Analysis of Technological Change and Relief Representation in
U.S.G.S. Topographic Maps

by

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(ABSTRACT)

In 1882, the United States Geological Survey began its National Mapping Program designed to map the nation using a series of several thousand topographic quadrangles. Since that date, the program and the maps themselves have undergone many changes due mainly to technological advances in mapping methods. The use of data collected from historic U.S.G.S. topographic maps in modern day applications necessitates a general knowledge of the potentials and limitations of these data. This study compares representations of terrain features on historic maps compiled using plane table methods with the same features as represented on more accurate modern maps compiled using photogrammetry. Using the modern map as a standard, errors in the old maps were identified and defined using statistical procedures. Measures of closed contour lines recorded the angularity of the line, the length of the line, the area within the contour, the shape of the feature and spatial relationships between contour pairs. The analysis attempts to relate errors to these geometric components of contour lines and to predict the occurrence of error. Due to practices of smoothing and generalization of contour lines in plane table surveys, measures of both angularity and shape were significantly different between older and newer maps. Systematic errors, a consistent displacement of contour lines in a similar direction, were also identified on the historic maps. Based on these results, several suggestions for continuation of the research are given.
Acknowledgements

Thanks and appreciation are expressed to several people, not only for guidance in completion of this work, but also for making my graduate experience at Virginia Tech enjoyable and successful. Gratitude is expressed to my advisor, Bill Carstensen, whose patience and support were a constant source of encouragement throughout my two and one-half years at Virginia Tech. Beyond academic guidance, Bill and Bob Morrill accompanied myself and other graduate students to several professional meetings where we were exposed to many different aspects of geography, not to mention learning both the "five-letter word game", as well as several different routes possible between Blacksburg, Virginia and Toronto, Canada.

My thesis work could not have been as successful without the guidance I received from committee members, Jim Campbell and Steve Johnson. I was encouraged to work on my thesis through a course taught by Jim which really gave me a clear understanding of the problem and a boost on the writing itself. Steve's expertise in photogrammetry and in surveying helped tremendously in producing accurate descriptions throughout the text. Thanks also go to Susan Brooker-Gross—we spent several hours discussing the various statistical procedures and the different methods of interpretation. Her knowledge of statistics was invaluable to me.
On a personal level, I'd like to thank my parents, James and Elizabeth Mahoney, who instilled in me the importance and value of education from a very early age. Hard work and perseverance will always lead to success no matter how difficult the problem. The key is not to ever give up. These values lead me not only to pursue a master's degree but to see it through until the end.

Finally, I must thank Glen Foster for his support throughout every class and every page of this thesis. He was patient, fun, tolerated my occasional outbursts and actually remained my boyfriend through it all.
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Chapter I

INTRODUCTION

*History of Mapping at the U.S.G.S.*

In 1882, the United States Geological Survey began the National Mapping Program to compile several thousand topographic quadrangles to map the nation. Since that date, the program and the maps themselves have undergone many changes due mainly to technological advances in mapping methods. This research will analyze these changes by examining differences in terrain representation between U.S.G.S. maps produced at the turn of the century using plane table methods and maps produced during the 1950s after photogrammetry had become the established method of production. Policy changes and events within the National Mapping Program will also be discussed.

The first maps produced by the Geological Survey were actually completed in 1884. These early maps were produced using plane table methods. Although there were ongoing improvements in plane table methods due to better instrumentation, this basic method of survey predominated at the U.S.G.S. for the next several decades.
The introduction of photography as an aid to topographers in the field began as early as the 1920s. Panoramic photos taken from the ground were used to supplement field surveys for more accurate positioning of ground control points. The instrument used to determine distance and direction on the photos was the photoalidade, which essentially replaced earlier instrumentation. The photoalidade was also used as an aid in elevation determination and contour sketching. Further experimentation with aerial photography continued throughout the 1930s, 40s and 50s. Perhaps the most important milestone in the use of aerial photography at the U.S.G.S. was a joint effort with the Tennessee Valley Authority in mapping the entire Tennessee River valley. This project, begun in 1933, was the first to map a large area using airphotos with multiplex methods. This project marked the operational beginnings of photogrammetric techniques. Although this project was successful, the rest of the nation was still being mapped using the traditional ground survey methods.

During the transition from plane table surveys to the use of aerial photos and eventually to full-fledged photogrammetry, a variety of instruments were invented and tested. The use of existing instrumentation of Swiss, Italian and German design provided principles and techniques upon which personnel at the U.S.G.S. could base new designs. The Kelsh plotter developed by H.T. Kelsh and others at the U.S.G.S. made a successful contribution to photogrammetry. European designers of instrumentation included Zeiss of Germany who invented the Zeiss Orthometar, a normal-angle photographic lens. This invention was advantageous over the wide-angle lenses as it was considered distortion-free eliminating need for compensation. The instrument was geared specifically for photography used in mosaic construction of areas "abounding in detailed culture" (Altenhofen, 1951). Another useful instrument was the Wild Autocartograph (A-5 and A-6), a plotter invented by Wild of Switzerland. The prospect of applications of photogrammetry in topographic mapping was exciting but expensive, and was not well-received by certain authorities at the U.S.G.S. Much debate transpired between proponents of photogrammetry, generally younger personnel, and older staff who still felt the only accurate survey was that conducted on the ground.
This transition period extended from about 1930 to 1943. During this time, maps were produced either by plane table methods, photogrammetric methods, or a combination of the two. It became apparent and eventually urgent that a set of accuracy standards be followed by all in the mapping profession. After much discussion and debate, the National Map Accuracy Standards were finally established in 1943. However, their existence did not necessarily mean that maps available at that time met their standards. A period of checking map accuracy began to determine those maps which required revision to meet the standards.

During the post World War II era, the acceptance of established photogrammetric methods became widespread. Many topographers who worked for the U.S.G.S. had joined the Army Corps of Engineers during the war and returned with new knowledge of photogrammetric techniques. By the 1950s, all maps were produced using one of the many photogrammetric instruments available at the time.

Photogrammetric methods continued to be exploited throughout the 1950s, 1960s and 1970s, and today, have been developed further in the context of digital photogrammetry. Map archives at the U.S.G.S. provide not only a wealth of information for anyone with an interest in historical mapping, but also important documents which are still useful in practical applications in today’s world.

Significance

From the viewpoint of sheer human interest, historic topographic maps provide every American with detailed information on the physical growth of his or her community. More specifically, these maps are absolutely invaluable to research efforts concerning growth patterns of urban and rural America.
Over the past few decades, there has been a heightened awareness of changes in our environment caused by the influence of mankind's activities. Much research has been conducted in this area in the fields of geography, hydrogeology, geomorphology and environmental science. More recently, the introduction of Geographic Information Systems (GIS) for handling large volumes of spatial data has facilitated progress of these studies. Because much of the information entered to a GIS comes directly from U.S.G.S. topographic maps, it is essential that we understand the quality of these data and the potentials of historic maps as well as modern maps.

Historic maps at the U.S.G.S. are most appropriately defined as those constructed in the early 1900s using plane table methods established at that time. Depending upon the application, budget considerations, and data compatibility, an organization may or may not use an historic U.S.G.S. map as data input to their GIS. The first consideration is the degree of accuracy essential for the particular project. For example, siting of a landfill requires close examination of topographic slope. As will be discussed later, a major flaw in old maps is the placement of contour lines. If they are positioned inaccurately, the slope will be inaccurate thereby contributing erroneous information to the GIS. In other applications, however, perfect accuracy is not always required, and use of old maps may be effective. Resurveying done in the 1950s focused on economically important areas. Consequently, many rural areas remain covered by either an old 1:62,500 map or by four newer 1:24,000 scale quads. If the 1:62,500 map provides data at a scale compatible with the rest of the information already in the GIS, use of the older map may be more appropriate. Considerable savings can be realized in digitizing smaller scale maps instead of more numerous larger scale maps. Less digitizing also saves time by requiring less error checking and perhaps more important, less chance for human error. As with any data source for a GIS application, historical maps have advantages and disadvantages. It is imperative for the GIS user to understand the quality of the information on these old maps and to know their limitations in the context of the particular research project:

The acceptance of historic maps as less spatially-accurate than modern maps does not render them useless in GIS applications. However, it does require the analyst to proceed with regard to their relative accuracy (Hodgson and Alexander, 1990:114).

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Topographic maps provide important sources of information for key environmental issues which face us today. Samsel and Colten (1988) were able to use data from historical U.S.G.S. maps as input to a GIS to identify locations of hazardous waste disposal areas. Map overlays in the GIS consisted of relief information and drainage patterns as depicted on both the old and the newer maps. They observed the hydrologic and surface alteration activity over time, screened areas indicative of prior hazardous material handling, and were able to delineate present areas of probable hazardous material accumulation.

Another obvious application of historical map data is in the field of geomorphology, especially the analysis of changing water levels in rivers, lakes and oceans. Butler (1989) utilized a succession of U.S.G.S. topographic maps (1904, 1938 and 1968--Chief Mountain, Montana quadrangle) to analyze geomorphic activity and, more specifically, lake morphology in the Glacier National Park area. The marked change in both length and shape in the depiction of Harrison Lake between the 1904/1938 and 1968 quads was questionable. Cartographic inaccuracy was suspected in the old map because field observations showed no evidence of major geomorphic change in the area. After further investigation he confirmed the inaccuracy of the early map due mainly to the absence of accurate ground truth checking at that time.

