APPLICATION OF DIGITAL PHOTOGRAMMETRY TO MONITORING SAND BAR CHANGE IN MARBLE CANYON, AZ

by

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Logan, UT

2000

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Thesis submitted in partial fulfillment
of the requirements for the degree

of

UNIVERSITY HONORS
WITH DEPARTMENT HONORS

In

Geography and Earth Resources

Approved:

Thesis/Project Advisor

Department Honors Advisor

Director of Honors Program

UTAH STATE UNIVERSITY
Logan, UT

2000

ABSTRACT

Digital photogrammetry provides an opportunity to quantitatively measure the topography of the land surface as it is depicted in aerial photographs. The software program Ortho*MAX*™ was used to measure the topography of an important riverside sand bar along the Colorado River in Marble Canyon as it existed in October 1984. The topography of ninety-five percent of the area, as determined from photogrammetry, was within 25 cm of the topography as it was surveyed in May of 1985. These results demonstrate that digital photogrammetry can be used to accurately measure geomorphic features on historic photographs, thereby significantly lengthening the time period over which quantitative measurements of land surface change can be made.

ACKNOWLEDGMENTS

This project was funded by the Grand Canyon Monitoring and Research Center. I would like to thank Kiran Panja and the INSE lab for technical assistance and support. I would also like to thank Andre Coleman, Paul Grams, and everyone else who offered input and help. I would especially like to thank Jack Schmidt for providing this opportunity and for his guidance throughout the project.

Brandy L. Blank

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INTRODUCTION

Landscape change is of longstanding interest to geographers and geomorphologists; river managers, informed citizens, and scientists are concerned about measuring and describing how streams and their alluvial deposits change over time. The Colorado River, like all rivers is both a physical and a historical system (Schumm, 1977), and the changes in physical features cannot be understood without a clear understanding of past change. This is especially true of some of the geomorphic features along the Colorado River in Marble and Grand Canyon, downstream from Glen Canyon Dam. The number and area of sand bars that line the river at low discharge have decreased since closure of the dam in 1963 (Schmidt and Graf, 1990; Kearsley et al., 1994; Webb, 1996). This has reduced the quality of the river running experience and may have contributed to the endangerment of endemic fish populations (Schmidt et al., 1998). Understanding the magnitude and role of change in sand bars is very important in developing new plans of dam operation intended to mitigate the impact of the dam and restore the pre-dam condition of the river corridor.

Monitoring landscape change through historical analysis often is difficult. In Grand Canyon, the remoteness and inaccessibility of the canyon, its large size, and limited historical data make historical analysis particularly challenging. Past studies have relied on repeated surveys of topography first undertaken in 1975, as well as analysis of aerial and oblique photographs. Most obviously, these methods are limited by the richness of the historical data. Field surveying analysis is also limited, because historical comparisons can only be made back to the time of the first ground surveys. Traditional surveying also has difficulty recording rapid changes in fluvial morphology due to the length of time it takes to conduct surveys during field expeditions and the fact that survey crews may not be at the right place at the right time. The

cost of ground surveying, including the cost of equipment, food, and personnel is high. All of these factors limit the application of traditional field surveys to specific study sites, so that those results must be extrapolated to other locations. Application of photogrammetric techniques and analysis have the potential to greatly expand the area of measurement and thereby reduce the need for extrapolation.

Softcopy, or digital, photogrammetry is a newly-emerging technology that is increasingly being used to detect landscape change and may prove useful in overcoming the challenges of monitoring sand-bar change in Grand Canyon. Softcopy photogrammetry offers many advantages over traditional methods of photographic analysis, including the production of orthophotos, digital terrain models (DTMs), and topographic contours. The possibility of automation and the fact that these products can be easily imported into a geographic information system (GIS) make digital photogrammetry attractive. Some believe that this method is also easier to learn, is faster to use, and has greater potential for further advancements than its traditional counterparts (Cory et al., 1999).

The purpose of this study is to evaluate the application of digital photogrammetry for the analysis of historical aerial photography in Grand Canyon. Using digital photogrammetry, the potential exists to accurately determine the topography of sand bars from past photographs, thereby extending the detailed historical record of landscape change. In essence, this technology can provide a time machine for scientific investigations of the river corridor. Digital photogrammetry has the potential to dramatically increase the body of precise and accurate historical data that can be used to improve our understanding of sand bar change over time.

Photogrammetry as an Emerging technique

Photogrammetry, or the analysis of photographs to obtain reliable measurements of surface features, was first widely used as an aid in U.S. military reconnaissance during World War II (Avery and Berlin, 1992). Since those early beginnings, the technologies associated with photogrammetry have advanced greatly. Ranging from oblique photogrammetry to satellite imagery and digital elevation models (DEMs), the field of photogrammetry has truly become a science of its own. These technologies are being applied in countless ways, and can be used by any researcher interested in measuring features on the earth's surface.

The calculation of topographic contour lines itself is also an evolving science. Falkner (1995) summarized this evolution, starting with traditional ground surveys and proceeding to photogrammetric techniques. Mechanical stereoplotters were the first machines that incorporated stereoscopic viewing of aerial photography to obtain elevation data. Using these machines, operators were able to see aerial photos in stereo and use a tracing table to hand draw contours. The next innovation was analog steroplotters, which incorporate a low intensity light that could be aligned with the stereoscopic surface by adjusting various knobs and screws (Avery and Berlin, 1992). The analytical stereoplotter employed a computer capable of helping the operator orient the images by precise mathematical means (Falkner, 1995). Some of the first digital means of generating contours were developed in the early 1990's. Since that time, their use has increased dramatically in many different fields.

Beyond simple contouring, digital photogrammetry has been used for such varied research as mapping vegetation, monitoring the health of forests, determining treatments for ailing crops, and urban planning (Campbell et al., 1996; Khuen, 1997). For example, the city of Logan, Utah, recently acquired digital orthophotoquads to use for storm and waste water

management, mapping the distribution of criminal activities, and utility maintenance (GEO/Graphics, 1999). Digital orthophotos have also been used to monitor the size of landfills by detecting changes in the overlying surface (Stohr et al.,1994).

Digital photogrammetry and other related technologies have the potential to provide highly accurate spatial data. One study that monitored the migration of sand dunes in Egypt was able to obtain 20 cm resolution in X, Y, and Z directions (Borges, personal communication to McCarthy). Wall et al. (1991) compared automatic and manual methods of stereogrammetry using data obtained by radar from helicopter. Their calculated average error for elevation data was 3-4 mm. Ridley et al. (1997) automatically created DEMs of 1:7500 scale aerial photography in an effort to detect topographic changes in low-lying coastal regions.

Digital photogrammetry has also been used to create detailed DEMs of the Flathead River in Montana and the Klamath River in California. Using this technique, Panja (personal communication) was able to obtain accuracies in the X, Y, and Z directions of 5 cm. When combined with bathymetry data, these methods proved capable of accurately measuring the topography of river corridors.

Differences in precision among these different techniques are related to a number of factors. Quality of ground control points (GCPs) is perhaps the most important. The triangulation and block adjustment are only as correct as the precision and accuracy to which ground control points can be located (Swanson, 1966). Some types of GCPs are easier to locate than others, and the studies mentioned above had a variety of target types. In some cases, the GCPs were specially designed targets; in others, GCPs were road intersections or golf balls. The degree to which the precise location of these GCPs is known also varies depending on whether

coordinates were obtained from ground survey, global positioning systems (GPS), orthophotoquads, or other maps.

The scale of the imagery used also defines the obtainable precision. For 1:20,000 scale photographs, 1 m on the ground is approximately 0.045 mm on the photograph (Swanson, 1966). Thus, scale can strictly limit how precisely GCPs can be selected and how much detail can be obtained from the image. Because of this, large-scale imagery will produce more precise results.

Effects of Glen Canyon Dam in Grand Canyon

Glen Canyon Dam was completed in 1963, creating entirely new hydrologic and sediment transport systems (Williams and Wolman, 1984). The river hydrology was transformed from one with annual spring floods driven by snow melting in the Rocky Mountains to one in which the discharge was dictated by the power demands of major cities. Lake Powell reservoir, formed by Glen Canyon Dam, traps the sediment laden water of the Colorado River, and releases clear water downstream. These changes have consequences downstream, including changes in channel bed elevation, channel width, and bed material size (Webb, 1996; Topping et al., 2000a). The area, volume, and number of sand bars decreased (Kearsely et al., 1994). It is these changes to the geomorphic system that have prompted systematic monitoring of sand bars in Grand Canyon.

Efforts at Monitoring Sand Bar Topography in Grand Canyon

Repeated surveys of sand bar profiles have been an important tool in monitoring sand bars in Grand Canyon. Surveys of sand bar topography were first employed by Howard (1975) and have been repeated by many other scientists including Beus (1985), Schmidt et al. (1999), Hazel et al. (1999). The techniques employed in these field surveys have varied, and include hand level, engineers level, plane table, and electronic distance meters. By combining these

historical data, Grams and Schmidt (1999) have produced integrated data sets for several sites for periods exceeding 25 years.

In addition to surveying, analysis of aerial photography has been a primary tool used by scientists to monitor sand bar changes in Grand Canyon (Schmidt et al., 1999; Grams and Schmidt, 1997; Schmidt and Leschin, 1995). Schmidt et al. (1999) have shown that mapping from air photos can yield results comparable to ground surveying, but applicable over much longer reaches in the canyon. Data collection is rapid when using air photos, but still requires considerable laboratory processing. Processing typically takes about one week for each year of coverage for each 1- river-mile long section at a scale of 1:2400 (Schmidt and Leschin, 1995). While this method reduces costly fieldwork, the cost of laboratory analysis is high. Errors are introduced to the data through simple human error or the use of unrectified photos. While this method is able to delineate different types of sand deposits based on location and shape, the method is not capable of precisely representing 3-dimensional topographic changes. Another important tool in documenting changes in sand bars over time has been repeating photographs first taken over one hundred years ago. Using this method, researches have been able to document large scale changes in sand bar shape and size (Webb, 1996).

Currently, scientists at Northern Arizona University are experimenting with the use of oblique photogrammetry to monitor long-term changes. These techniques show promise as demonstrated by Lane et al. (1996) in an experiment using oblique photogrammetry to monitor changes in braided channels downstream from an active glacier at a 1 to 2 hour time scale; the precision of this method was 2.5 cm.

LIDAR, or laser imaging direction and ranging, is a new technology that has the potential to produce accurate topographic data quickly and relatively cheaply. One experimental

technique used laser altimeters to measure the distance between the land surface and the airplane (Ritchie, 1994). Using this method, measurements were taken at 0.015 to 0.02 m intervals along the flight line with a vertical accuracy of 0.05 m. LIDAR was first used to create a contour map of Marble Canyon from Glen Canyon Dam 38 km downstream to Badger Creek Rapid in 1998 (Mike Liszewski, personal communication).

McCarthy et al. (1999) used digital photogrammetry to monitor changes in sand bars at Badger Creek Rapids caused by the controlled flow of 1996. They used an automated point collection algorithm within ERDAS Imagine software to determine elevations of the land surface. The results of this study suggest that digital photogrammetry has great potential for mapping topography in Grand Canyon. My study examines if digital photogrammetry also has the potential to be used for the analysis of historical aerial photographs.

STUDY AREA

The study area for this project was a 840 m^2 portion of a sand bar located on river left, immediately downstream from Badger Creek Rapids, approximately 13 km from Lees Ferry (Figure 1). This site was the same one analyzed by McCarthy et al. (1999). One reason why this site was chosen was that we could use some of the GCPs that had been established by the GCMRC for the McCarthy et al. study (1999). Additionally, this site has been mapped from aerial photographs using photogeologic techniques (Schmidt and Graf, 1990) and is the current focus of work being conducted by Sondossi (written communication). Thus, there is an extensive database for this site containing maps of fluvial geomorphic features based on aerial and oblique photography between the late 1890's and present.

