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AN ANALYSIS OF ERROR IN DIGITAL IMAGE RECTIFICATION

By

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ABSTRACT

AN ANALYSIS OF ERROR IN DIGITAL IMAGE RECTIFICATION

By

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The Farm Services Agency of the United States Department of Agriculture, along with other public and private agencies, records thousands of small scene 35 mm aerial images annually. With georeferencing, these images could be a valuable source of land management information, especially for natural resources. This research began as a funded project to evaluate the efficacy of software developed by Michigan State University's Center for Remote Sensing to rectify the 35 mm images. Evaluation of those rectifications was hampered by the absence of a good measure of image error.

Two digital images were selected and georeferenced using global linear transformations of first-, second-, and third-order and local or piecewise linear transformation. These georeferenced images were used for error analysis. Independent check points were tested in each image and error surfaces were generated from those measurements for visualization and analysis of error. In addition, the areas of representative fields were measured for each transformation to test the effect of error on secondary products.

It was found, first, that the images contained systematic error, and that any pattern of control points for a global transformation was forced to accommodate that error. It was also found that, even though the images did contain this systematic error, discontinuous transformations with from ten to twenty control points could produce corrected images with root mean squared error less than 15 meters in flat terrain. It was further found, that, with a continuous transformation and as few as three control points, large areas of the corrected image have absolute positional error less than 20 meters.

To Pam, Cory and Brandon

ACKNOWLEDGMENTS

This thesis began with a grant from the U.S. Department of Agriculture to study geographic information systems. Recognizing the importance of GIS to natural resources management, the National Employee Development Center accepted my offer to study at Michigan State University. The time spent was interesting and rewarding.

Also recognizing the importance of GIS, the staff of the Natural Resources Conservation Service in Hawaii offered me a position to use the knowledge gained in a tropical setting. I gratefully accepted.

Since the list of people who contributed to the completion of this thesis are too numerous to print (and I risk forgetting some who helped over the years), I will simply thank my advisor, and express my gratitude for the opportunity to work on this thesis, and especially, my appreciation for the indulgence of my supervisor as this project forged ahead.

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LIST OF ABBREVIATIONS

AM/FM .... Automated Mapping/Facilities Management

ASCS .... Agricultural Stabilization and Conservation Service

DOQ .... Digital Orthophoto Quad

DPWS .... Digital Photogrammetric Workstations

FSA .... Farm Services Agency

GIS .... Geographic Information System

GRASS .... Geographic Resource Analysis Support System

LIS .... Land Information Service

NRCS .... Natural Resources Conservation Service

NRI .... National Resources Inventory

PSU .... Point Sample Unit

RMSE .... Root Mean Squared Error

SCS .... Soil Conservation Service

TIFF .... Tagged Interchange File Format

USDA .... U.S. Department of Agriculture

CHAPTER I

INTRODUCTION

Image Information

Maps are an efficient way to convey information, and planimetric aerial images provide an important source for map information. The importance of aerial images for storage and retrieval of geographic information can hardly be overstated. "For example, since 1957, all operational maps produced by the US Government have used some form of remote sensing as a base." (Davis and Simonett, 1991, p.192)

One type of aerial image, the 35mm slide has been used in some applications, both because of its convenience and its density of information. The common 35mm slide can contain a large amount of information. Depending on film density, resolving power can range from 50 lines/mm to 500 lines/mm (International Encyclopedia of Photography, 1984). At the low end of resolution, and even given the small image size (nominally 34 x 23 mm), features can be detected at nearly 2 million locations on a given slide.

The Farm Services Agency (FSA), formerly the Agricultural Stabilization and Conservation Service (ASCS), an agency of the U.S. Department of Agriculture, uses aerial photography in the form of 35mm slides to record (and monitor) compliance with agency programs involving crops, windbreaks, stream management, and other resource issues. These compliance slides have been taken annually in Michigan since 1986 and vary in scale from