The historical record should be consulted to determine the extent of ground-truth observations that supported the original mapping. Otherwise, a comparison of landform morphology on original and later topographic maps may lead to erroneous conclusions regarding geomorphic change (Butler, 1989:70).

Technological change in mapping methods over a period of several decades is bound to have a marked effect on the accuracy of the final product. This has been alluded to by studies cited in this chapter. Close examination of the vast amount of information available on technological change at the U.S.G.S. is needed to answer questions which, no doubt, arise in the minds of researchers utilizing data from historic topographic maps.

INTRODUCTION
Chapter II

LITERATURE REVIEW

Personnel at the U.S.G.S. as well as other experts in the surveying and mapping professions have made available an abundance of information on the technique of plane table surveying and the subsequent advance to photogrammetry. The nature of this research necessitates a thorough discussion and understanding of each of these methods.

The technique of plane table mapping has been described as the "classical" method of topographical land survey (Imhof, 1982). Bagley (1917) described it as the best method of survey suited to mapping a variety of relief.

The necessary instrumentation needed for a plane table survey included the plane table and tripod, the telescopic alidade, the stadia rod, and a collection of drafting tools. The telescopic alidade (Fig.1) was positioned on the plane table and tripod assembly, and was used to determine both distance and direction to the feature being mapped. The telescope was oriented with magnetic north, and direction lines were easily drafted directly onto the plane table sheet by drawing a pencil line along a beveled edge attached to the alidade. Within the lens of the telescope were three stadia wires (horizontal wires) and a cross wire (vertical wire) for centering the feature. Distances were
determined by observing the portion of the graduated stadia rod seen between the upper and lower stadia wires. A simple conversion based on a fractional relationship (1:100 in most instruments) between stadia wire distance and ground distance provided the horizontal distance to the feature. The instrument was also equipped with a vertical angle arc and arc vernier to determine inclination. The topographer could read vertical angles off the scale and make simple calculations for reduction of horizontal distance caused by slope. In moderate or level terrain, the alidade was also used to determine elevation. Elevations of unknown points were determined from known elevations by observing the stadia and the inclination of the telescope and computing the difference between the two points.

As in any type of survey, accurate results in plane table surveys were largely dependent upon the amount and distribution of control, as well as the degree of accuracy to which measurements were made. Bagley (1917) described map control as being divided into two classes: 1) precise control—correct positioning of the map on the earth’s surface according to latitude and longitude, including correct positioning of the stations relative to one another. This type of control was relatively expensive, and was obtained independently of topographic surveys; and 2) less precise control—a network of elevation points and distances commonly carried along simultaneously with the topographic survey. It was the uniformity in distribution of elevation points, and distances from which features were mapped that determined the accuracy of the final product.

Difficult topographic situations had an effect upon accuracy of surveyed points for the mapping project. Distances from which contouring could be done were dependent upon the contour interval to be achieved, but in steep terrain had to be left up to the topographer. Birdseye (1928) stated that for a 20-foot contour interval, distance between the instrument station and the feature should range between a quarter mile and one mile. For larger contour intervals of 50 or 100 feet, distances were relatively longer, though no exact ranges were stated. This imprecision was due to the nature of the terrain where a larger contour interval was required. In rugged regions, topographers were limited in choice of stations to set up the plane table. In such situations, surveyors were forced to resort to very crude methods of distance measurement such as wheel traverse or pacing.
Figure 1. Topographic alidade. A) Telescope; B) Vertical circle or Beaman arc with horizontal and vertical stadia wires; C) Blade with distance rule. (Adapted from Low, 1952:21).
The amount of elevation points and uniformity of their distribution was also impaired by difficult topographic situations. Mountainous areas were simply harder to access and an adequate amount of elevation points could not always be acquired immediately. Therefore, it was often necessary to subdivide the area into regions according to drainage, and to sketch preliminary form lines to represent contours. When the necessary points could be acquired, contours could be sketched with the aid of form lines without returning to the area. This problem resulted in non-uniformity of accuracy within a map covering a wide range of terrain types.

In addition to topography, basic methods of map compilation also had an effect upon accuracy. A field scale for mapping of 1:48,000 was used for all terrain types. This was necessary mainly due to limitations in instrumentation. In production, these sheets were reduced to what was termed the "general utility scale" of 1:62,500, "thus rendering field errors less conspicuous" (Sherman, 1933:77).

Beyond the aforementioned practical considerations and, perhaps partly, as a result of obstacles which faced surveyors, a large element of subjectivity characterized plane table surveys. This subjectivity was termed "topographic expression". Plane table surveys have been referred to as an "art" in many references (Birdseye, 1928; Imhof, 1982; Low, 1952). "The most accurate geometric representation of a land form may appear wooden or lifeless on a map unless it is also given its true characteristic expression" (Birdseye, 1928:254). The idea of perception on the part of the individual topographer was very significant. To a certain extent, actual sketching of contours was done with reference to the control in the area. However, one person may have chosen to emphasize or exaggerate a feature while another may have smoothed it over. Contours were drawn in groups, and care was taken in the alignment of contours with one another. Separate features which were close to one another as part of the same ridge, for example, were also drawn in groups to emphasize their relation to one another and to portray a smooth appearance. Edge lines, including drainage lines, shorelines, terrace edges, rock edges, edges of ditches and prominent ridge lines were used as topographic guidelines. Contours would be drawn with reference to these lines. It was thought that this technique would insure the true characteristic representation of a feature. Topographers were required to read textbooks and other references to learn about geology and geomorphology to give
them a better understanding of relief forms. Thus, the accuracy of terrain representation was dependent upon the skill, knowledge and experience of the individual topographer.

Smoothing of contour lines is very characteristic in these old maps. In addition to the field surveyor, the draftsman inking the map in the office was also allowed a certain amount of topographic expression, and often would alter the relief forms slightly to produce either a smoother appearance or one which he thought corresponded more closely to the edge lines of the area.

The whole notion of accuracy in historic U.S.G.S. maps was best summarized by a well-known topographer experienced in plane table mapping:

Accuracy in a topographic map can be truly measured only by a combined appraisal of the character and amount of its control, its adjustment, the accuracy with which field measurements have been taken and plotted, the ease with which the features mapped can be identified, its amount of detail or degree of generalization, the consistency of its parts, its freedom from errors and omissions, and its date of survey (Birdseye, 1928:181).

With the introduction and eventual widespread application of photogrammetric techniques in the 1950s, the National Mapping Program at the U.S.G.S. was able to produce maps which were uniformly accurate over a wide variety of terrain. This was a major improvement over the early surveys. Using aerial photography more of the terrain can be seen, and distances from which features are mapped remains constant. In a mountainous area, the topographer at the turn of the century may have only been able to see part of the feature from his vantage point--accuracy was dependent upon interpolation and experience. With the photogrammetric instrument, the floating mark could be fixed vertically, allowing horizontal movement of the tracing table over the map surface. The element of interpolation was greatly reduced. Each contour line was drawn independently with the greatest care taken in showing the detail of the terrain. It was also easier and less expensive to obtain a very dense network of elevation points. Use of edge lines as topographic guidelines was sometimes applied in mountainous terrain as was the case in plane table surveys, but accurate positions were more easily obtainable using photogrammetric instruments.
The limitations of photogrammetric surveys are obviously of a lesser extent than those with the early plane table surveys. However, as with any mapping procedure, there are always factors which contribute to errors. A major area of research in the late 1940s and early 1950s was devoted to estimation of effects of lens distortion in aerial photography. Davey (1949) found that up to 10 percent of the aerial photography obtained for the U.S.G.S. by various contractors was wholly or partly unusable. This was due not only to effects of lens distortion but also to effects of air turbulence, exhaust gases, atmospheric conditions and heat within the field of the lens. Another factor affecting accuracy was the skill of the photogrammetrist. There were many types of instrumentation available, each suited to a particular terrain condition, and the adaptability of the operator to learn a new instrument along with his ability to guide the floating mark had an effect upon the end product.

Compilation of maps using aerial photography has some specific advantages over ground survey methods. Control over flying height of the airplane enabled acquisition of photographic coverage over a wide range of scales, accommodating varying amounts of relief. The many different instruments available were each capable of producing accurate results from photography at a particular scale. The accuracy of each instrument was denoted by its "C-factor", the ratio of flight height to contour interval (Table 1). To get accurate results with the Multiplex at a 20-foot contour interval, the flying height must be no greater than 16,000 feet. The photography for the more sophisticated Stereoplanigraph could be acquired at heights of over 24,000 feet, and the accuracy would still be maintained. With the variety of instrumentation available, a range of compilation scales could be used (Table 2). This flexibility had obvious advantages over the constraints involved in plane table surveys.

The rapid advance of technology and the increasing variety of options available at the U.S.G.S. necessitated the adoption of some standards to be used in map construction. As stated in Chapter I, the National Map Accuracy Standards were first established in 1943. However, the latest revision, made in 1947, is still in effect today (Table 3).
Table 1. Photogrammetric instrumentation in order of accuracy capability as determined by the C-factor (From Altenhofen, 1951).

