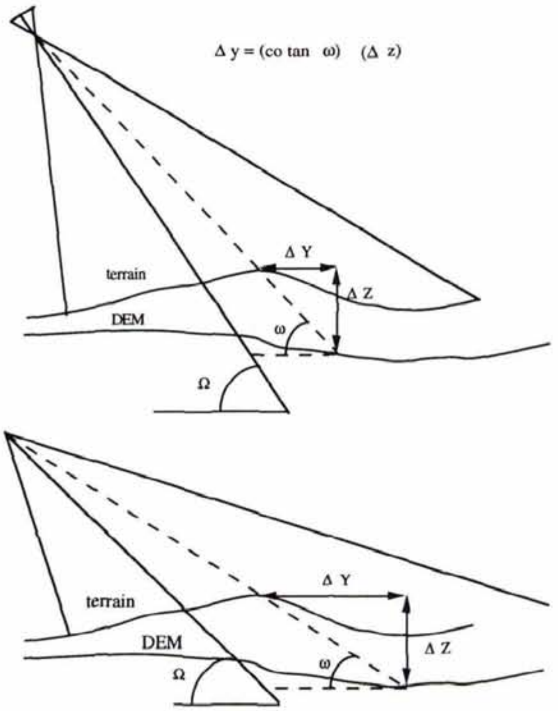


Fig. 3. Influence of DEM elevation upon planimetric measurements. (a) Angle of camera depression (Ω) 55 degrees. (b) Angle of camera depression (Ω) 45 degrees.

Conclusions

By capturing numerous parallax-free points from a 35-mm oblique stereo pair, a functional DEM can be created which will provide elevation data for moderately accurate relative measurements. This conclusion is based upon two rudimentary points: (1) the stereo-pair should have a B/H ratio >1.5, and (2) the camera's angle of depression should be relatively large ($\Omega > 45$ degrees).

A practical consideration in capturing parallax-free points is the time it takes to identify identical points on an oblique stereo-pair. For this study it took about two hours to identify 100 matching points. Keep in mind, however, that most of this time was devoted to carefully marking and la-

TABLE 3. RELATIVE ACCURACY USING 93 POINTS ON LEFT PHOTO, WITH DIFFERENT INTERNAL DEMs FOR CONTROL.

Enhance-Internal	Relative Accuracy (metres)								
	X			*Y*			*Z*		
DEM		Gap			Gap			Gap	
(*pts used*)	S.D.	(min)	max	*S.D.*	(min)	max	*S.D.*	(min)	max
55	2.44	11.25	7.43	7.37	9.54	28.19	5.34	16.42	8.49
74	1.79	8.70	7.49	5.35	5.51	21.85	4.02	14.67	6.67
109	1.16	2.55	4.07	3.47	11.01	7.43	2.67	5.94	6.89

TABLE 4. PLANIMETRIC DEVIATION/SCALE RATIOS OF SMALL-FORMAT OBLIQUE AND LARGE-FORMAT STEREOSCOPIC MEASUREMENTS.

DEM Used	Scale (1:)	Planimetric Standard Deviation (metres)	Plan-Dev/Scale Ratio (mm)
35-mm oblique			
Internal	37,000	13.19	0.36
Enhanced-55	37,000	7.74	0.21
Enhanced-74	37,000	5.64	0.15
Enhanced-109	37,000	3.65	0.10
Map	37,000	2.98	0.08
23 × 23 cm stereo	6,000	0.18	0.03

beling the points for comparative measurements. After the points are identified, however, dual digitizing is straightforward and not substantially more time consuming than digitizing only one photo. Thus, for all practical purposes, dual digitizing 100 points is not considerably time-consuming.

Admittedly, digitizing numerous objects on two obliques is prone to error. In this study 2 percent of the sample points were considered blunders. However, errors were immediately detected in relative orientation: i.e., any matching points with a residual greater than three times the overall standard deviation were identified and eliminated. Admittedly, this is a crude method, but it can be justified if the remaining points are well distributed.

The relative accuracy of oblique monoscopic measurements, controlled by an *Enhanced-Internal DEM*, suggests that the system is suited for (1) natural resource map revision where extreme metric precision is not required, and (2) measuring objects within a very small areas. An example of the former might include mapping soil, forest, and wildlife boundaries where fragmented edges are estimated; consequently, planimetric measurements are not critical; or mapping wetlands where variation in elevation is relatively small; thus, a detailed DEM is not necessary. Examples of the latter might include measuring coal piles at very large photo scales, in which case moderately accurate three-dimensional measurements can be used to compute volume (Huberty and Anderson, 1990), and identifying structural improvements to residential buildings to assess permit compliance (Niedwiedz, 1990).

Though digital monoplotting has been suggested as a suitable technique for map revision, its successful implementation requires an existing DEM of the area (Tait, 1991). If a suitable DEM does not exist, then under most circumstances the operator must create one from either parallax-free points or from a map. The advantage of using an *Enhanced-Internal DEM* rather than one generated from a topographic map can be seen in two cases. In the first case, both the area of interest and the map scale are small, say, 10 square kilometres and 1:50,000, respectively. Here the map could be used for capturing control points (e.g., road intersections and river or railroad crossings). But, because the elevation contours are too gross for an acceptable DEM, one might rather build a suitable DEM by peppering the imagery with parallax-free points.

In the second case, the need is a very large-scale map of a small area with considerable relief (e.g., a 1:500-scale map of a gravel pit). Here the operator would first conduct a field survey after the photography was taken, and measure a few control points in a local coordinate system for absolute orientation. Afterwards, parallax-free points could be collected to create the DEM. This method seems most suitable for constantly changing sites or areas that pose a health hazard to an extensive field survey (e.g., hazardous waste sites).

Apart from the obvious limitations of using 35-mm photography for aerial survey work, including having to calibrate a geometrically unstable camera, small-format oblique photography can be used for photogrammetric purposes. Provided that (1) the small camera is used appropriately within the limitations of angular orientation and base-height ratios (Fleming and Dixon, 1981), (2) enlargements are not deformed (Warner and Andersen, 1992), and (3) measuring objectives fall within the scope and expected accuracy of DEM controlled-imagery, the application of small-format oblique photography appears promising.

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