The study site is part of a fan-eddy complex, as defined by Schmidt and Rubin (1995) (Figure 2a). Badger Creek Rapid is formed by two debris fans at the mouths of Badger Creek

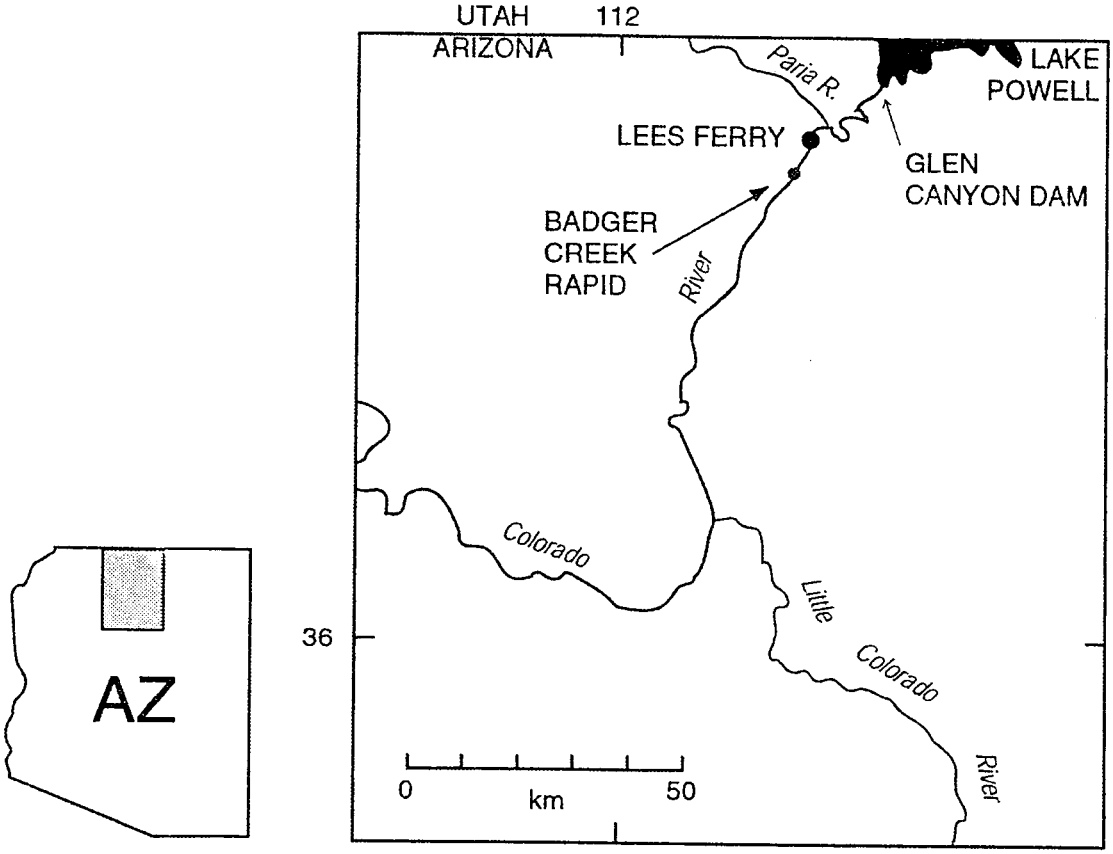
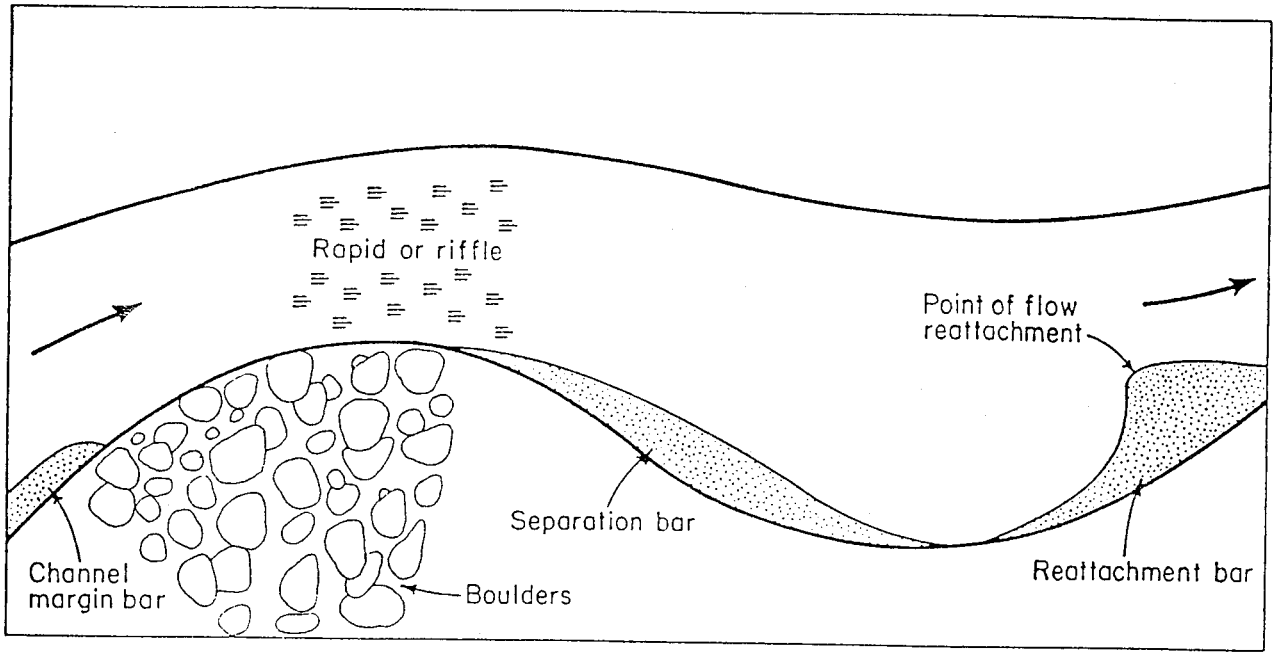


Figure 1. Location map of Badger Creek Rapids

A.



*Adapted from Webb (1996).

B.

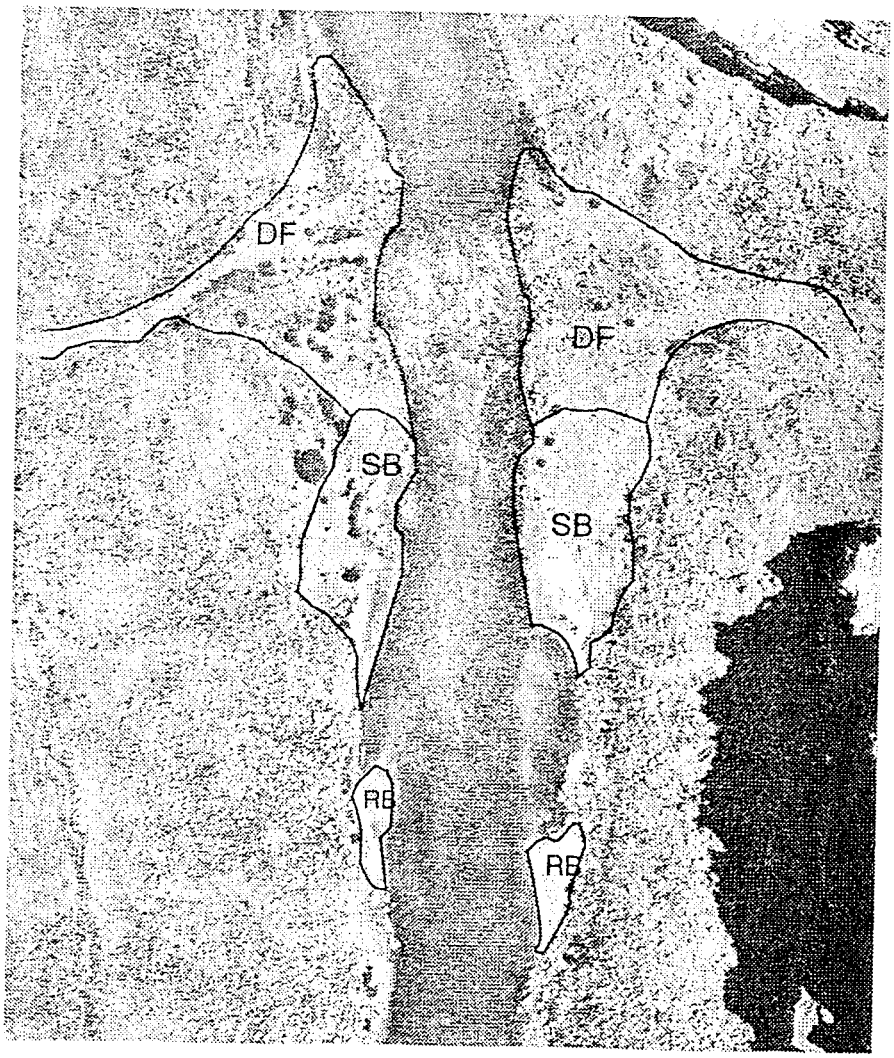


Figure 2. Diagram of a fan-eddy complex (a) and image of the debris fans (DF), separation bars (SB) and reattachment bars (RB) at Badger Creek Rapids as they existed June 16, 1973 (b).

and Jackass Creek canyons. These fans constrict the channel, forming a pooled backwater upstream from the debris fans and a rapid at the constriction. (Figure 2b.) At the downstream side of each fan, the main flow separates from the banks, and eddies exist along the banks further downstream. Separation bars have formed in the upstream part of these eddies, including the separation bar of Jackass Creek debris fan that is the subject of this study. Reattachment bars exist further downstream on each bank.

Previous data have shown that many changes have occurred to the sand bars at Badger Creek Rapids during the last century. The most extensive changes have occurred in the last 30 years (Schmidt, 1992). Much of the study site remained at a nearly constant elevation and similar appearance in photographs taken between 1890 and 1956. The upper portion of the bar began to erode in 1956, most noticeably after 1973. Between 1956 and 1991, nearly 2 m of sediment was removed from the upper portion of the bar on river left (Schmidt, 1992). The reattachment bars on river right and left were extensively eroded by October 1984. Schmidt and Graf (1990) speculated that this erosion was caused by high flows that occurred in 1983 and 1984. These dramatic changes may be due to the lack of rejuvenating sediment-laden high flows that reach high elevation stages. The absence of floods has allowed wind erosion to dominate, and to deflate the surface (Schmidt, 1992).

METHODOLOGY

Data

Diapositives of the three black-and-white, 1:3000 scale, aerial photographs taken October 21 1984, provide complete coverage of Badger Creek Rapids. These diapositives were used to determine the topography of the sand bar, using the method described below. GCPs provided by

the GCMRC for the McCarthy et al. (1999) study were used in this project. The calculated topographic surfaces were compared with the topographic surface calculated by McCarthy et al. (1999) for September 1996. The topographic surfaces generated in this study were also compared to a field survey made by Schmidt (written communication) in May 1985, seven months after the 1984 photos were flown. These survey data consisted of a detailed contour map constructed by hand from more than one hundred field surveyed points (Figure 3).

Photogrammetry Processing

The photo diapositives were scanned at 12 microns, which yielded a pixel resolution of 4 cm. The image files were imported into a digital photogrammetry software program (Ortho*MAX*™ in ERDAS on a UNIX Sun Station) and systematically oriented and registered to surveyed GCPs. Sixteen of the GCPs established by the field surveys for McCarthy et al.(1999) were usable because they could be accurately located on the 1984 photo. Six GCPs were used to generate the topographic model and these 6 points were evenly distributed and accurately located (Figure 4). Fifteen tiepoints, points common to at least 2 of the three diapositives, were selected to improve the distribution of points on the three images.

Using the GCPs and tie points, Ortho*MAX*™ was used to perform an image/match correlation using a triangulation algorithm, which incorporates a 'least-squares block bundle' adjustment, referred to below as the "block adjustment" (McCarthy et al., 1999).

After the block adjustment was completed, stereopairs and an "empty" triangulated irregular network (TIN) were generated. An "empty" TIN is essentially a file that contains 4 automatically generated points. These points are deleted and points representing the surface topography are subsequently generated either by automatic or manual means. I produced a

Figure 3. Surface topography of Jackass Sand Bar based on Schmidt's May 1985 field survey.

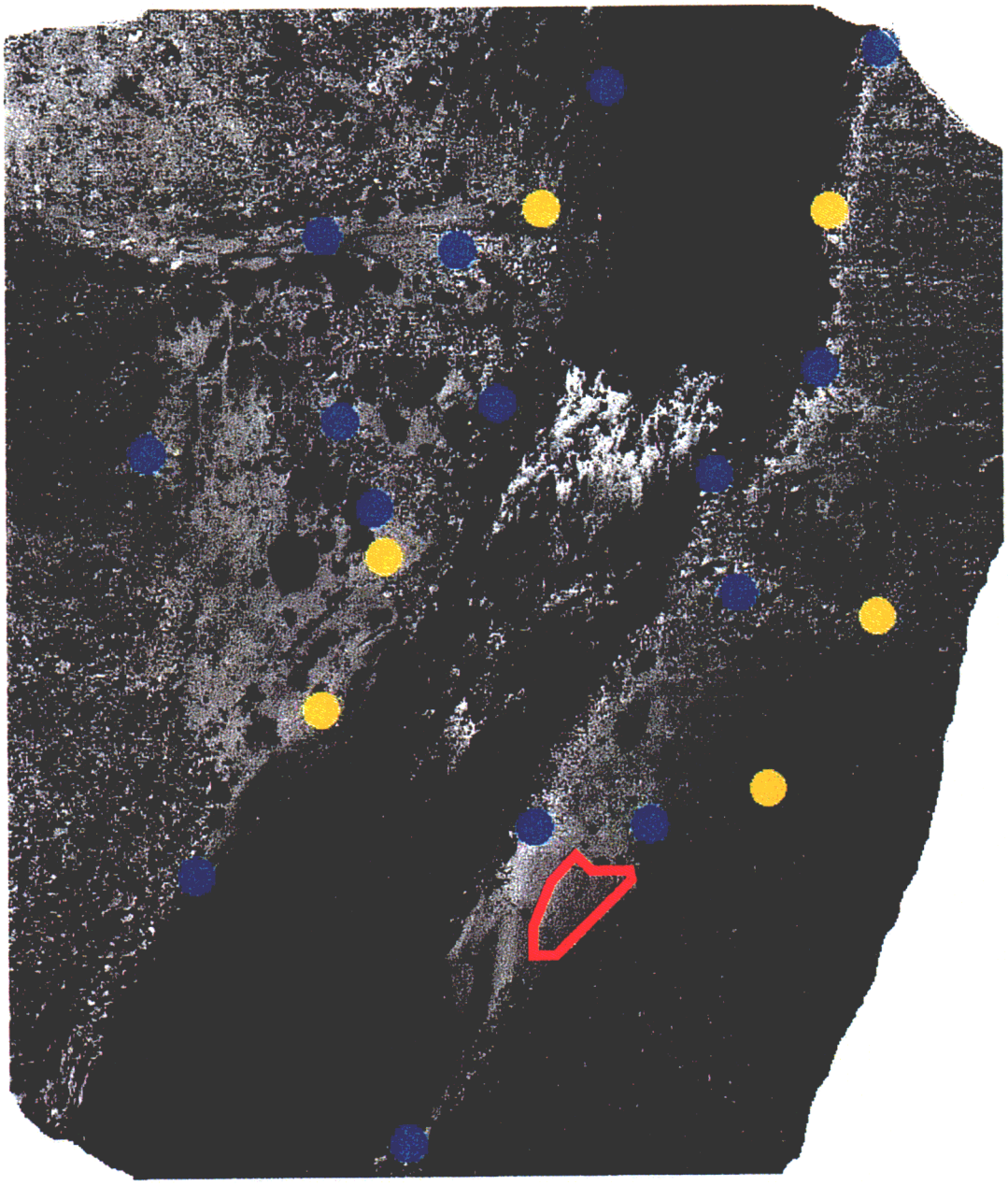


Figure 4. Image of the study area showing the distribution and location of ground control points (yellow) and tiepoints (blue). The outlined area is the clipped region used in all change detection maps and volume calculations.

manually created surface (MCS) and an automatically created surface (ACS); McCarthy et al. (1999) only generated an ACS.