<table>
<thead>
<tr>
<th>Instrument</th>
<th>C-factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Multiplex</td>
<td>600 to 800</td>
</tr>
<tr>
<td>Kelsh</td>
<td>850 to 1,000</td>
</tr>
<tr>
<td>Autograph A-6</td>
<td>900 to 1,100</td>
</tr>
<tr>
<td>Autograph A-5</td>
<td>1,000 to 1,200</td>
</tr>
<tr>
<td>Stereoplanigraph</td>
<td>1,200 to 1,250</td>
</tr>
</tbody>
</table>
Table 2. Options available due to the variety of photogrammetric instrumentation (From Altenhofer, 1951).

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Quad Size</th>
<th>Int. (ft.)</th>
<th>Plotting Scale</th>
</tr>
</thead>
<tbody>
<tr>
<td>Multiplex and Kelsh</td>
<td>All</td>
<td>10</td>
<td>1: 6,000 or 1: 7,200</td>
</tr>
<tr>
<td>Multiplex and Kelsh</td>
<td>All</td>
<td>20</td>
<td>1:10,000</td>
</tr>
<tr>
<td>Multiplex</td>
<td>All</td>
<td>40</td>
<td>1:15,840</td>
</tr>
<tr>
<td>A-6, A-5, Stereoplanigraph</td>
<td>7½'</td>
<td>All</td>
<td>1:15,840 or 1:20,000</td>
</tr>
<tr>
<td>A-6, A-5, Stereoplanigraph</td>
<td>15'</td>
<td>All</td>
<td>1:31,680</td>
</tr>
</tbody>
</table>
United States National Map Accuracy Standards

With a view to the utmost economy and expedition in producing maps which fulfill not only the broad needs for standard or principal maps, but also the reasonable particular needs of individual agencies, standards of accuracy for published maps are defined as follows:

1. Horizontal accuracy. For maps on publication scales larger than 1:20,000, not more than 10 percent of the points tested shall be in error by more than 1/30 inch, measured on the publication scale; for maps on publication scales of 1:20,000 or smaller, 1/50 inch. These limits of accuracy shall apply in all cases to positions of well-defined points only. Well-defined points are those that are easily visible or recoverable on the ground, such as the following: monuments or markers, such as bench marks, property boundary monuments; intersections of roads, railroads, etc.; corners of large buildings or structures (or center points of small buildings); etc. In general what is well defined will also be determined by what is plottable on the scale of the map within 1/100 inch. Thus while the intersection of two road or property lines meeting at right angles would come within a sensible interpretation, identification of the intersection of such lines meeting at an acute angle would obviously not be practicable within 1/100 inch. Similarly, features not identifiable upon the ground within close limits are not to be considered as test points within the limits quoted, even though their positions may be scaled closely upon the map. In this class would come timber lines, soil boundaries, etc.

2. Vertical accuracy, as applied to contour maps on all publication scales, shall be such that not more than 10 percent of the elevations tested shall be in error more than one-half the contour interval. In checking elevations taken from the map, the apparent vertical error may be decreased by assuming a horizontal displacement within the permissible horizontal error for a map of that scale.

3. The accuracy of any map may be tested by comparing the positions of points whose locations or elevations are shown upon it with corresponding positions as determined by surveys of a higher accuracy. Tests shall be made by the producing agency, which shall also determine which of its maps are to be tested, and the extent of such testing.

4. Published maps meeting these accuracy requirements shall note this fact on their legends, as follows: "This map complies with National Map Accuracy Standards."

5. Published maps whose errors exceed those aforesaid shall omit from their legends all mention of standard accuracy.

6. When a published map is a considerable enlargement of a map drawing (manuscript) or of a published map, that fact shall be stated in the legend. For example, "This map is an enlargement of a 1:20,000-scale map drawing," or "This map is an enlargement of a 1:24,000-scale published map."

7. To facilitate ready interchange and use of basic information for map construction among all Federal mapmaking agencies, manuscript maps and published maps, wherever economically feasible and consistent with the uses to which the map is to be put, shall conform to latitude and longitude boundaries, being 15 minutes of latitude and longitude, or 7.5 minutes, or 3-1/4 minutes in size.

Issued June 10, 1941
Revised April 26, 1943
Revised June 17, 1947

U.S. BUREAU OF THE BUDGET
Attention is directed to Item no. 2 of the Map Accuracy Standards which states the fact that the accuracy requirement is based on the contour interval of the map. Item nos. 4 and 5 should also be noted—they simply exemplify the economic considerations that must be realized. Even in a photogrammetric survey, it was not economically feasible to attempt to map difficult terrain to the highest degree of accuracy.

Since the adoption of the National Map Accuracy Standards, the U.S.G.S. has been conducting accuracy tests on their maps by identifying the actual position and elevation of points on the ground and comparing them to their positions on the map. This method is used in determining the accurate placement of cultural features as well as physical features. In Figure 2, Thompson (1956) illustrates the confusion in defining the error in linear features with an example of the positioning of a railroad track on two surveys of different orders of accuracy. At point O the linear features are in perfect alignment; at point A-A' the error is large, and at point B-B' the error is small. Obviously, when using single points, the overall accuracy of the feature cannot be defined without some bias involved.

The British Ordnance Survey uses a method similar to that used by the U.S.G.S. They employ a ground survey to determine the actual elevation at points where random transect lines intersect contour lines on the map. Again, the ability to determine accuracy of the linear feature is only possible at particular points.

Errors which can occur in contour lines as the result of an inaccurate survey can be placed into categories as described by Imhof (1982). The first error type concerns the source of error and consists of errors relating to geometric components. These are errors in shape, direction errors, curvature errors, errors in lengths, and slope errors. A second category concerns the behavior or effect of the error and consists of errors classified as "blunders", systematic errors, and random errors. A systematic error is a displacement of all contours in an area in a constant direction and often by a constant amount. Random errors can be described as random variation in measurements—there is no obvious pattern to these errors as there is with systematic errors. Gross errors or
Figure 2. Horizontal error of aligned feature (From Thompson, 1956).
Figure 3. Alteration in character and position of contour lines due to smoothing (From Imhof, 1982).
"blunders" are simply human errors and can occur for numerous reasons--misinterpretation, transposing of figures, mathematical blunders, etc. They are easily identifiable as a large error occurring suddenly in an area of small errors. The practice of smoothing contour lines in plane table surveys can result in errors relating to shape, curvature, length, slope and overall position. These errors will cause a larger horizontal distance between lines making the slope appear more uniform than it actually is (Figure 3).

**Literature on Accuracy Assessment in Historical Maps**

Although much of the literature on assessing accuracy in historical maps deals with documents which are perhaps three or four centuries old, basic ideas and methods of measurement can be extended to the accuracy assessment of maps of any age. There are some characteristics inherent in very old maps, however, that create difficulties which would not occur in analyzing more modern maps. A major problem can occur with paper distortion. This produces an obstacle to the researcher of trying to isolate error due to surveying (which is generally the original objective) versus error due to shrinkage or expansion of paper resulting in scale variation throughout the map. Another problem which occurs in very old maps is the lack of, or lack of information leading to, any system of spherical coordinates which may have been used in constructing the map. When there is no coordinate system on the map itself, the researcher cannot be sure whether the cartographer used any accepted method of map projection.

The method used throughout the literature for analysis of an historic map is to compare it to a more modern map. Often the "modern map" is not so new, especially in comparisons of successive maps. However, the newer map is always assumed to be of a higher order of accuracy and serves as a standard for the older map(s). Comparisons of point locations, line lengths, shapes and areas are among the methods used to determine the accuracy of old maps.
Analysis of errors in different regions within a map is a popular objective throughout the literature. Lloyd and Gilmartin (1987) analyzed the relative inaccuracies of separate sections of the South Carolina coast as well as analyzing the coast as a whole. They hypothesized the more accurate areas of the coast were due to greater population densities in those areas. An analysis of variance was used to look at the significance of differences between regions. Error vectors were graphically represented along an X-Y axis to show amount of longitude error and amount of latitude error. Clutton (1982) analyzed separate sections of coastline along the island of Crete on successive maps. She hypothesized different levels of inaccuracies being due to the degree of strategic importance of certain sections of coastline. She also compared differences in shape representation of the island. Hooke and Perry (1976) devised a method of looking at different regions on their maps in an effort to extract error due to surveying versus error due to paper distortion and scale variation.