1:63,000 to 1:158,000. Since they employ Kodak™ Ektachrome film, a film with 60 line/mm resolution, the slides have an effective ground resolution that varies from 1 to 2 meters (Enslin, 1995). This resolution is comparable to that investigated in a study conducted at the Rocky Mountain Mapping Center, Denver Colorado (Skalet et al., 1992). In that study, feature recognition was reported to be good in areas unobscured by dense or tall vegetation. The FSA slides have a much higher resolution than that of scenes recorded by satellite, and represent a large volume of potential, but largely unexploited, information. Compounding the volume of information contained in a single slide is the large number of compliance slides available. In 1991 alone FSA produced 55,000 aerial photographs of Michigan in 35mm slide format. Unfortunately, partly because of the inconvenience of storage, slides from earlier years have been thrown out (Bowman, 1998). Recognizing these slides as a valuable resource, the Natural Resources Conservation Service (NRCS) , formerly the Soil Conservation Service (SCS), has initiated a process to convert the slides to digital images using a commercial product of Kodak™ called Photo-CD™.

National Resources Inventory

The NRCS has been tasked with conservation planning, wetlands inventories, and land use updates. The NRCS is also tasked by Congress, under the Rural Development Act of 1972, with conducting the National Resources Inventory (NRI), a land inventory and monitoring program at not less than 5 year intervals. The inventories produce a nationally consistent data set consisting of 800,000 point sample units (PSUs). At each PSU several hundred data elements were recorded. Recent inventories were collected in 1975 (The Potential Cropland Study), 1977, 1982, 1987, and 1992 (National Resources Inventories). Procedures for collecting these data were conditioned by past NRCS (SCS) resource inventories, available funds and personnel, and available technology.

Although costs are difficult to determine with accuracy, the cost of the 1982 NRI was approximately $100 million (Goebel, 1998). The 1982 NRI was accomplished almost entirely by field visits. This meant that the soil conservationist, or other NRI tabulator, spent the time and effort to visit the location of each point sample. In 1987, the inventory was accomplished by field visits alone at approximately 30% of the sites, by image analysis alone at another 30% of the sites, and by both techniques combined at the remaining 40% of the sites. The costs were decreased to $50 million. In 1992, the inventory was accomplished with approximately 75% of the sites being evaluated from imagery and the costs were estimated at $25 million. Direct savings from the substitution of image analysis for field visits are difficult to estimate, but a decrease of $75 million in budget suggests significant savings.

One of the sources of imagery used for NRI measurements is the compliance photographs which were taken by the FSA. The procedure employed for the NRI was to find those FSA slides that included a PSU and to project them on a ground glass screen, adjust the projection to a usable scale, and make NRI measurements from the projected slide using a digital planimeter. These measurements were made at a (nominal) scale of 1:7920, and precision was estimated to be +/- 30 meters (Bowman, 1998). Information about distortion was not evaluated in the existing analog method of measurement. As noted by Enslin et al. (1995), several of the data elements required by the NRI (farmsteads, small built-up areas, large urban and built-up areas, windbreaks, streams and other water bodies to a minimum size of 2 meters) could be detected and measured using the projected 35mm slides. An alternative source of imagery, orthophotoquads, created from the National Aerial Photography Program (Light, 1993), exist for some counties, but FSA slides cover almost all land in Michigan and the annual flights ensure current coverage.

The Digital Paradigm

Analog methods of remote sensing are giving way to digital methods. Slow manual methods of information management in general, and hard copy cartography in particular, are giving way to high speed storage and processing of information in a digital format. For hardware, we are past the "break-even point" in the cost of switching to soft copy photogrammetric workstations from analog methods (Welch, 1992). In 1992, the high end Maxtor© 650Mbytes, the largest commonly available drive cost $5,000 (Mueller, 1992). Since then, prices have plummeted. In October 1997, drives twice that size, the smallest commonly available, are available from many sources for less than $200. In response to these price reductions, and similar reductions in processors and memory, the market responded with a flood of digital workstations useful for softcopy photogrammetry.

Heipke (1995) identified 37 digital photogrammetric workstations (DPWS), a class of equipment at the heart of a digital photogrammetric system. As of 1993 when the article was last revised, only one of the 37 DPWS was devoted to point transfer without stereo imaging. Point transfer without stereo imaging is the type of system this thesis will concentrate on. It is possible to effect low cost image registration with DPWS without specialized equipment and without stereo modeling. Such low cost image registration is the subject of this thesis.