The production of MCSs requires special hardware in the form of stereo goggles, which allow the technician to see the stereopair in three-dimensions. Using a cursor that can be manipulated to appear to "float" above or "sink" into the surface, the technician can essentially survey the surface with the click of the mouse. I created the best surface possible by selecting more than 1300 points and breaklines as necessary to convey the topography of the entire sandbar and a portion of the debris fan on river left. The elevations of these points were independently evaluated by other trained technicians, and adjustments were made to create the most accurate surface possible. These points were then exported to *Terramodel*, a software program, that was used to create the manually generated contours (MGCs) from the point data. This software also allowed the data to be converted into a format useable by *Arcview*, another software program.

Using the same block adjustment, Ortho*MAX*™ was also allowed to make an ACS for the same sand bar by generating approximately 13,200 points spaced 30 cm apart. None of these points were corrected by technicians. These points were exported to *Terramodel* and processed in the same manner as the manually selected points, making automatically generated contours (AGCs) that could be imported into *Arcview*.

Once the MGCs, AGCs, and the contour map from the May 1985 survey had been imported to *Arcview*, a number of steps were taken to assist with analyzing the data. First, a TIN was created for each of the three contour files. These TINs were then converted into grids, which were then clipped to be the same area. The clipped area was the upper-most elevation portion of the bar, which was assumed to have experienced little or no change in the 7 months

between October 1984 and May 1985 since no flows reached that elevation during that time. These two data sets were compared.

Testing For Accuracy

Several tests were developed to check the accuracy of this methodology. Two tests were designed to compare the MCS to the 1996 ACS produced by McCarthy et al. (1999). Several more tests were designed to test the accuracies of the 1984 MCS and ACS using the 1985 survey data. These tests were designed to test the accuracies of individual points and the overall topography for both the automatic and manual surfaces generated using the 1984 imagery.

Comparison of the 1984 and 1996 photogrammetry

In Test 1, a simple comparison was made of the quality of the block adjustment used for the 1984 imagery and the block adjustment used for the 1996 imagery for the study conducted by McCarthy et al. (1999). To do this, the locations of 10 GCPs were identified in empty TINs created from the 1984 data and from the 1996 data. The coordinates for these points were recorded and compared to the surveyed coordinates of the GCPS. Test 2 was to select approximately 30 points common to the 1984 and September 1996 TINs. The X, Y, and Z coordinates were compared. These points were typically small rocks or sharp corners of large rocks that could easily be identified in the 1984 and 1996 imagery.

Accuracy of the 1984 photogrammetry bbased on point analysis

The accuracy of the 1984 MCSs and ACSs was tested on a point-by-point basis. In Test 3, 86 survey points from the May 1985 field survey were "dropped" onto the 1984 MCS and a comparison was made of the elevation values. The same 86 points were then "dropped" onto the 1984 ACS to determine the accuracy of the elevations predicted by the computer.

Accuracy of the 1984 photogrammetry based on topographic analysis

Two tests were preformed to determine the overall accuracy of the 1984 MCS and ACS. The May 1985 survey data were transformed into the same coordinate system so that the three surfaces could be compared. In Test 4, a visual comparison was made by overlaying the MGC and the contours mapped in May 1985. A visual comparison was also made of the automatically generated contours (AGCs) and surveyed contours. Test 5 created maps that detected differences between the created surfaces and the surveyed surface. These maps were made for both the MCS and the ACS. In Test 6, volumes were calculated and compared for the MCS, ACS, and surveyed surface.

Human Error

Test 7 was conducted to assess the human error associated with correctly identifying the locations of the GCPs using the stereo-goggles. To do this, three different skilled technicians selected the same 10 GCPs in the 1984 imagery and their coordinates were compared to the actual surveyed locations of the GCPs.

RESULTS

Photogrammetric Processing

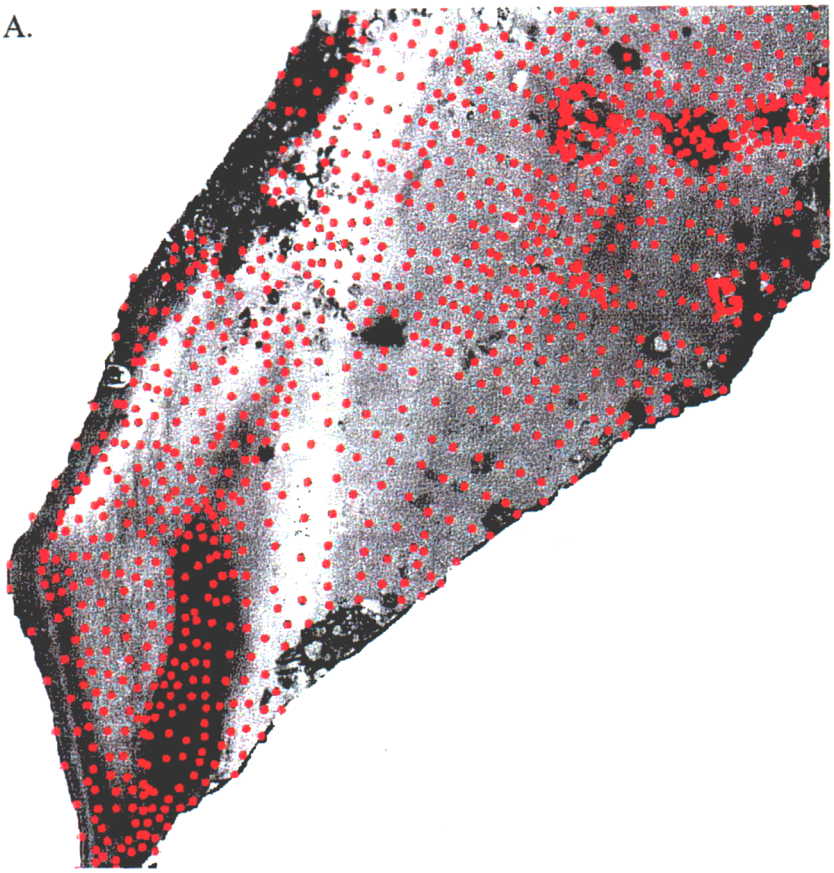
The block adjustment of the 1984 airphotos was within the recommended tolerances established by ERDAS. During the block adjustment process, a report is generated containing information about the quality of the triangulation. This report can be used to identify poorly placed control points and tiepoints so that adjustments can be made to obtain better results. After several adjustments, the triangulation root mean square (RMS) error was 0.78 for all three images, which is well within the 0.5-2.0 range ERDAS recommends. A value of 1.0 indicates the best possible agreement (ERDAS, 1998). The triangulation reported also indicated that all GCPs had all been placed within 2 cm of their actual positions in the X, Y and Z directions.

It should be noted that a different RMS error was associated with the orientation of the images, which is based on locating the exact centers of the fiducial marks. This RMS error did not meet ERDAS recommendations. Values for the RMS error ranged between 5.5 and 7.8 for the three images; the recommended RMS error is 0.5. Although locating the center of the actual cross hairs within the fiducial marks was difficult because the fiducial marks were nearly blacked out, the author and several consultants agreed that the centers had been accurately placed.

There are several possibilities to explain the poor RMS error, but no error source was confirmed. One possibility is that the camera used to obtain this series was incorrectly identified and thus the wrong calibration report data were used in the block adjustment. However, the company that flew the 1984 photography confirmed that the calibration report they had supplied was correct. Another possible source of the high RMS error was that the camera was altered or damaged and the calibration report was inaccurate for the new condition of the camera. However, since previous and subsequent calibration reports were similar, the camera could not have been damaged between reports. Since no source of the poor RMS error could be identified, the block adjustment was accepted.

The end products of the digital photogrammetry process were two topographic surfaces composed of hundreds of points, one created by manual point collection (Figure 5a) and the other by automated means (Figure 5b). The maps showing the MGC and the AGC can be seen in Figures 6 and 7, respectively. An orthophoto of the sand bar was also generated and can be seen as background in several of the figures (Figure 4, 5a, and 5b). This orthophoto was then "draped" over the MCS and vertical exaggeration was applied to emphasize the topography (Figure 8).

A.



B.

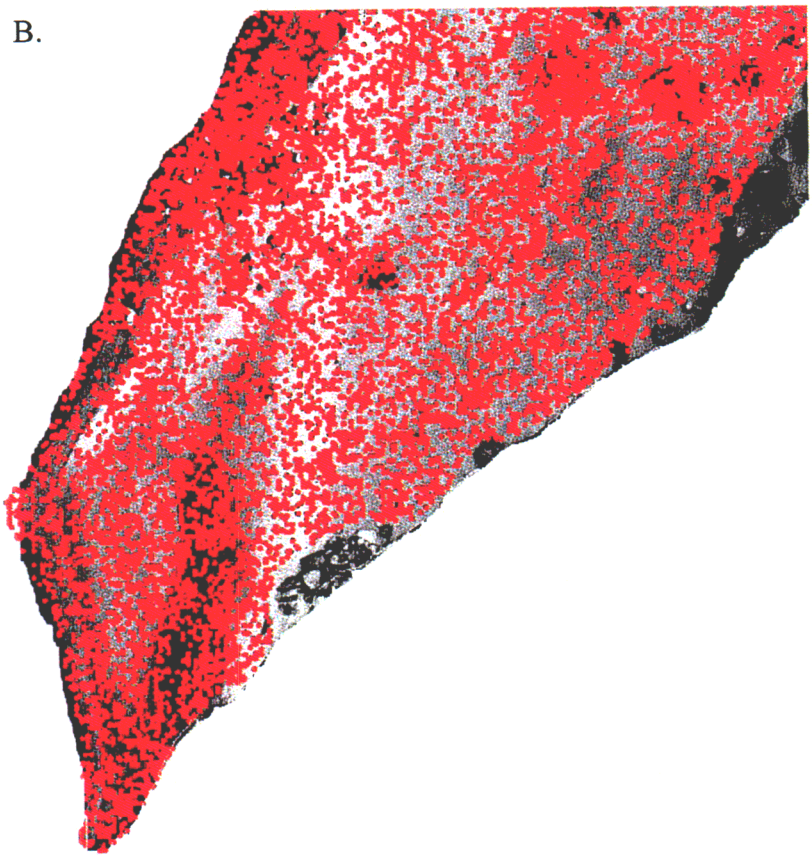


Figure 5. Image showing the manually (a) and automatically (b) collected points for the topography of the sand bar at Badger Creek Rapids in 1984.