Some studies have used locations of points representing cultural features to compare maps. To do this, the same points must be identified on both the historical map and the modern map. The maps are registered, and distance and direction between pairs of points can be measured to determine error. The points may be road intersections, boundary intersections, structures, etc. Difficulty arises in finding enough static points (i.e. points whose locations have not changed) that are well dispersed throughout the map so as to fairly represent the overall accuracy of the map. This problem leads to an unavoidable bias in the results if too many points are concentrated in one area of the map. However, in an area of substantial cultural activity, this method can be fruitful. Ravenhill and Gilg (1974) were able to utilize this method in analyzing historical maps of Britain. Because of the early establishment of a system of latitude and longitude (some time between 1534 and 1546) and the number of old churches throughout the landscape, they were able to record the precise locations of a sufficient number of cultural features. They measured the distance between churches to a second of latitude and a second of longitude. Error vectors were shown directly on an outline of the map which was analyzed; this was a very straightforward and revealing method of visually representing the different areas of error in the map.
In a study conducted by Stone and Gemmell (1977) pairs of points that could be identified on both the historical map and the modern map were used to study the accuracy of 47 regional maps of Scotland published in 1654. Distances between the points were determined for pairs of points on each map to come up with a single correlation coefficient showing the degree of association between the historical map and the modern map. Thus, the accuracy of each map in the atlas was defined by its correlation coefficient.

Errors in maps caused by paper distortion have interfered with or even changed the original objective of many studies on historical maps in the literature. The maps in this study are assumed to be free of this type of error for two reasons: 1) Topographers in the early 1900s were well aware of the problems of paper distortion due to changes in atmospheric conditions so that plane table sheets were always "well-seasoned" (Birdseye, 1928:166) before being attached to the plane table; and 2) The reproductions to be used in this study are made from very high quality (archival) 35-mm film, and, therefore, scale is constant throughout the entire map (U.S. Dept. of the Interior, 1981). Since all maps in the study were at the same scale, no reductions or enlargements were necessary thereby eliminating possible distortion through use of copying machines. The difficulty of determining the coordinate system used in the old maps was also avoided as all maps analyzed in the study were constructed using the same polyconic projection. These facts were key elements in this study of old topographic maps as they facilitated ease and confidence of registration.

Some of the methods used in previous studies were also appropriate for this study of historical topographic maps, and accuracy tests were developed based on these concepts. In addition to use of established statistical tests, an element of visual, subjective analysis was used in this study through illustration of error vectors. Although point comparison is perhaps the most popular method of accuracy analysis, the cause and nature of errors in terrain representation in these maps required a less rigid approach to the problem and, therefore, point comparisons were not among the methods used.
Chapter III

METHODOLOGY

The use of data collected from historic U.S.G.S. topographic maps in modern day applications necessitates a general knowledge of the potentials and limitations of these data. This study addresses an important aspect of this problem with a focus on assessing inaccuracy in contouring on older maps. The accepted method of using the most recent map as an accuracy standard was employed. Pairs of maps were chosen representing the photogrammetric survey and plane table survey of the same area. Several measurements were made on paired contour lines throughout the maps, and the significance of differences between measures defined error in the old maps. The analysis attempts to relate errors to geometric components of contour lines and to predict the occurrence of error.
Map Selection

Six pairs of maps representing three terrain types mapped at 20, 40, and 80-foot contour intervals were analyzed to determine relative accuracies among differing terrains. Due to advances in methods and instrumentation, care was taken to select maps from approximately the same time periods to validate comparisons. All maps in the study were at a scale of 1:62,500, a popular scale both in the early 1900s and in the 1950s (Table 4).

For this analysis, observations consisted of closed contour lines (closed polygons) which could be identified on both historic and modern maps. A closed contour line represented one feature on which measurements could be made simultaneously on an entire set of points as opposed to taking measurements only at single, randomly chosen points. The maps selected had to have a sufficient number of observations spread throughout the map to fairly represent the overall quality of the map. It was also necessary to choose maps which represented features of varied size and shape. Care was taken to identify and include only those terrain features which were represented as a single closed contour on both the old and the new map. Given the inherent differences between the two survey methods, this obstacle imposed itself many times, especially on the 40 and 80 foot contour interval maps (Fig. 4).

Observations were identified and traced onto a piece of mylar taped to the old map in each pair. For purposes of registration to the new map, the map corners were traced as well as the eight latitude and longitude minute markers along the sides of the map. The mylar was then registered to the new map, and both maps taped to a digitizer. This method enabled each contour to be digitized as a set of vector points in the same X-Y space. FORTRAN programs were then written to analyze individual contour lines, as well as spatial relationships between pairs of contours.
Table 4. List of maps analyzed.

<table>
<thead>
<tr>
<th>20-foot contour interval maps</th>
<th>Date</th>
<th>Range (ft.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Poland, ME</td>
<td>1956</td>
<td>1600</td>
</tr>
<tr>
<td>Poland, ME</td>
<td>1908</td>
<td></td>
</tr>
<tr>
<td>Skowhegan, ME</td>
<td>1955</td>
<td>780</td>
</tr>
<tr>
<td>Skowhegan, ME</td>
<td>1913</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>40-foot contour interval maps</th>
<th>Date</th>
<th>Range (ft.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bennington, VT</td>
<td>1954</td>
<td>3243</td>
</tr>
<tr>
<td>Bennington, VT</td>
<td>1898</td>
<td></td>
</tr>
<tr>
<td>Ticonderoga, VT-NY</td>
<td>1950</td>
<td>1330</td>
</tr>
<tr>
<td>Ticonderoga, VT-NY</td>
<td>1902</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>80-foot contour interval maps</th>
<th>Date</th>
<th>Range (ft.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boulder, CO</td>
<td>1957</td>
<td>4073</td>
</tr>
<tr>
<td>Boulder, CO</td>
<td>1902</td>
<td></td>
</tr>
<tr>
<td>Georgetown, CO</td>
<td>1957</td>
<td>6738</td>
</tr>
<tr>
<td>Georgetown, CO</td>
<td>1905</td>
<td></td>
</tr>
</tbody>
</table>

Note: All maps are at scale 1:62,500
Figure 4. Representation of the same terrain feature on the Bennington, Vermont maps.
Description of Variables

To provide a thorough analysis of contour inaccuracy on older maps, several types of measures were made on contour pairs. The first set of measures was made on each contour line individually: average angularity of the line, shape of the feature, total area within the line and perimeter. Together, these four measures formulated the basis for an analysis of geometric components. Several slopes were also measured throughout the maps given the direct relationship of slope to the four original measures. Finally, three additional measures were attained from each map pair: percent intersection between contour pairs, distance between centroids of contour pairs, and azimuth of the center-to-center line beginning at the centroid of the contour on the old map.

Measures of angularity and shape were made to examine the amount of smoothing and generalization of contour lines on the old maps. Angularity is a measure of the complexity of the line. The algorithm measures the angularity between successive line segments, and the result gives the average angularity of the line (Fig. 5). Shape is a measure of the circularity of a line. The shape measure used, the “compactness ratio” suggested by Unwin (1981), ranges in value from 0 to 1.0 with values close to 0 representing very elongated shapes and values close to 1.0 representing circularity (Fig. 6). Shape measures used in many previous studies result in an infinite range of values, producing difficulties in interpretation. The small, conclusive range in values of the compactness ratio renders the index easy to interpret and especially suited to the comparisons of this study. Although measures of area and perimeter were less complicated in the context of computer programming required for this study, they were equally important in providing examination of geometric components of contour lines. Area and perimeter are not defined here since they are simple algorithms based on well known geometric principles.

Although this research focuses on analysis of individual contour lines, slope measurement (involving more than one contour) could not be overlooked. Slope is also a geometric component of a
Figure 5. Graphic description of angularity measure.
SHAPE = \((A/A_c)^{0.5}\)

where:

\(A\) = MEASURED AREA OF THE SHAPE

\(A_c\) = AREA OF THE CIRCLE HAVING THE SAME PERIMETER AS THE MEASURED AREA

Figure 6. Graphic description of shape measure.
terrain feature and is one of the most important measurements interpreted from topographic maps. Slopes, randomly chosen throughout the area of each map, were carefully measured using a ruler graduated specifically for precise measurement on 1:62,500 scale maps. Centroids of closed contour lines were visually located to mark the tops of slopes, and road intersections which could be identified on both maps represented the bottoms of slopes. Slope measurements were then tested to determine significance of differences between the two maps.

Percent intersection between contours was measured using a combination of operations in the Map Analysis Package (MAP--Tomlin, 1983), a raster-based Geographic Information System. Use of a vector-to-raster conversion program was necessary to ready the existing polygon data for input to MAP. MAP permitted convenient calculation of percent intersection by dividing the number of cells in the intersection by the number of cells in the union of the two polygons (Fig. 7). A low percent intersection indicated a high amount of error in the old map for a particular contour pair. Conversely, a high percent intersection indicated a relatively accurate representation of the feature on the old map. This measure assisted in determining differences in terrain representation between maps.

Distance of the center-to-center line between each pair of contours and azimuth of this line were calculated based on geometric principles involving calculation of X and Y slopes. Radians were converted resulting in direction measured in degrees (Fig. 8). The centering algorithm used was chosen based on findings of a study by Carstensen (1987). Results of the comparison of four different centering algorithms showed the Trapezoid-Area Weighted Method most closely approximated the visual centroids of irregular shapes. The number of irregularly shaped contours on the maps in this study, especially in mountainous terrain, made this centering method an important choice. The method is based on the *trapezoidal rule* as defined by Monmonier (1982). For any shape in X-Y space, a number of trapezoids are formed by dropping perpendicular lines to the X and Y axes. A weighted mean center is calculated separately for X and Y by giving positive or negative weights to centers of the individual trapezoids based on relative area of each trapezoid. The resulting coordinate approximates the centroid of the original shape (Fig. 9). These three
Figure 7. Calculation of percent intersection between contour pairs using the Map Analysis Package. MAP provides the number of cells intersecting ($$$\$, and the number of cells not intersecting (—) so that a percentage may be calculated.
Distance = \((\Delta X)^2 + (\Delta Y)^2\)^{0.5}

Direction = \arctan\left(\frac{\Delta X}{\Delta Y}\right) \times 57.29578
\[
X_{\text{center}} = \frac{\sum_{i=1}^{n} ((X_{i+1} + X_i)/2)(X_{i+1} - X_i)((Y_{i+1} + Y_i)/2)}{\sum_{i=1}^{n} (X_{i+1} - X_i)((Y_{i+1} + Y_i)/2)}
\]

\[
Y_{\text{center}} = \frac{\sum_{i=1}^{n} ((Y_{i+1} + Y_i)/2)(Y_{i+1} - Y_i)((X_{i+1} + X_i)/2)}{\sum_{i=1}^{n} (Y_{i+1} - Y_i)((X_{i+1} + X_i)/2)}
\]

\textbf{Figure 9.} Calculation of contour centers using the Trapezoid-Area Weighted centering method.
measures were used in conjunction to display error vectors on the old maps to reveal any systematic errors. Since nearby terrain features were often contoured as a group in plane table surveys, some systematic error was expected in these situations.

Assessment of effects of heavily forested land and higher elevations on survey accuracy was a continued focus throughout the study. However, only the 40-foot contour interval maps provided enough variation in both these measures to be used in the testing. Elevations of contours and the percentage of each contour falling in forested land were recorded. Since it was easier to obtain a dense network of ground control at lower elevations, where terrain was generally less rugged, higher elevations in mountainous terrain may be associated with more error. Forested land was especially difficult to map by plane table because forest vegetation often obscured the ground surface from observation at a distance. Of course, forest land is difficult to map by either plane table survey or photogrammetry, but the additional obstacles were reduced in the context of photogrammetric methods. Therefore, it was expected that contours in forested areas would be less accurate than those in sparsely forested areas.

Statistical Methods

Differences between the modern and historic maps (as revealed by the measures described above) were examined using the Wilcoxon Signed Ranks Test for Matched Pairs, the non-parametric analogue to the t-test. A preliminary investigation using both parametric and non-parametric methods concluded that non-parametrics should be used for the remainder of this study. The assumptions to be met are much less stringent using non-parametric tests, yet the results are just as reliable. According to both Gibbons (1976) and Chao (1969), as a sample size gets larger, the power of a non-parametric test is greatly increased and can be just as powerful as its parametric analogue. Because the preliminary investigation showed population distributions of some variables
to be less than normal, use of non-parametrics was appropriate. In addition, sample sizes from all map pairs in the study were more than adequate so that results using the non-parametric methods were considered extremely reliable.

The Wilcoxon test was used to determine significant differences between means for the four original measures made on contour pairs (angularity, shape, area and perimeter), as well as for the slope measures. Hypotheses were formulated based on extensive review of both plane table methods and photogrammetric methods as well as visual inspection of the map pairs. Due to the practices of smoothing and generalization in plane table methods and, conversely, to the precision of photogrammetric instrumentation, angularity should be lower in contours on the old maps. This result is evident from direct inspection of the maps themselves. Also evident are differences in shape between contour pairs. Shapes appear more circular on the old maps in many cases. This may also be a result of smoothing and generalization. Shape measures should, therefore, be lower on the modern maps. Hypotheses regarding angularity and shape were stated as follows:

\[
H_0: \text{oldangularity} = \text{newangularity} \\
H_A: \text{oldangularity} < \text{newangularity}
\]

\[
H_0: \text{newshape} = \text{oldshape} \\
H_A: \text{newshape} < \text{oldshape}
\]

As described in Chapter II, measures of angularity, shape, area and perimeter are all interrelated as they refer to geometric components of a contour line. Therefore, it follows that inaccuracies in measures of angularity and shape may translate to inaccuracies in area and perimeter. However, as there were no immediately obvious differences between contour pairs to justify specification of direction, hypotheses for area and perimeter were stated for a two-tailed test:
\[ H_0: \text{oldarea} = \text{newarea} \]

\[ H_A: \text{oldarea} \neq \text{newarea} \]

\[ H_0: \text{oldperimeter} = \text{newperimeter} \]

\[ H_A: \text{oldperimeter} \neq \text{newperimeter} \]

Inaccuracies in these four original measures may in turn affect the accuracy of slope measures on the old maps. Determination of any significant differences between slope measures will make an additional contribution to the overall conclusions. At this point, a two-tailed test is appropriate to simply determine whether slope measures are significantly different between the two maps:

\[ H_0: \text{oldslope} = \text{newslope} \]

\[ H_A: \text{oldslope} \neq \text{newslope} \]

The next section of the analysis focused on the prediction of error in the historic maps. The calculation of percent intersection between contour pairs served as an error measure. The correlation coefficient, Spearman’s rho (non-parametric analogue to Pearson’s r), was used to determine the association between percent intersection and the four measures taken on contours on the old maps. Significant correlations may help define sources of error. To determine the effects of elevation and heavily forested areas on survey accuracy, correlations were also tested between these measures and percent intersection (40-foot contour interval maps only).

The last part of the statistical testing used a discriminant analysis to predict probability of error in the old maps. The method is much more complex than others used in the study and, therefore, was considered purely experimental in the context of this research. However, the nature of the data seemed particularly suited to a discriminant analysis and made the method a logical choice for a preliminary investigation. A main assumption in using this classification algorithm is a priori
knowledge of the existence of distinct and separate groupings within the data. A sufficient number of contour pairs on each map in the study could be divided into two separate groups for use in the analysis—those exhibiting a close match (small amount of error), and those where there was relatively little coincidence between the contours (large amount of error). The measure of percent intersection combined with visual inspection of the contour pair was used to place observations into one of the two groups. Measurements made on observations on the old map were used in the analysis. The discriminant analysis then extracted interrelationships between these variables, and found the one linear combination which produced both maximum difference between the two groups and minimum variance within each group. The function provided a discriminant score which was translated into a probability level for each contour on the old map. Probability levels were then used to place contours into either the low error group or the high error group.

The measurements and statistical methods set forth in this chapter attack the problem of identifying contouring errors in plane table surveys from two different viewpoints. This approach was appropriate given knowledge thus far of the practices of smoothing and generalization on the older maps. Smoothing, by itself, affects the accuracy of individual contour lines. Measures of angularity, shape, area and perimeter provided an examination of individual lines. Smoothing and generalization together have an effect on groups of contour lines i.e. the contours of a slope or a group of knolls close together along the top of a ridge. Measures of percent intersection, and the vector data provided a look at this type of error. Although only closed contour lines were used as observations, the variety of methods employed provided answers that could be extended to contouring in general.
Chapter IV

RESULTS

Section 1--Testing Difference Between Variable Means

The first part of the statistical testing focused on the four measures made on individual contour lines. Results of the Wilcoxon test with associated probability levels are shown in Table 5. The Result column was based on an alpha level of .05. Probability levels enabled comparisons to be made among the different contour intervals. Higher values indicated a higher probability of accepting the null hypothesis that means are equal. Thus, a higher probability level indicated a more accurate representation for that variable on the historic map.

As was expected, the angularity measure was significantly lower on all the older maps. The research hypothesis for shape was also proven true for each pair of maps indicating more circular shapes on the older maps. However, the 80-foot contour interval maps had the highest probability levels for these two measures. Thus, these historic maps were most accurate in shape representation and degree of angularity. Much of the terrain on the 80-foot contour interval maps is, of course, very
<table>
<thead>
<tr>
<th>H₀</th>
<th>Prob. of accepting H₀</th>
<th>Result based on alpha .05</th>
</tr>
</thead>
<tbody>
<tr>
<td>20-foot contour interval (Maine maps) n=99</td>
<td></td>
<td></td>
</tr>
<tr>
<td>oldang = newang</td>
<td>.0000</td>
<td>oldang &lt; newang</td>
</tr>
<tr>
<td>newshape = oldshape</td>
<td>.0033</td>
<td>newshape &lt; oldshape</td>
</tr>
<tr>
<td>oldarea = newarea</td>
<td>.0000</td>
<td>oldarea ≠ newarea</td>
</tr>
<tr>
<td>oldperim = newperim</td>
<td>.0001</td>
<td>oldperim ≠ newperim</td>
</tr>
<tr>
<td>40-foot contour interval (Vermont maps) n=66</td>
<td></td>
<td></td>
</tr>
<tr>
<td>oldang = newang</td>
<td>.0000</td>
<td>oldang &lt; newang</td>
</tr>
<tr>
<td>newshape = oldshape</td>
<td>.0007</td>
<td>newshape &lt; oldshape</td>
</tr>
<tr>
<td>oldarea = newarea</td>
<td>.0425</td>
<td>oldarea = newarea</td>
</tr>
<tr>
<td>oldperim = newperim</td>
<td>.5827</td>
<td>oldperim = newperim</td>
</tr>
<tr>
<td>80-foot contour interval (Colorado maps) n=46</td>
<td></td>
<td></td>
</tr>
<tr>
<td>oldang = newang</td>
<td>.0285</td>
<td>oldang &lt; newang</td>
</tr>
<tr>
<td>newshape = oldshape</td>
<td>.0474</td>
<td>newshape &lt; oldshape</td>
</tr>
<tr>
<td>oldarea = newarea</td>
<td>.0170</td>
<td>oldarea ≠ newarea</td>
</tr>
<tr>
<td>oldperim = newperim</td>
<td>.0019</td>
<td>oldperim ≠ newperim</td>
</tr>
</tbody>
</table>
rugged and mountainous. In such areas, shapes of mountain peaks form sharp, distinct features. Rock faces give an angular appearance to the landscape. A surveyor experienced in landform representation in such precisely defined areas would have little difficulty in relatively accurate depiction of shapes and angles. This explains the high probability levels found in these maps for angularity and shape. In an area of gently rolling hills such as that on the 20-foot contour interval maps, difficulty in accurate landform representation is greatly increased. Shapes are not so well-defined, and even an experienced surveyor must use some degree of guesswork. Perhaps smoothing and generalization of contour lines in such areas was greater since the surveyor did not have as many topographic guidelines and sharp edge lines to aide in contour sketching. This may explain the near zero probabilities for angularity and shape found in both the 20-foot and 40-foot contour interval maps.