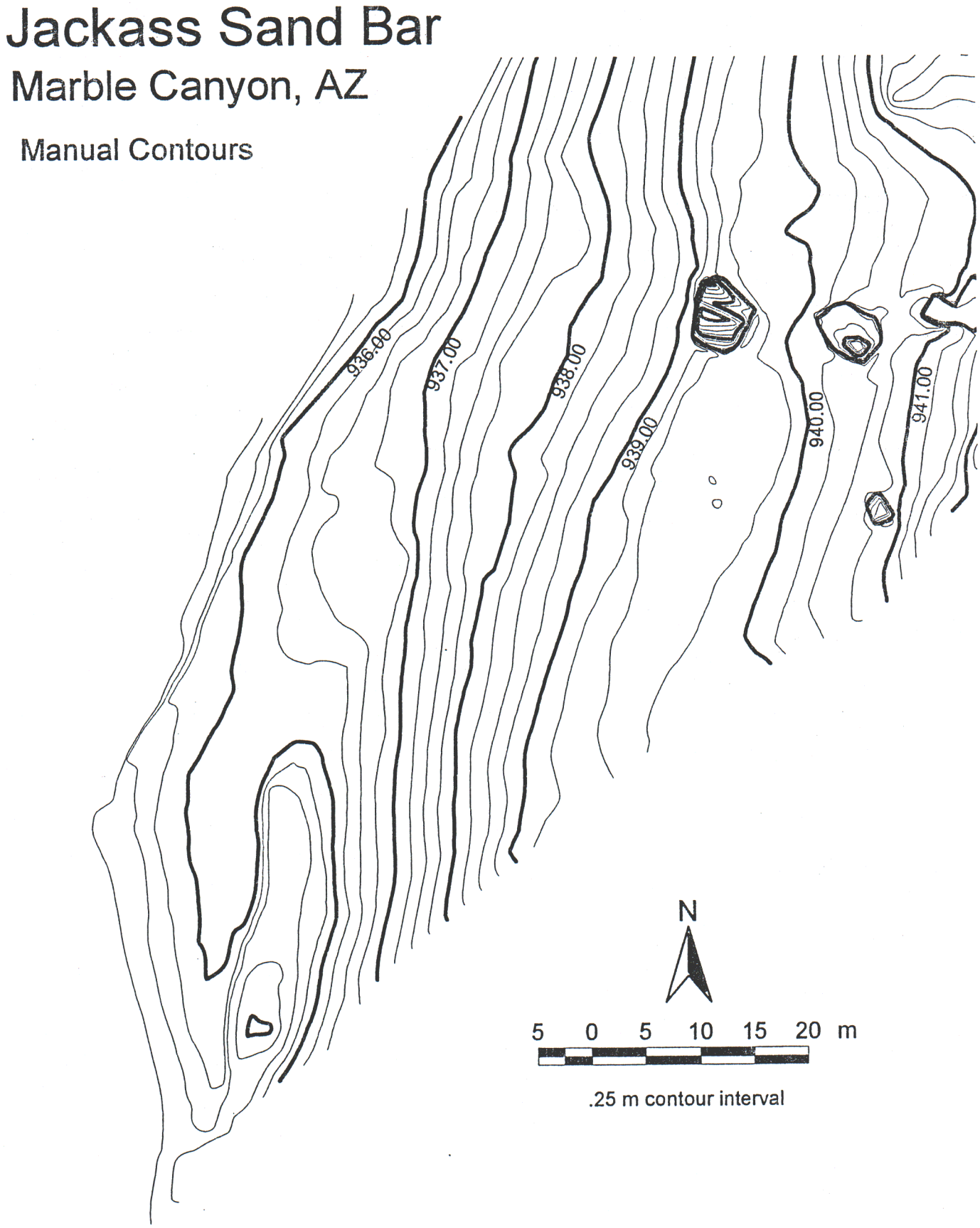


Figure 6. Topography map of the 1984 surface of the sand bar at Badger Creek Rapids created using the manual method.

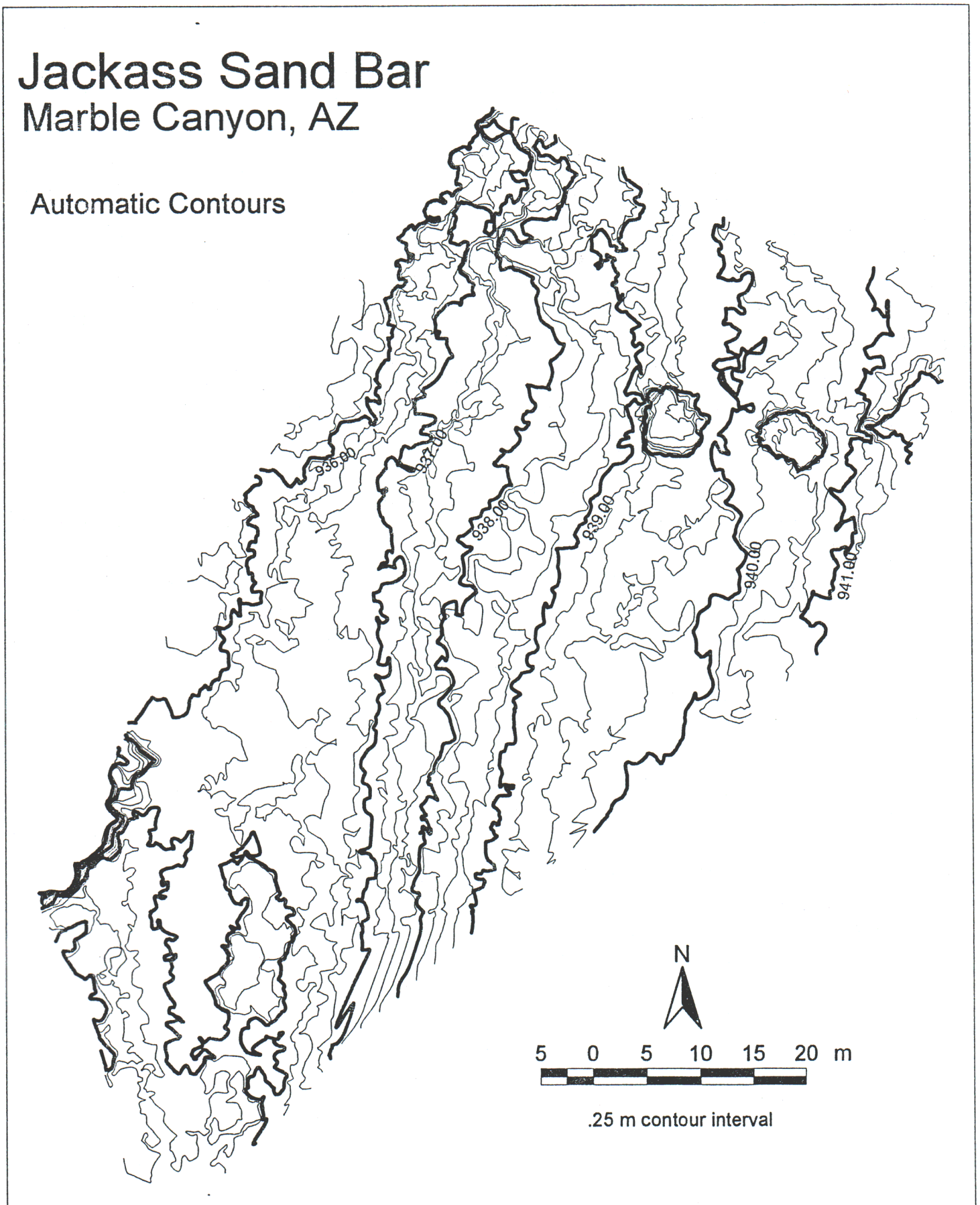


Figure 7. Topography map of the 1984 surface of the sand bar at Badger Creek Rapids created using the automatic method.

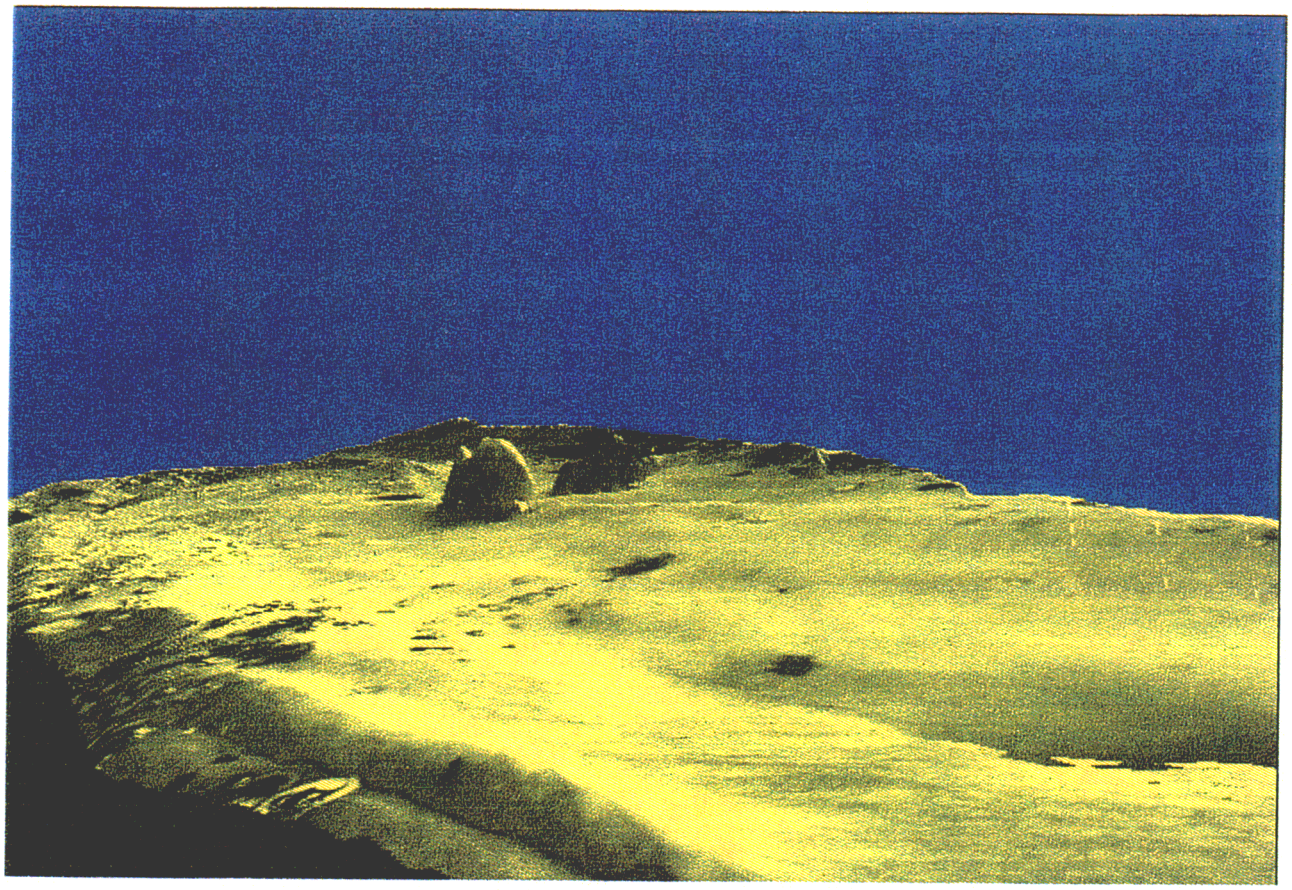


Figure 8. Image drape of orthophoto over a vertically exagerated manually created surface. View is as if we are looking from the river upslope and upriver towards the study site.

Comparison of the 1996 and 1984 photogrammetry

The 1996 photogrammetry of McCarthy et al. (1999) is slightly more accurate than the 1984 photogrammetry, based on comparison of GCPs in Test 1. The average error in the coordinates of 10 GCPs for the 1996 photogrammetry in the X, Y, and Z directions was 11.7 cm, 19.6 cm, and 7 cm, respectively. For the same 10 GCPs in the 1984 photogrammetry, the errors in X, Y, and Z were 11.6, 25.6, and 18.7 cm, respectively. However, 5 of the 10 GCPs examined had been used in the triangulation of the 1996 imagery. When those 5 GCPs were removed, the accuracies of both years of photogrammetry changed only slightly (Table 1). The implication of the accuracies obtained using the 10 GCPs in the 1984 photogrammetry is that no point computed in Ortho*MAX*™ can be expected to be any closer to its true X, Y, Z position than these results indicate. However, the reader should keep in mind that the relief in the study area of $840m^2$ is approximately 3 m.

The precision of any identified point in the 1984 photo was less than 20 cm. In Test 2, the coordinates of the 30 points selected in the 1984 and 1996 photogrammetry differed by between 10 and 20 cm. The average differences in the X, Y and Z directions were 11 cm , 18.1 cm, and 17.5 cm, respectively. This means that by selecting as close to the same point as possible for each year, the points will have slightly different coordinates. However, the usefulness of these tests was compromised by the methodology employed. Because each of the GCPs and the 30 points in both years were selected by hand, human error is difficult to separate from actual differences between the block adjustments for the 1996 and 1984 imagery.

Accuracy of the 1984 photogrammetry based on point analysis

There was little difference between the average point accuracy of the manual and automatic methods; of the 86 points dropped on to each surface, approximately 80% were within

# of GCPS	Year	Error in m for each direction		
10 GCPs		X	Y	Z
	1984	0.117	0.256	0.187
	1996	0.117	0.196	0.072
5 GCPs				
	1984	0.090	0.245	0.193
	1996	0.106	0.199	0.059

Table 1. Error in selecting GCPs between the 1984 and 1996 photogrammetry depending on the number of GCPs compared

25 cm of the surveyed elevations for both surfaces. In Test 3, 79% of the points were within 25 cm for the MCS. The 25 cm level of accuracy has been used by Schmidt et al. (1999) as the level of detail against which to detect significant change. On average, the points dropped onto the manual surface were within 17.5 cm of their surveyed elevations. Of the 86 survey points dropped onto the automatic surface, 80% were within 25 cm and the average error for all points was 17.4 cm, slightly less than the manual methods.