In regard to measures of area and perimeter, probability levels indicated again that the 20-foot contour interval maps were least accurate. Probabilities for the 40-foot contour interval maps were considerably higher than the others and, in fact, the null hypothesis was accepted indicating these maps were most accurate with respect to these two measures.

To determine the effects of heavily forested land on survey accuracy, a number of observations on the 40-foot contour interval maps were divided into either those falling in a completely forested area or a completely non-forested area as depicted by the forest overprint on the photogrammetric map. The Wilcoxon Test was used again with the same four measures (Table 6). Given the difficulties of conducting a survey in a forested area, it was expected that contouring would be less accurate in these areas. Probabilities were expected to be higher for the non-forested observations. However, the probability was significantly higher only in the measure of angularity. Probabilities for area and perimeter were quite similar for both sets of observations, and the probability for shape was significantly higher for the forested observations. Therefore, with respect to these particular measures, it could not be concluded that contouring was more accurate in non-forested areas.
Table 6. Results of Wilcoxon Test—Forest vs. Non-forested areas.

<table>
<thead>
<tr>
<th>40-foot contour interval maps</th>
<th>Prob. of accepting $H_0$</th>
<th>Result based on alpha .05</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Forested Observations, n = 30</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>oldang = newang</td>
<td>.0013</td>
<td>oldang $&lt; newang$</td>
</tr>
<tr>
<td>newshape = oldshape</td>
<td>.1986</td>
<td>newshape = oldshape</td>
</tr>
<tr>
<td>oldarea = newarea</td>
<td>.0752</td>
<td>oldarea = newarea</td>
</tr>
<tr>
<td>oldperim = newperim</td>
<td>.2536</td>
<td>oldperim = newperim</td>
</tr>
</tbody>
</table>

| **Non-forested Observations, n = 11** |                           |                           |
| oldang = newang               | .0409                    | oldang $< newang$         |
| newshape = oldshape           | .0505                    | newshape = oldshape       |
| oldarea = newarea             | .0505                    | oldarea = newarea         |
| oldperim = newperim           | .2477                    | oldperim = newperim       |
Table 7. Results of Wilcoxon Test—Slope measures.

<table>
<thead>
<tr>
<th>H₀</th>
<th>Prob. of accepting H₀</th>
<th>Result based on alpha .05</th>
</tr>
</thead>
<tbody>
<tr>
<td>20-foot contour interval</td>
<td></td>
<td></td>
</tr>
<tr>
<td>oldslope = newslope</td>
<td>.0468</td>
<td>oldslope = newslope</td>
</tr>
<tr>
<td>40-foot contour interval</td>
<td></td>
<td></td>
</tr>
<tr>
<td>oldslope = newslope</td>
<td>.3343</td>
<td>oldslope = newslope</td>
</tr>
<tr>
<td>80-foot contour interval</td>
<td></td>
<td></td>
</tr>
<tr>
<td>oldslope = newslope</td>
<td>.1252</td>
<td>oldslope = newslope</td>
</tr>
</tbody>
</table>
The difference in probability levels for angularity and shape lead to some important conclusions. The non-forested sections on the Vermont maps lie in generally flat and even swampy areas. Therefore, the probabilities indicated that angularity was maintained better not only in non-forested areas but also in flatter areas. The probability level for shape in the forested section was considerably higher than for the non-forested section. The forested areas on the maps are also quite rugged and mountainous with some well-defined features. Again, it seems accurate depiction of shape was attained easier in mountainous areas where landforms were more distinct.

As stated in Chapter III, some measurement of slope was important given the direct relation of this measure to the four original measures made on contour lines. Results of slope measures made throughout the area of each map pair are shown in Table 7. Although this test was done for preliminary purposes only and, therefore, sample size was comparatively small, probability levels make sense given the conclusions thus far. The value of 0.0468 for the 20-foot contour interval maps is considerably lower than the 40 or 80-foot contour intervals. Again, this indicated the 20-foot contour interval maps were the least accurate. The results indicated that perhaps slope measures on historic maps are more accurate in mountainous areas. The outcome of this test supports previous conclusions and, therefore, suggests an interesting focus for further research.

Section II--Error Prediction

The purpose of this section was to determine the association between error and characteristics of contour lines on the old maps. Using percent intersection between contour pairs as an error measure, calculations of Spearman's rho were used in prediction of error in the old maps. Results are shown in Table 8. A direct correlation was found between percent intersection and the size of the polygon (i.e. area and perimeter). The strength of the correlation was much the same among all the contour intervals, albeit slightly weaker for the 40-foot contour interval. It seems logical to
conclude that larger contours contain less error than smaller contours. However, inspection of some of the contour pairs on the maps presents a situation which must be considered (Fig. 10). Although a pair of very small contours may have little or no area of intersection, they may be in relatively close proximity to each other. On the other hand, closed contours covering large areas are bound to have a larger percentage of their total union in common. Thus, with the introduction of a spatial measure such as percent intersection, the issue of positional accuracy becomes an integral part of the study. Although percent intersection was a useful error measure in the remainder of this section, any error prediction using measures of either area or perimeter would be premature at this point. Positional accuracy in the context of this research problem is dealt with in Section III of this chapter.

Inverse correlations were found between percent intersection and both angularity and shape for all maps in the study. Although the values of Spearman's rho were not significant for the 40-foot contour interval maps, they fell close enough to the critical value so that a general conclusion suggested for all maps in this study was made—smoother, more elongated contours tend to be associated with less error. Precise study of error in these old maps is no doubt a complex problem and would involve the addition of several variables. However, the consistency of significant, inverse correlations in regard to angularity and shape suggest that these measures would make an important contribution to the problem of defining error in historical maps.

Since the terrain on the 40-foot contour interval maps was quite variable with respect to both elevation and amount of forest, these maps were used to determine effects of these two situations on survey accuracy. Percent intersection was used again as an error measure. Results of correlations were as follows:
40-foot contour interval maps (critical value = -.20)

Spearman’s rho

% intersection vs. elev.  .32
% intersection vs. % forested  .35

The significant inverse correlations indicated contours at lower elevations falling in sparsely forested areas had a higher percent intersection and, thus, tended to be more accurate. These results make sense given the difficulties of surveying forested areas at higher elevations. Certainly it was easier to obtain a more dense network of ground control at lower elevations where more of the ground could be seen from a distance. More ground control is obviously conducive to more accurate interpolation for purposes of contouring.

Results using discriminant analysis as a method of error prediction were not entirely successful, but indicated further work in this area could be fruitful. A total of six measures made on contours on the old maps were used in the analysis: angularity, shape, area, perimeter, elevation and percent forested. Thus far, these variables have been examined separately. The discriminant analysis provided a look at combinations or interrelationships among the variables.

Probabilities derived from the discriminant function were used to mark observations as either belonging to the high error or the low error group. An observation was not classified if the probability was less than 95%. Variables not contributing to the discriminant function were dropped during the analysis. The contributing variables for each contour interval are shown in Table 9.

Contour pairs for each contour interval were examined closely to determine how well a discriminant analysis using these variables would work in the prediction of error. In some cases the function worked quite well in classifying contours. However, there were many situations where obviously accurate representations were deemed inaccurate by the function. Conversely, many bad matches
Table 8. Results of Correlation Testing.