The type of error of the MCS and ACS methods differs. Manual data collection methods resulted in a systematic underestimation of the elevations, because most of the errors are positive (Figure 9a). The histogram of the error associated with the surface created by automatic collection is more evenly distributed with equal amounts of positive and negatives errors (Figure 9b), indicating that the points were randomly located both above and below the actual surface. Histograms of the absolute value of the error associated with both types of surface may indicate automatic method is slightly more accurate (Figure 10a and b). The correlation coefficient of the elevations of these 86 points for both surfaces indicates that the manual method produces slightly more precise elevation values. The coefficient was 0.982 for the manual method as compared to 0.975 for the automatic method (Figure 11a and b). Thus, the MCS method was more precise, but less accurate since it was biased to estimate a lower topography than actually existed. The ACS was less precise, but more accurate, and did not contain systematic errors.

To better understand why these two methods produced different types of errors, two things were done. First, the 86 survey points were placed on the ACS and the MCS to see where the errors occurred (Figure 12 a and b). Many of the most inaccurate points were concentrated in certain areas such as the base of the talus slope, or around the large boulders located on the sand bar. Second, the 86 surveyed points were imported into Ortho*MAX*™ and viewed in stereo.

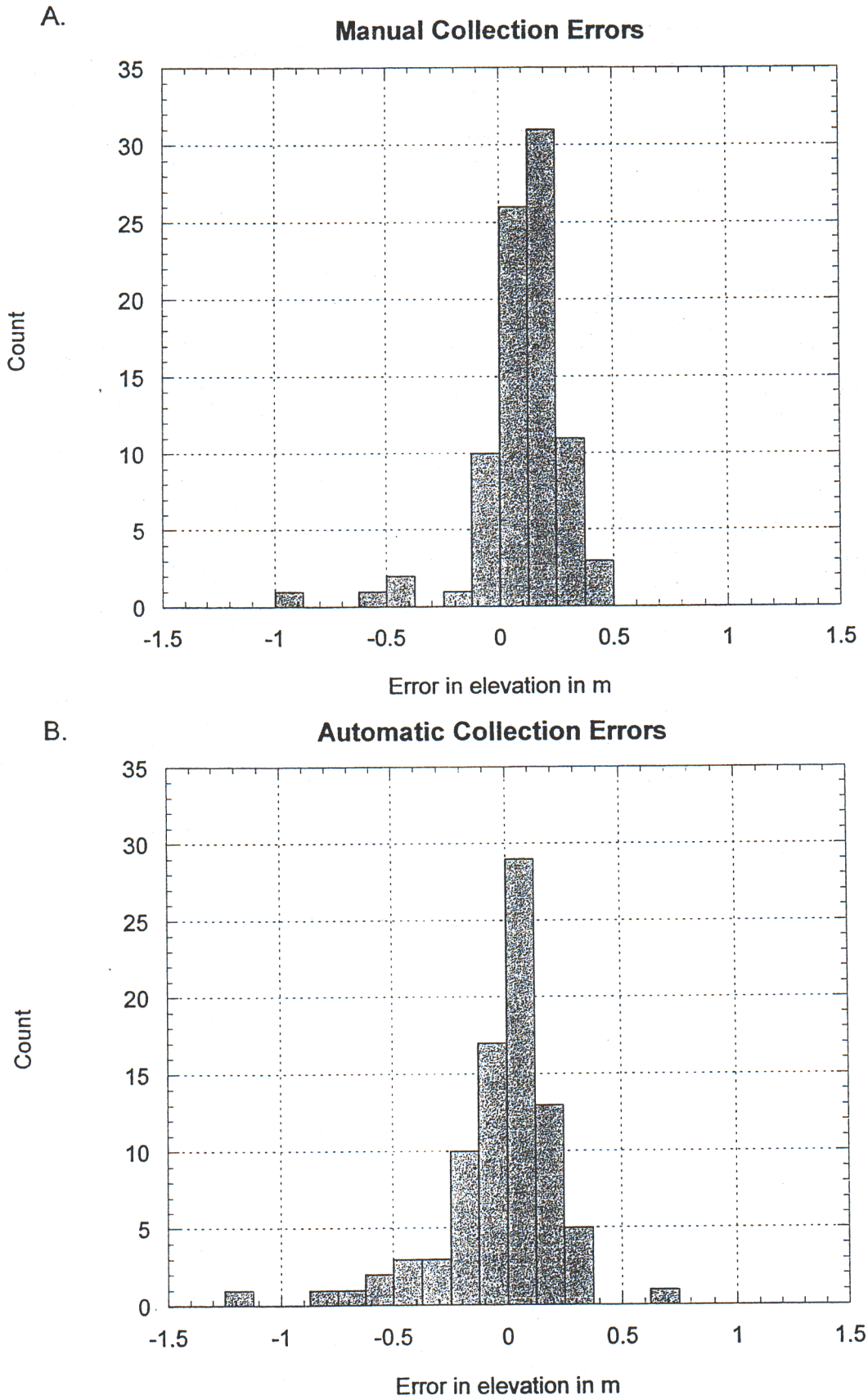
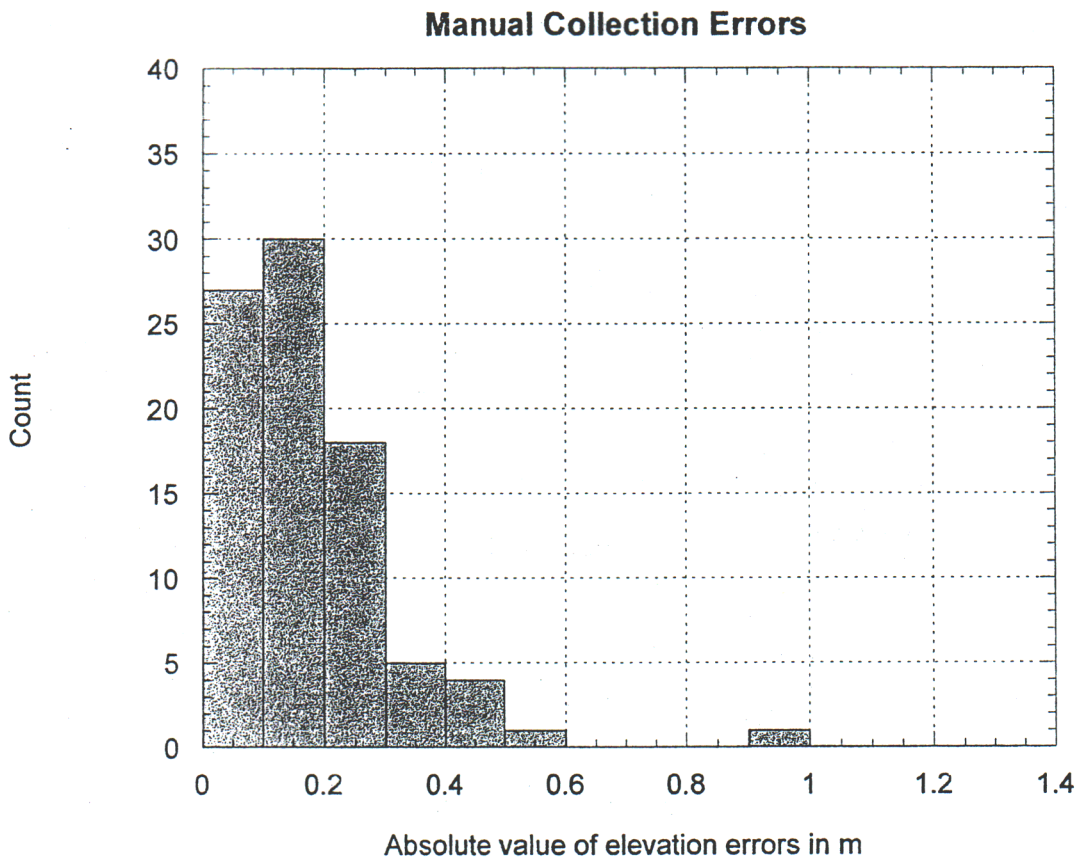


Figure 9. Histograms of the deviation of the elevation-values from their surveyed postion for the manually collected surface (a) and the automatically collected surface (b) for 86 points.

A.



B.

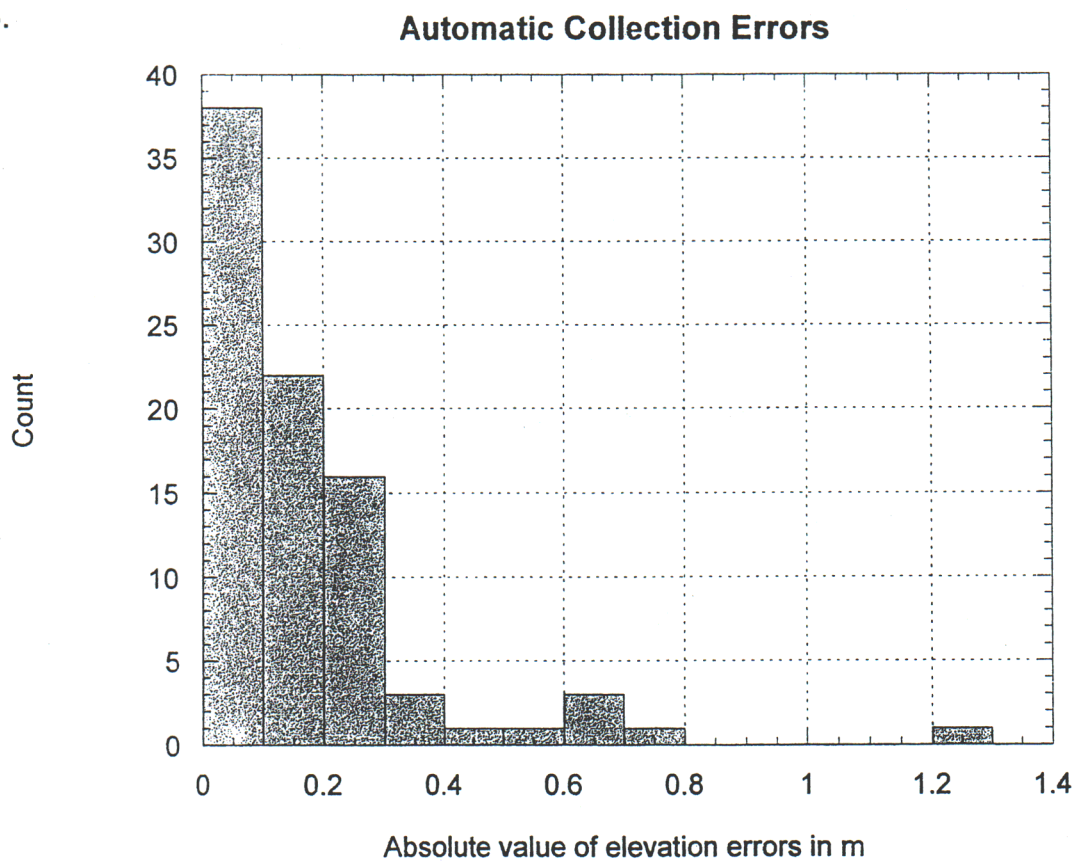
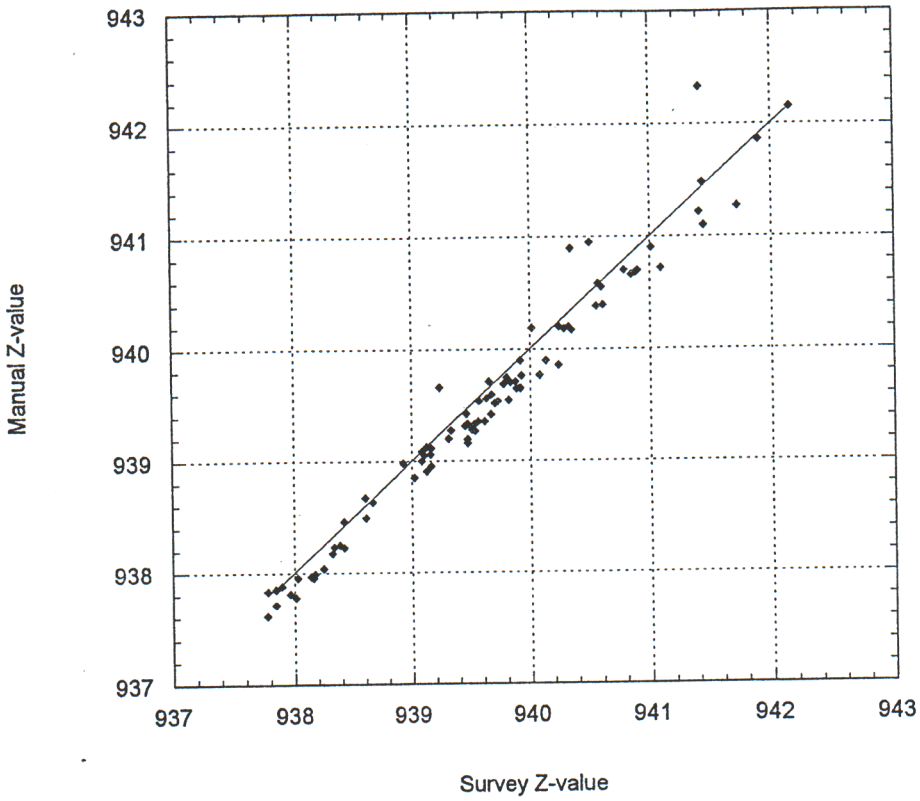


Figure 10. Histogram of the absolute value of the deviation of the elevation-values from their surveyed position for the manually collected surface (a) and the automatically collected surface (b) for 86 points.

A.



B.

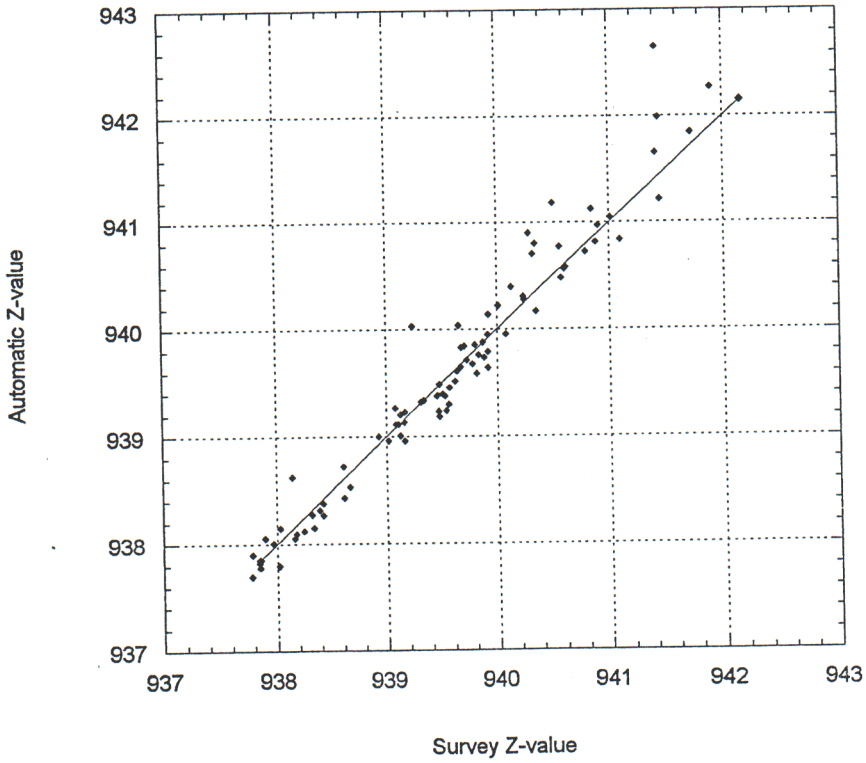


Figure 11. Histograms of the deviation of the z-values from their surveyed postion for the manually collected surface (a) and the automatically collected surface (b) for 86 points.

A.

Error in m

0 - 0.1
0.1 - 0.2
0.2 - 0.3
0.3 - 0.4
0.4 and greater

B.

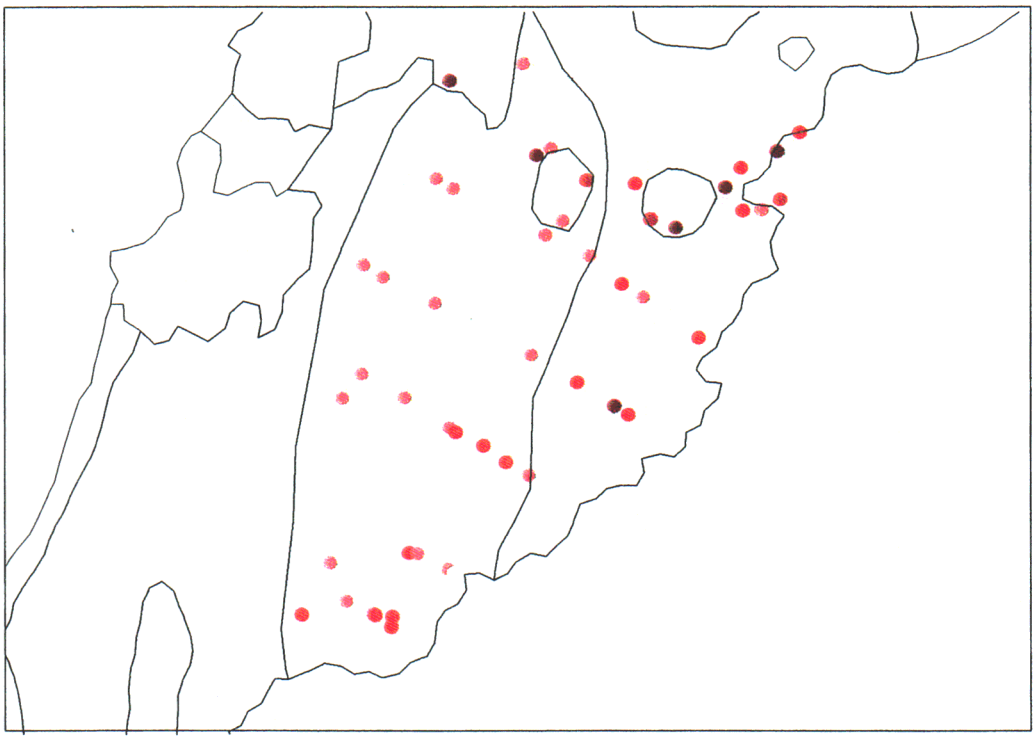


Figure 12. Maps of the 86 points and the amount of error for both the manual (a) and automatic surfaces (b).

This revealed a slight lateral shift in some portions of the survey when it was transformed into the Arizona State Plane coordinate system. The shift was identified by points that were embedded in rocks, when they should have been located on the ground, adjacent to the rock. There were also some discrepancies in the Z direction, with many points appearing slightly too high or low. Thus, while the actual survey data represents the surface of the sand bar in 1984 imagery fairly accurately, small differences in some points may be the cause of many minor discrepancies.

Accuracy of the 1984 photogrammetry based on topography analysis

The MGC method generates much more accurate topographic contours based on a comparison of the contours generated by the 3 methods (Test 4). The contours generated from the MCS are very similar in position and elevation to the field survey (Figure 13). The AGC reflect an intricately dissected surface that does not exist (Figure 14). Overall, the AGC's are generally located in the correct positions, but they are "squiggly" and do not reflect the smooth topography that exists in the photos. The width of the "squiggles" gives some indication of how precisely Ortho*MAX*™ can define a contour, which is within 2 to 7 meters. If the AGCs and MGCs are compared for the entire bar and not just the clipped portion, the AGCs differ radically, in some places, crossing as many as 3 of the MGC's (Figure 15). When viewed in stereo, many of the AGCs in some portions of the bar poorly represent the surface. In some cases, the contours appear to be "floating" above the surface, while in others they appear to be embedded in the sand. Vegetation and abrupt changes in topography seem to be the main cause of errors such as these.

The change detection map based on the ACS method is more accurate then the one using the MCS methods (Test 5). Ninety-six percent of the ACS is within 25 cm of the surveyed

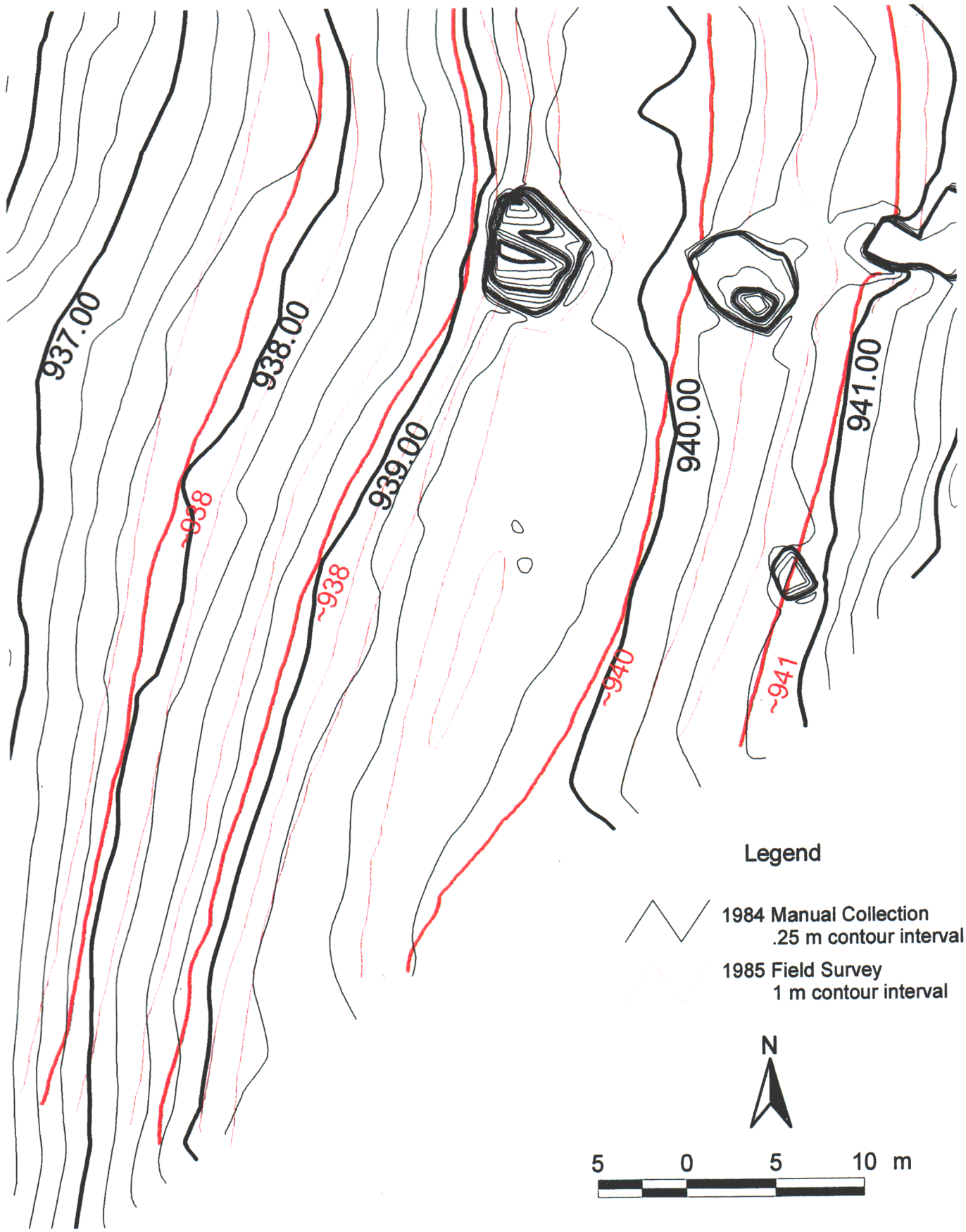


Figure 13. Map showing the manual and field survey contours.

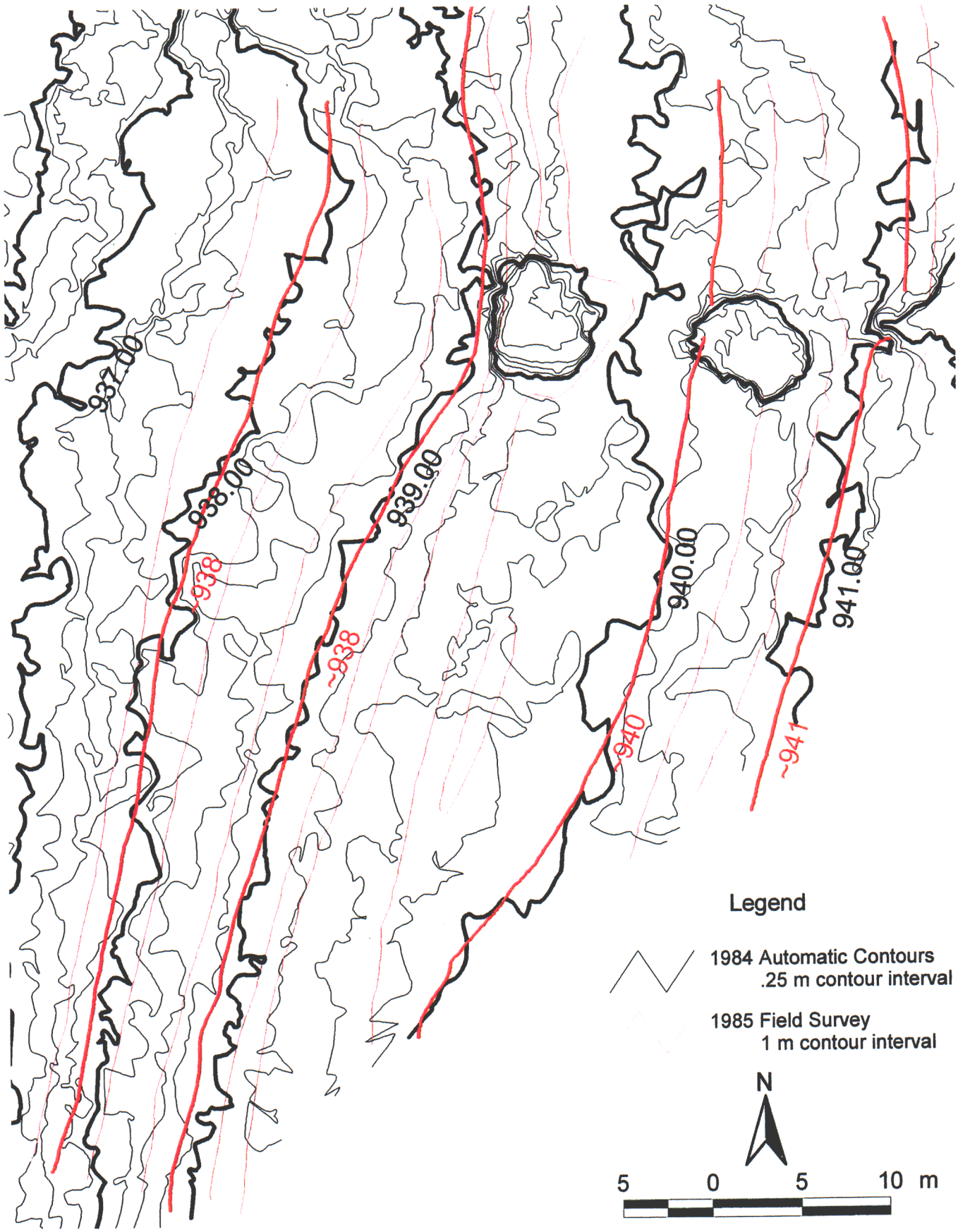


Figure 14. Map showing the automatic and field survey contours.