<table>
<thead>
<tr>
<th>20-foot contour interval (critical value = ±.17) n = 99</th>
<th>Spearman's rho</th>
</tr>
</thead>
<tbody>
<tr>
<td>%intersection vs. oldang</td>
<td>-.27</td>
</tr>
<tr>
<td>%intersection vs. oldshape</td>
<td>-.32</td>
</tr>
<tr>
<td>%intersection vs. oldarea</td>
<td>.64</td>
</tr>
<tr>
<td>%intersection vs. oldperim</td>
<td>.64</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>40-foot contour interval (critical value = ±.20) n=66</th>
</tr>
</thead>
<tbody>
<tr>
<td>%intersection vs. oldang</td>
</tr>
<tr>
<td>%intersection vs. oldshape</td>
</tr>
<tr>
<td>%intersection vs. oldarea</td>
</tr>
<tr>
<td>%intersection vs. oldperim</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>80-foot contour interval (critical value = ±.25) n=46</th>
</tr>
</thead>
<tbody>
<tr>
<td>%intersection vs. oldang</td>
</tr>
<tr>
<td>%intersection vs. oldshape</td>
</tr>
<tr>
<td>%intersection vs. oldarea</td>
</tr>
<tr>
<td>%intersection vs. oldperim</td>
</tr>
</tbody>
</table>
Approx. 10% intersection

Approx. 30% intersection

Figure 10. Example of percent intersection between contour pairs.
Table 9. Variables contributing to discriminant functions for each contour interval.

<table>
<thead>
<tr>
<th></th>
<th>20-foot</th>
<th>40-foot</th>
<th>80-foot</th>
</tr>
</thead>
<tbody>
<tr>
<td>angularity</td>
<td>angularity</td>
<td>shape</td>
<td></td>
</tr>
<tr>
<td>area</td>
<td>%forested</td>
<td>area</td>
<td></td>
</tr>
<tr>
<td>perimeter</td>
<td>area</td>
<td>perimeter</td>
<td></td>
</tr>
<tr>
<td>Contour Interval</td>
<td>Percent Classified</td>
<td>Percent Correctly Classified</td>
<td></td>
</tr>
<tr>
<td>------------------</td>
<td>--------------------</td>
<td>----------------------------</td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>83</td>
<td>59</td>
<td></td>
</tr>
<tr>
<td>40</td>
<td>92</td>
<td>52</td>
<td></td>
</tr>
<tr>
<td>80</td>
<td>89</td>
<td>63</td>
<td></td>
</tr>
</tbody>
</table>
were incorrectly placed in the low error group. Table 10 is a summation of these results. Percentages of correctly classified contours were insignificant enough to indicate a discriminant analysis using these variables could not be relied upon as an error predictor. However, since many observations were properly classified, use of a discriminant analysis still seems suited to this research problem. The method could possibly be shown to be successful with additional observations and new variables.

Section III--Systematic Errors

The final section of this chapter looks at a common type of error found in contour lines—the systematic error. Systematic errors refer to a positional inaccuracy and have been studied at length throughout the technical literature on this subject. Most studies have dealt with either errors in the positioning of single points or errors in the positioning of line sections (Imhof, 1982). The focus of this study remains on examining closed contours as single entities.

A systematic error is defined as a consistent displacement of contours in a certain direction. Distance may also play a role in identification of error. The center-to-center line and azimuth measures were used to reveal systematic errors throughout the maps. These two measures define systematic errors in a rather unique way by looking at the general displacement of terrain features as a whole. This section complements results of the study thus far as it provides a close inspection not only of individual observations, but also of the effects of surrounding terrain on error.

Prior to visual examination of the maps themselves, bar graphs were constructed to reveal possible patterns of systematic errors (Fig. 11). The graphs indicate that, indeed, errors are not random but are concentrated in certain directions. Concentrations are stronger for the 20 and 40-foot contour
intervals than for the 80-foot contour interval. Examples taken from the maps reveal strikingly obvious systematic errors.

Since systematic errors were most evident in the 40-foot contour interval maps, these were examined first. Error vectors on the Bennington, VT map showed that features close together were almost always displaced in the same general direction. The distance error was also similar in most of these cases (Fig. 12). The constant displacement in a north/northeast direction of the three spatially associated contours shown in Fig. 12 indicated that perhaps these features were surveyed and contoured as a group on the plane table sheet. It seems even more obvious in observations 1 and 2 where vectors are near identical in both distance and direction. Note these observations are part of the same ridge. The early method of contouring nearby terrain features together rather than separately is exemplified here. This map is dominated by ridge and valley systems which explains why examples such as that in Figure 12 are found throughout the majority of the map.

The Ticonderoga, VT-N.Y. map, although contoured at a 40-foot interval, has a considerable amount of flat, swampy terrain. The few areas of mountainous, forested terrain, and vectors in these areas show displacement of nearby features in the same general direction. Fig. 13 shows features in the flat area of the map. Although some features are quite close together, dissimilarities in vectors indicate features were probably not surveyed as a group. Certainly the surveyor had fewer obstacles to overcome and could obtain the optimum (and different) vantage point as he moved from feature to feature.

The 20-foot contour interval maps showed situations typical of those found in the 40-foot contour interval maps. Since the terrain type was similar between these two contour intervals (Northern New England), illustrations from the maps were not necessary. Poland, ME is located near the coastline, and the quadrangle contains some relatively flat terrain dotted with lakes and swampy areas. Although there are small hills and knolls on the map, a regular system of ridges and valleys is not at all prominent. As was expected, very few systematic errors were found. Conversely, Skowhegan, ME is inland in a much more mountainous area of the state. Many systematic errors
Figure 11. Total length of error vectors by octant.
Surrounding terrain (map slightly enlarged from original scale).

Error vectors on overlay of plane table and photogrammetric contours.

<table>
<thead>
<tr>
<th>Observation No.</th>
<th>Contour Elevation</th>
<th>Center-to-Center Distance (ft.)</th>
<th>Azimuth</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3000</td>
<td>414</td>
<td>29</td>
</tr>
<tr>
<td>2</td>
<td>3000</td>
<td>511</td>
<td>46</td>
</tr>
<tr>
<td>3</td>
<td>2800</td>
<td>961</td>
<td>9</td>
</tr>
</tbody>
</table>

Figure 12. Systematic error on 40-foot contour interval map (Bennington, VT).
Surrounding terrain (map slightly enlarged from original scale).

Center of photogrammetric contour

Center of plane table contour

Photogrammetric Contour

Plane table Contour

Error vectors on overlay of plane table and photogrammetric contours.

<table>
<thead>
<tr>
<th>Observation No.</th>
<th>Contour Elevation</th>
<th>Vector Data</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Center-to-Center Distance (ft.)</td>
</tr>
<tr>
<td>1</td>
<td>360</td>
<td>757</td>
</tr>
<tr>
<td>2</td>
<td>360</td>
<td>270</td>
</tr>
</tbody>
</table>

Figure 13. Error vectors in flat area on 40-foot contour interval map (Ticonderoga, VT-NY).

RESULTS
Surrounding terrain (map slightly enlarged from original scale).

Error vectors on overlay of plane table and photogrammetric contours.

<table>
<thead>
<tr>
<th>Observation No.</th>
<th>Contour Elevation</th>
<th>Vector Data Center-to-Center Distance (ft.)</th>
<th>Azimuth</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>12800</td>
<td>512</td>
<td>242</td>
</tr>
<tr>
<td>2</td>
<td>12800</td>
<td>547</td>
<td>328</td>
</tr>
<tr>
<td>3</td>
<td>13200</td>
<td>149</td>
<td>180</td>
</tr>
</tbody>
</table>

Figure 14. Error vectors in extremely rugged terrain of 80-foot contour interval map (Georgetown, CO).
were found throughout the map and were again most notable on ridges where closed contours were in close proximity to each other.

The 80-foot contour interval maps cover terrain much more rugged and mountainous than the other maps in the study. Features are more distinct and separate from one another even when in close proximity. Figure 14 shows an area on the Georgetown, Colorado map which is certainly the most rugged terrain to be found on any of the maps in the study. The error vectors appear haphazard in this area with no similarities in direction. Even observations which seem to be part of the same ridge have very different error vectors. Given knowledge of plane table methods, the distribution of error vectors in this very rugged region makes sense. Features are so sharp and enormous that they may partially or completely hide other nearby features. Therefore, the surveyor would have to continually obtain new vantage points with the outcome being that of completely separate features. Indeed, features should be separated in such an area and not drawn as a group. Very few systematic errors were found on the remainder of the Georgetown, Colorado map.

The map of Boulder, Colorado is quite mountainous but not nearly as rugged as the Georgetown map. Only 20 observations were identified on this map pair, and only a few fell in relatively close proximity to each other. However, those observations which were close together exhibited definite systematic errors indicating features were obviously drawn in relation to each other.

Results show that systematic errors (or lack thereof) are quite predictable on the old maps. Knowledge of early methods of contouring help us to understand and predict systematic errors in certain topographic situations. In flat areas, this type of error simply does not seem to exist. In mountainous areas dominated by ridge systems, however, these errors are very obvious.

Though length of vectors was not as important as direction in revealing systematic errors, it provides additional information on differences between contour intervals. Average vector lengths are indicated next to the bar graphs in Fig. 11. Since center-to-center distance was slightly longer in
the Vermont maps (Maine and Colorado having similar lengths), this indicated a greater tendency for overall displacement of terrain features on these maps.