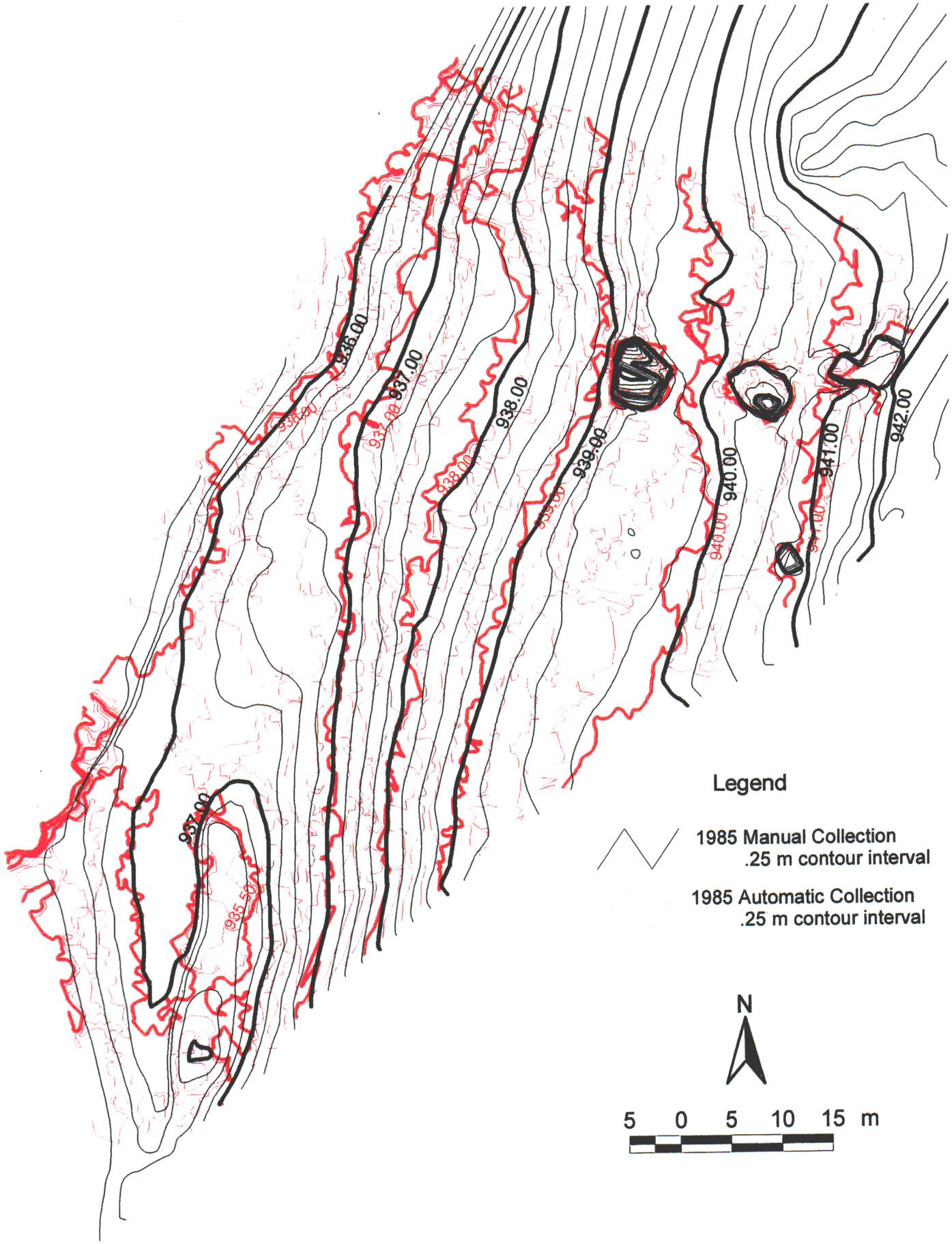


Figure 15. Map showing the manual and automatic contours for the entire sand bar.

surface, compared to 83.7% of the MCS. However, the most inaccurate point on the MCS differs by 67 cm from the surveyed ground surface, while the most inaccurate ACS point was nearly 1 m different. The change detection map between the MCS and the actual surveyed surface shows that much of the surface has been slightly underestimated, which can be anticipated by the results of Test 3 (Figure 16). The change detection map between the surveyed surface and the ACS shows that in some places the automatic method has underestimated the elevation, while in others it has overestimated it (Figure 17).

Table 2 shows the accuracy of both surfaces for given tolerances. Overall, this table indicates that the automatically created surface in general is more accurate then the manually generated surface. However, at the 40 cm and larger tolerances, the manual surface is more accurate, which is most likely a reflection of a few extremely poorly placed automatic points.

Using Test 6, both the MCS and the ACS underestimated the estimated volume of the sand bar in relation to the field survey. The volume of the bar in the clipped region above the 939 m contour is 771.5 m^3, estimated from the surveyed surface. The volume estimated at the same base level for the manual surface is 607.5 m^3, which is 21% less than the actual surface. The automatic surface volume estimate was only 8% less, 709.9 m^3. Clearly the automatic surface seems to provide a more accurate estimation of volume than the manual surface because of the manual method's systematic underestimation of the sand bar topography.

Discrepancies in point data and the overall surfaces for both the manual and automatic surfaces can be attributed to a number of reasons. One possibility is the vertical and lateral shifts noted above. Another possibility stems from the varying densities of data. Approximately 1,300 points were used to create the manually generated surface, while just over one-hundred points were used to create the field map. Thus, the manual contours may be capturing more detail,

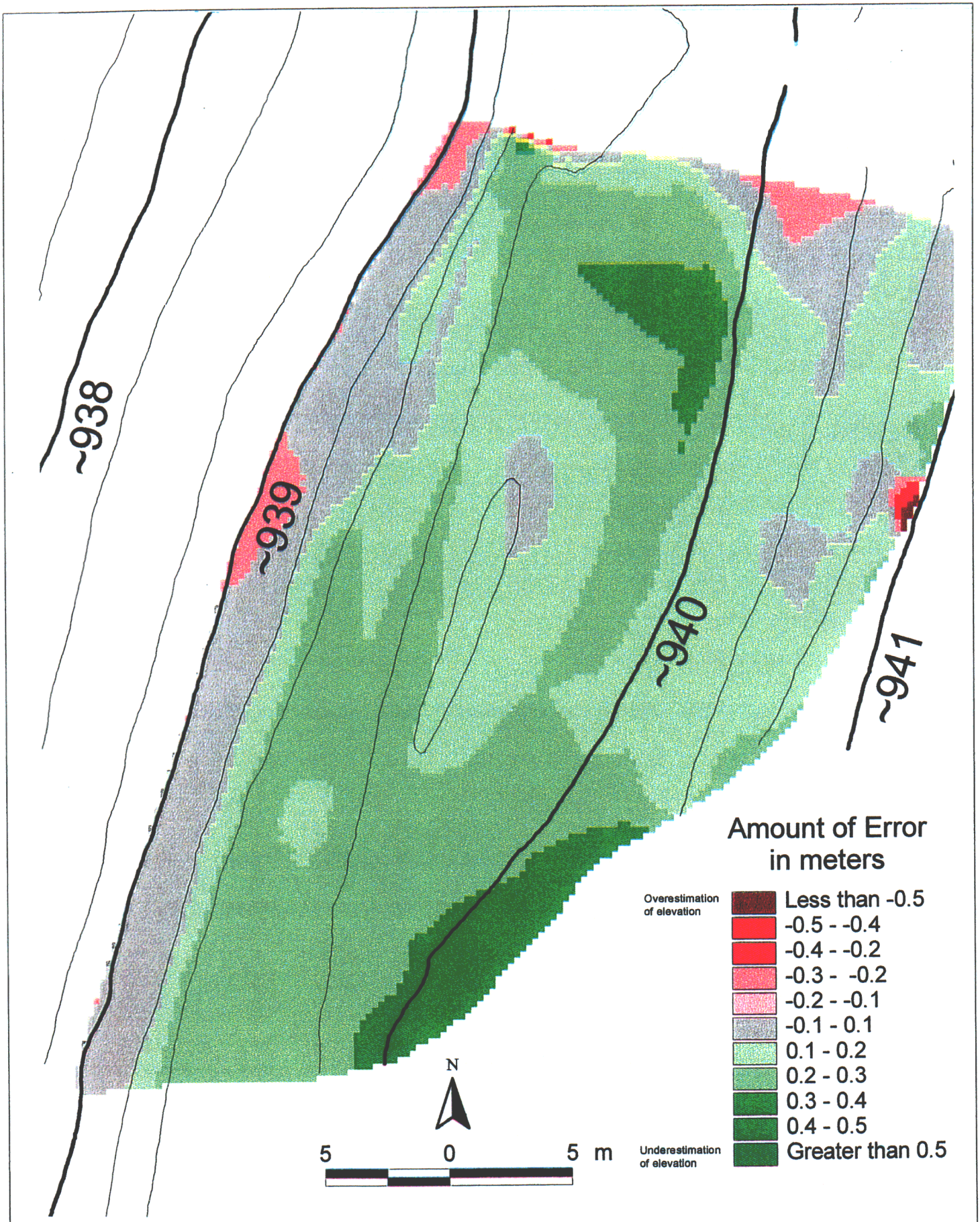


Figure 16. Map showing the error between the manually generated surface and the surveyed topography for Jackass Sand bar in October of 1984. The contours are from the survey field map.

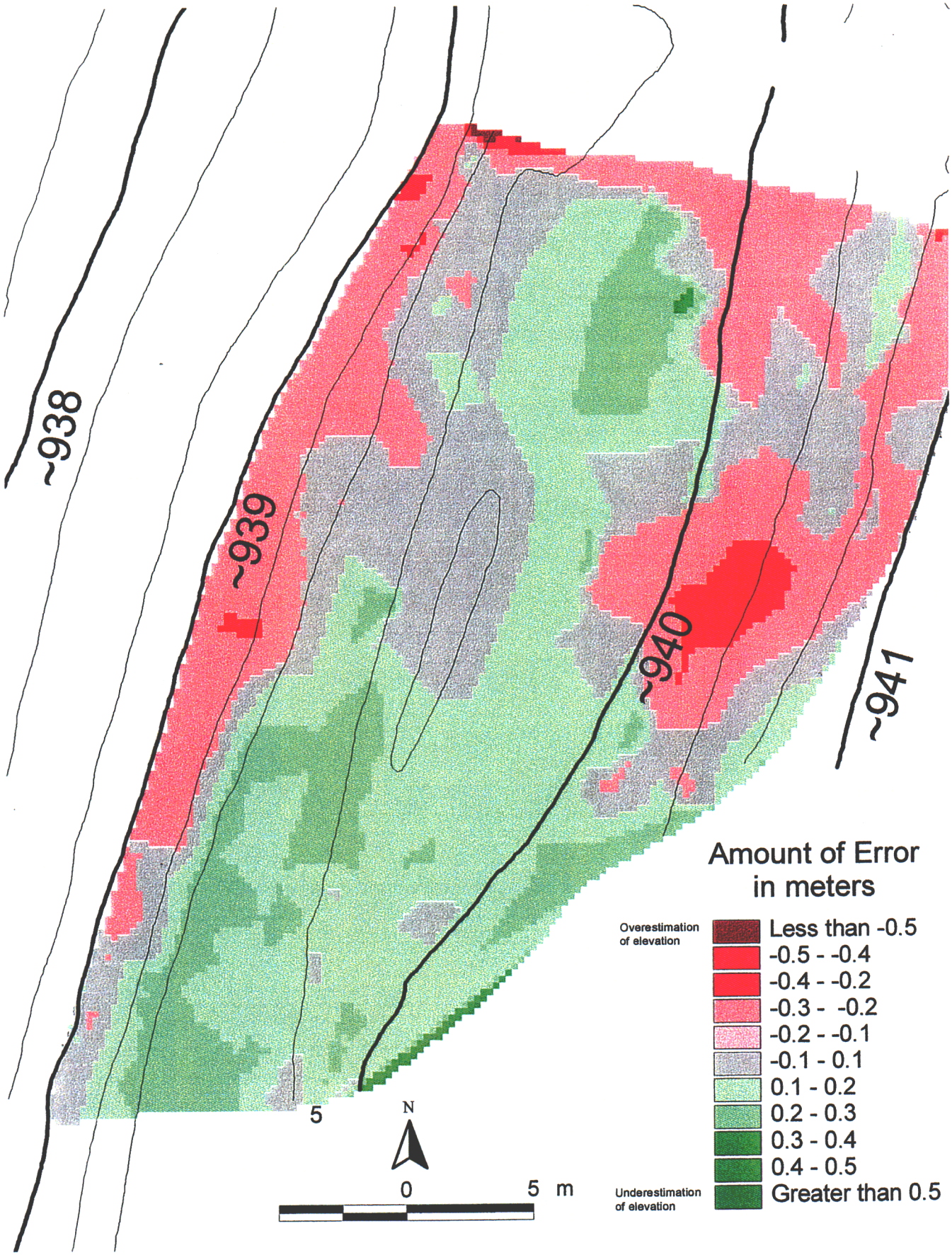


Figure 17. Map showing the error between the automatically generated topography and the surveyed topography. Contours are from the survey data.

Percent within:	Manual	Automatic
5 cm	17.4%	22.1%
10 cm	31.4%	44.2%
20 cm	66.3%	69.8%
30 cm	87.2%	88.4%
40 cm	93.0%	91.9%
50 cm	97.7%	94.2%

Table 2. Percent of the tested points with z-values within a certain amount.

which causes the contours to change slightly. This could also be true for the automatic surface, which is again an order of magnitude richer in data density then the manual surface.

Human Error

In selecting GCPs, it was found that skilled technicians deviated from the true position of the GCPs by an average of 30cm in the X, Y, and, Z directions (Test 7). The histogram of the error for all technicians in the X, Y, and, Z directions show that the amount of error fluctuates greatly (Figure 18). This is a significant finding, because the entire triangulation process depends on being able to accurately determine the location of the GCPs. Accurate placement of the GCPs depended on how well each technician was able to select the exact spot in which the survey rod was held from an oblique photograph taken by a 35 mm camera during the ground control survey. Although this error seems poor, it is primarily a reflection of techniques employed when the GCPs were originally established. The systematic bias of the MCS may also be a result of human error, however the cause of this bias is unknown since 4 different technicians independently evaluated that surface.

DISCUSSION and CONCLUSIONS

Overall, both the manually and automatically generated surfaces were quite accurate in relation to the field survey. Although these methods did not reach the standards of traditional survey methods, they did reach a high level of accuracy. Thus, both methods have great potential to have a significant impact on the way that historical data in Grand Canyon is analyzed.

However, the accuracy and precision of the manual and automatic methods varied depending on what features were examined. The manual method produced much more accurate

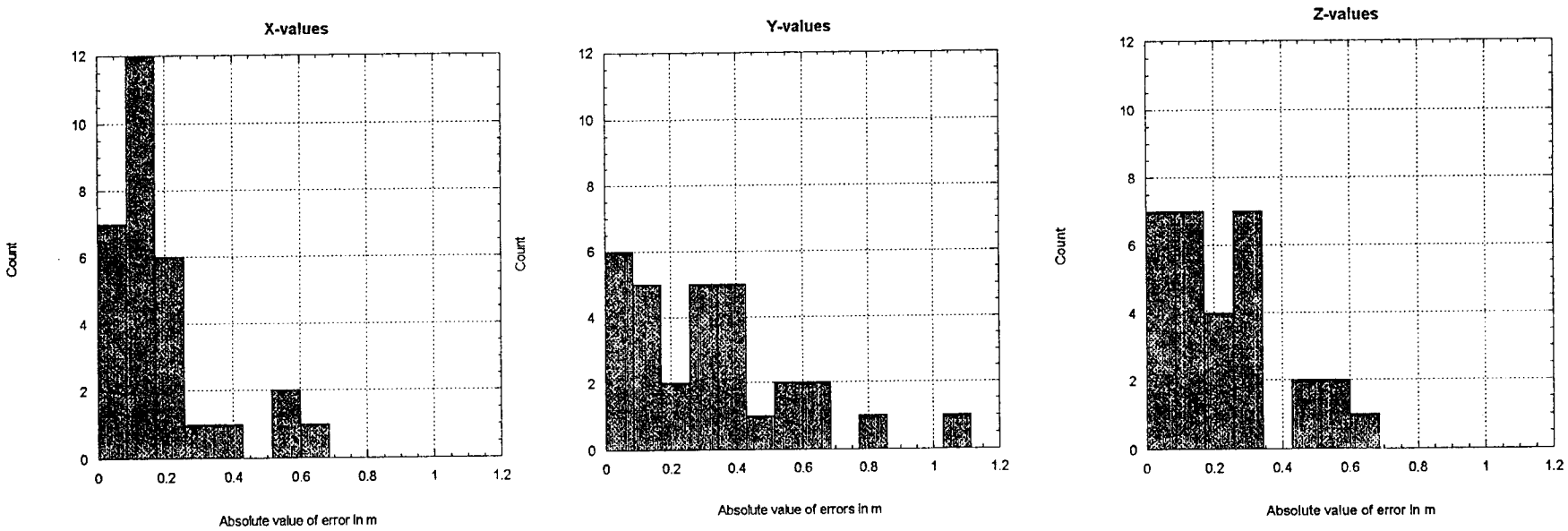


Figure 18. Histograms of the absolute value of error in placing GCPs for 3 technicians in the X, Y, and Z directions.

topographic contours, but introduced the opportunity to have systematic error. The automatic method excelled by creating topographic surfaces that agreed with the field survey over 96% of the surface. The automatic method also produced volume estimates within 10% of the surveyed volume. On a point-by-point analysis, both methods were actually very similar, with neither method noticeable better.

In many ways, these are very interesting findings given that the points Ortho*MAX*™ automatically generates do not seem to truly capture the surface topography in many instances. When viewed in stereo, many of these points appeared to be embedded or floating above the surface by up to 2 meters or more. In many instances, the software seemed to have become confused by vegetation, rocks, and other abrupt elevation changes. The contours also varied in quality, at some points they appeared to follow the surface closely, while at others they deviated substantially.

There are several possible ways to explain why the automatic surface was more accurate in respect to overall topography and volume calculations than the manual method. One possible explanation is that the higher density of points essentially disguises poor points and causes the overall surface to average out and be quite accurate. Another possible explanation for the high degree of accuracy obtained for the automatic surface is related to the area compared. Because the area tested was gently sloping, contains few large rocks, and little vegetation, the site represents essentially the most ideal condition under which the computer can automatically collect points. Finally, the better estimates for the volume of sand produced by the automatic method may be somewhat ficticious. The ACS may only appear to be a better estimator of volume because Ortho*MAX*™ created errors that both underestimated and overestimated the

elevation of the sand bar. Thus, the "holes" and "hills" it created average out and are closer to the surveyed volume.

In the end, an integrated approach, which makes use of the benefits of both methods is probably the best strategy in applying softcopy photogrammetry to historical analysis of Grand Canyon sand bars. A skilled technician is an essential part of the digital photogrammetry process, because a technician is not likely to mistakenly place a point meant to represent the surface of the sand bar in the top of a tree or other similar errors. A technician can also better judge where points are needed to accurately map abrupt changes in a surface by either placing more points or creating breaklines. However, since the automatic method is much faster and cheaper, and on the whole more accurate, it makes sense to use Ortho*MAX*™ to quickly generate a surface. Technicians can then judiciously evaluate and edit the automatically generated topography to create the most representative surface possible. By using this integrated approach, there exists the potential to rapidly and accurately monitor on-going and historical changes in sand bar topography in Grand Canyon.

Potential as a long term monitoring tool

Although there were differences in the degree of accuracy, both techniques yielded quite accurate topographies and have excellent potential as a long term tool for monitoring changes in sand bars in Grand Canyon. No other tool in use or currently being explored (such as LIDAR or oblique photogrammetry) has the potential to accurately reconstruct the topography depicted in a historical photo. This could prove a powerful tool for any site with aerial photography after 1970. Prior to that year, no calibration reports exist for cameras used in Grand Canyon, and the information from the calibration report is essential for the block adjustment process. However, new software is currently being developed that does not require calibration reports. This

advancement in digital photogrammetry could make this technique even more useful because older photos could be analyzed.

Considerations

Although the actual aerial photography is relatively inexpensive and easy to obtain (or, in the case of Grand Canyon, already exists, substantial time is required to process the imagery and generate the topographic surfaces. Experienced technicians can usually complete the triangulation process for one stereo pair in approximately 1 day. If multiple images (i.e. an entire reach) are processed, the block adjustment can be completed in approximately 24 hours for 10 frames. Glitches can and do occur and can necessitate beginning the process over again. One stereopair takes 1-4 hours to generate and a reach of 10 aerial photographs can take up to 24 hours, however, this process can generally be run as a computer batch job overnight. If a surface is generated manually, an experienced technician should be allowed at least 16 hours to create the surface topography, per stereopair. This, however, is dependent on the level of detail required, the complexity of the surface in the imagery, and the amount of area deemed important to map. One to 2 hours should be allowed if a technician only edits extremely poor point on an automatically created surface. Generating the orthophoto is another process that can be run on a computer overnight, and generally takes 1-24 hours, depending on the number of photos used. A highly detailed TIN is the resulting product. Additional time is necessary for analysis and cartography.

Even though digital photogrammetry takes less time to learn than the use of stereoplotters, training new technicians can still take a substantial amount of time (Table 3). The author learned these techniques by assisting the McCarthy et al.(1999) project, with the help of consultants and by trial and error. A technician could also learn these techniques through classes

Activity	Approximate Time to Learn	Approximate Time to Do
Enter data necessary for the block adjustment	2 – 3 hours	1-2 hours
Block Adjustment	2 – 5 hours	4-8 hours
Create manual surface	16 - 80 hours	~40
Check quality of manual surface	None required by trained technicians	1

Table 3 summarizes the steps and the time involved in each photogrammetry process for one stereo pair.

taught by ESRI, the software company that developed Ortho*MAX* and *Terramodel.* The block adjustment process can be learned from several practice sessions with an experienced technician. This can take three to four days to fully master. Creating stereopairs and empty TINs are essentially one step commands that should not take more than one or two attempts to understand. Being able to see the stereopairs in 3-dimensions and have the ability to accurately determine the elevation of the surface is highly dependent on the individual. Some technicians have become adept after 1-2 days, while others need 80 or more hours of practice.

Cost is also a consideration. If diapostives do not already exist, they must be made from the negatives at a price of approximately $20 a piece. These must then be scanned using specialized scanners that do not introduce any distortion, with a cost of $20-$40 per photo, depending if the photo is color or black and white. All of the costs of obtaining targets (survey crew, food, boats, etc) should also be factored in. The wages of the skilled technicians should also be considered. This does not include the cost of machines capable of running the software and storing extremely large amounts of data. It also does not include the cost of the photogrammetry software, programs start at $8,500 and go up depending on the quality of the package.

Recommendations

Several things should be considered when selecting GCPs for historical photogrammetry. First, only rocks that appear in every year of photography should be selected. This will avoid the cost of sending multiple survey trips to set up GCP's for different years. Rocks that are selected should have definite characteristics so that they can be easily identified when viewed in planview. The placement of the rod of the rock is extremely important if highly accurate results are desired. The rod should be placed on definite features of the rock such as sharp corners,

edges of varnish, cracks, or the highest peak on the rock. A planview photograph of the rock with the location of the GCP is also essential for easy and accurate triangulation. GCPs should also be widely distributed over the area of the photos and at least 20 points for each site should be chosen to give the technician options in selecting the best points for triangulation.

To use this method on future photogrammetric projects using new imagery, GCPs should consist of targets that are set out and surveyed. Rocks should not be used as GCPs because of the difficulties in accurately placing GCPs during the block adjustment process. Panja (personal communication) has been able to produce accuracies of about 5 cm using targets, while his few attempts of using natural features in the landscape as GCPs had poorer accuracy. Setting out targets would increase the costs due to the necessary field work, but the increased level of accuracy would easily rival that produced by survey crews.

Another finding of this study is the need to use stereopairs larger than the area of interest in the triangulation process. Extra pairs insure stereo coverage of the entire site and also act to stabilize the triangulation, since the most deviation in elevation values occur on the edges.

Digital photogrammetry has been shown to provide highly accurate, georeferenced data that have great potential to revolutionize both historical and future analyses of changes that occur to alluvial deposits in Grand Canyon. The results of this study indicate that the application of either the manual or automatic techniques both yield very accurate topographies. The most efficient means of using photogrammetry in future studies of Grand Canyon may be to use automatic point collection that is manually edited by a technician. However, extensive editing by technicians may be required to correct error related to vegetation and abrupt changes in topography. In essence, further testing of this technique should be conducted. A repeat of the 1996 imagery using the manual collection technique would be an excellent test.

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