The results of this study answer many questions about the effects of smoothing and generalization of contours on old maps. In addition to inaccuracies in characteristics of individual contour lines, inaccuracies were also found in specific topographic situations involving groups of contour lines. Although the focus remained on the effects of topographic expression, the variety of methods and subsequent results provided a broad array of answers. The results, in effect, widened the focus of the study. Therefore, many new ideas are left open for exploration. These are outlined in detail in Chapter V.
Chapter V

SUMMARY AND SUGGESTIONS FOR FURTHER RESEARCH

The study of historic U.S.G.S. topographic maps by the method of analyzing closed contours, rather than by use of point comparisons, has provided a unique approach to the study of accuracy in contouring. The results provide new information on the accuracies/inaccuracies of early plane table surveys, and raise thought-provoking questions. This chapter addresses some of these questions providing both further analysis of the results and several suggestions for future study of the problem.

Perhaps the most important question answered in this study regards "topographic expression." The practice of smoothing and generalization in the early plane table surveys had a marked effect on the accuracy of contouring on the final product. Most obvious was the effect upon angularity and shape of contour lines. Angularity was significantly lower on all the older maps, and shapes were always more circular on older maps. These inaccuracies, in turn, affected other geometric properties of contours. As explained in Chapter IV, these results could be anticipated by a visual comparison of contouring on the modern and historic maps. However, less obvious effects of topographic ex-
pression (i.e. grouping of features) contributed to systematic errors found on the maps. In the majority of cases, closed contours that were near to each other and part of the same ridge were displaced in the same general direction (and often by a similar distance). This effect was recognized only after all measurements were taken and vectors plotted onto the maps. The search for effects of topographic expression on contour accuracy would no doubt be an integral part of any further study of relief representation on historic topographic maps. Throughout this research, topographic expression remained a major factor contributing to analysis of contour accuracy. Any research effort on this subject must begin with a careful reading of Birdseye’s “Topographic Instructions of the United States Geological Survey” (1928), an excellent explanation of early plane table methods with continuous reference to “topographic expression.”

In Chapter IV, applications of the Wilcoxon test determined that the 80-foot contour interval maps were most accurate with respect to all four measures (angularity, shape, area and perimeter), and the 20-foot contour interval maps were least accurate (Table 5). Probability levels in Table 5 showed the probability of accepting the null hypothesis that means are equal. Since probabilities were higher overall for the 80-foot contour interval maps, this indicated terrain representation was more closely matched with the more accurate, photogrammetric product. Thus, accuracy was maintained better in the most mountainous terrain. Flat areas were much more difficult to map. So, the probability levels revealed some differences between maps at different contour intervals. This indicated that historic U.S.G.S. topographic maps should indeed be analyzed separately based on contour interval. These results were based on computerized measures with little subjectivity involved. As the research progressed, however, close visual inspection revealed that even within maps at the same contour interval, distinct terrain types could be identified. This fact must be taken into account in any future research. A more focused study would stratify observations by terrain type. Perhaps each terrain type could be defined by steepness of slope. Consider the example of the White Mountains of New Hampshire versus the Green Mountains of Vermont, which differ greatly in structure and topography. The Green Mountains have a smoother appearance, and slopes are less precipitous. The rocky structure of the White Mountains creates a more jagged ap-
pearance, with distinct shapes and steep slopes. However, these two contrasting terrains are often contoured at the same 40-foot interval. Although this may be the appropriate interval if relief alone is considered, a focused analysis of contour accuracy should divide the two areas according to slope, and statistical testing should be done separately.

In addition to stratification by slope, observations should also be stratified according to amount of forest cover. Fortunately the 40-foot contour interval maps in this study provided some variation in forest cover so that a preliminary investigation could be conducted. The significant difference between probability levels for the measures of angularity and shape (Table 6) indicated that indeed forested and non-forested areas should be analyzed separately. Identification of maps with ample variation in forest cover would be advantageous to future research on this subject.

The importance of analyzing contour intervals separately was exemplified in the results of the discriminant analysis as well. Although results using this method were not entirely useful for error prediction, they set the stage for some further research. Table 9 indicated the function used different discriminating variables for each separate contour interval. The variable, shape, for instance appeared only in the function for the 80-foot contour intervals. Therefore, future use of discriminant analysis for error prediction in different terrains should always consider the shape measure important in very mountainous areas. Angularity, on the other hand, is not as important in mountainous areas as it is in flatter areas. Similar conclusions can be drawn with the other variables.

Discriminant analysis is a complex method. However, the preliminary results provide information which indicates that with a little perseverance, the method may be successful in solving the problem of error prediction in historic topographic maps. Although some of the variables used in this study would be important in a discriminant analysis, the success of the method depends on the addition of some new variables. The measures used in this study focus on characteristics of individual lines. New variables should focus on characteristics of the topography around the contour lines in question. Perhaps the amount of ground control in the area should be acquired from the archives at the U.S.G.S. A new variable could be density of ground control. Logically, interpolation should

SUMMARY AND SUGGESTIONS FOR FURTHER RESEARCH
be more accurate in areas containing a dense network of ground control. Another variable may be mean slope within a certain distance of the area in question. One more variable, perhaps related to amount of ground control, would involve some measure of cultural activity in the area. For example, an index could be created based on number of road intersections in the area, road classification, distance to nearest settlement, etc. The problem must be viewed from a perspective of surrounding terrain, and new variables created accordingly. Certainly the utility of this research rests in being able to predict areas of error in historic U.S.G.S. topographic maps. To be able to use a function to predict probable error in contouring on the maps would be invaluable to research dependent upon these maps for data acquisition.

A measure important in many applications in physical geography and related studies is that of slope. Since this study focused on individual contour lines, the purpose of the slope measures was to complement prior results. Indeed, the results of the Wilcoxon test on the paired slope measures made sense in the context of previous findings. However, determination of slope accuracy on historic maps should be examined more carefully and more thoroughly in any future research. Data acquisition should be computerized to maintain consistency among slope measures made in all terrain types. The trapezoidal rule could be used to locate centroids of closed contours at the tops of hills. Such computerization would enable acquisition of a larger data set than that used in this study. For example, manual calculation of slope in this study required far too much time. Fortunately, results using the non-parametric statistics were reliable even with small samples. However, increasing the size of the data sets will increase the strength of the non-parametric methods. Given the importance of slope measures in any study dealing with physical characteristics of the land, further assessment on slope accuracy would be productive in several spheres.

Patterns of systematic errors found on the maps in this study were very regular. Not only were error vectors most obvious in the mountainous areas on the 40-foot contour interval maps, but direction of vectors was generally parallel to the major axis of the ridge system itself. Since these types of errors have proven to be quite predictable, hypotheses for future studies could be formulated based on these findings. Maps of the Appalachian chain, for example, would most likely exhibit some
systematic errors. These mountains have a definite northeast/southwest orientation with a fairly regular pattern of smooth shapes and rolling hills, similar to topography of the Green Mountains of Vermont. In contrast, systematic errors in mountains characterized by sharp peaks and jagged, dissected slopes would be much less regular and difficult to predict. Again, findings in this study were significant enough to warrant continued research in this area. To start, correlation testing could determine the relationship between direction of the long axis of the ridge system and direction of error vectors. A thorough examination of this particular research problem would use statistical tests directed specifically toward analysis of directional data.

The basic methodology of analyzing closed contour lines as single entities in this study was chosen to approach the problem in a way not explored by previous researchers. As the research progressed and the effects of topographic expression became increasingly apparent, the basic methodology chosen seemed more and more appropriate. If contours were generalized, smoothed and drawn in groups, and drawn in relation to each other, the method of analysis should approach the problem in a similar way. The contours should be analyzed in groups; they should not be studied based on single points. For the same reasons, analysis of a map compiled using photogrammetry should use point by point comparisons since this is the method of original construction. In short, analysis of maps of any kind should be conducted only after a clear understanding of original methods of construction. The human factor involved in plane table surveys made the analysis of errors especially interesting—and more complex. Many obstacles faced the early surveyors resulting in a strong element of subjectivity present in contouring on the final product. This explains why there seem to be many avenues of further research available for the analysis of errors in plane table surveys. Analysis of a photogrammetric product would be much more clear cut due to the precision of the method of construction—answers would be more conclusive. The continuation of this research should certainly involve further analysis of the human element in plane table surveying, but should not be completely devoid of some measure of point distribution. Certainly accurate terrain representation was somewhat dependent upon density of elevation points. Addition of a variable
measuring this density would combine the two established methods of error analysis and constitute a more comprehensive study.
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Patricia Mahoney was born on June 28, 1959 in Ridgewood, New Jersey. She grew up in Acton, Massachusetts graduating from Acton-Boxborough Regional High School in June, 1977. She attended Salem State College in Salem, Massachusetts where she was graduated cum laude with a B.S. in Geography in June, 1981. Until August, 1988 when she began her graduate work at Virginia Tech, she worked as a draftsperson in several different capacities. Her drafting expertise includes all types of mapping, as well as civil, architectural and electrical detailing. She attended Virginia Tech for two and one-half years completing her M.S. in Geography in January, 1991. Her thesis work was honored at the annual meetings in Columbia, South Carolina, November, 1990, where she was given the “Best Student Master” award by the Southeastern Division of the Association of American Geographers. Her career interests include computerized cartography and applications of geographic information systems to environmental and resource planning.