The low cost of processing uncontrolled photographs digitally is also a driving force for the interest in digital image rectification. A full image pack on Kodak's Photo-CDs currently costs less $200.00 and can include up to 100 digital images at five different resolutions.

Applied Spatial Information Systems

Systems for managing geospatial data are complex and evolving. Implementations of softcopy photogrammetry are described in the literature. Skalet et al. (1992) detailed the advent of softcopy photogrammetry at the U.S. Geological Survey. Many other agencies and companies are looking at the new technology. One of the uses is for companies in rights-of-way management (Jadkowski et al., 1994). Until the development of digital aerial photographic imagery, the ability to cost-effectively acquire and incorporate up-to-date land information into a geographic information system (GIS) had been out of the reach of most pipeline companies. Companies such as the James W. Sewall Company, faced with the management of large volumes of spatial data, have developed a system called Automated Mapping/Facilities Management/Geographic Information Systems (AM/FM/GIS) in partnership with the National Aeronautics and Space Administration (NASA). Existing alignment sheets were usually outdated. Existing county maps and U.S. Geological Survey 7.5 minute quadrangle maps were not detailed enough. Satellite imagery was too coarse and manual handling of hundreds or thousands of hard copy aerial photographs was unmanageable. Hardware advances made storage, manipulation and printing of high quality images an economical and versatile alternative. Jadkowski et al. (1994) detail the benefits of AM/FM/GIS, and the framework of a system that facilitates the acquisition, management and storage of spatial and temporal data for right-of-way management.

Pries (1995) reports another example: the Bonneville Power Administration (BPA). BPA manages some 24,000 circuit kilometers of electrical transmission lines, while marketing power to nearly 130 Pacific Northwest utilities and 17 industrial customers. BPA uses its AM/FM/GIS to oversee its power lines, and in addition has gained responsibilities for regional planning, energy conservation, and fish and wildlife management, as a result of Federal legislation. While differences in hardware exist between BPA and the James W. Sewall Company, both manage geographic information to the same purposes (facilities management), and both depend on the georeferencing of digital aerial images.

The system this thesis will consider for study is that proposed by the Natural Resources Conservation Service (NRCS). In NRCS as well, analog methods of photogrammetry (slide measurement) are being considered for replacement with digital tools. In 1994 NRCS funded a project entitled "Image Correlation Based Ground Resolution Techniques" in which scanned digital images of these 35mm slides were to be rectified using digital orthophotoquads (DOQs) for a source of ground control points. Part of that study was to evaluate the precision of the image rectification done using new software developed as part of that project. The rectifications were done using different orders of spatial transformations. This thesis extends that work by evaluating both the magnitude and spatial distribution of error in rectified 35mm images.

From this promising situation, large volumes of valuable information in the form of digital images, and public domain (free) software to rectify them, comes the practical reason to undertake this research. This thesis will evaluate both global estimates and spatial distribution of the error in the images, to assess, both the software, and the images as a source of information.

Image Registration

> "Registration is a fundamental task in image processing used to match two or more pictures taken, for example, at different times, from different sensors, or from different viewpoints." (Brown, 1992, p. 325.)

Registration is the process of restoring the "shape" of an image, of making an image orthogonal, and correlating features in an image to those same features in another image or on the ground. It is a tool used in many disciplines. Registration is needed for satellite remote sensing, aerial imaging and map making, but it is also useful for industrial processes and medical technology. The generalized procedure for image registration involves feature identification, feature matching, spatial transformation and interpolation (Fonseca and Manjunath, 1996). Each of these steps can be carried out using several alternative approaches or search spaces (Brown, 1992). For this thesis, the operations of feature identification and matching were combined in the common method of manual point detection and matching. Spatial transformations were limited to global linear transformations of first, second and third order (Brown, 1992), as well as the discontinuous piecewise linear transformations (White and Griffin, 1985).

Overall three types of misregistration exist between images of the same place (Brown, 1992). Type I misregistration is a result of using a different sensor or different viewing angles. This type is correctable by spatial transformations. Type II misregistration results from differences in acquisition which are less easily modeled, such as differences in lighting intensity or atmospheric conditions. Type III misregistration is the result of changes in the subject, i.e. growth, deformation or movement. Type III changes make registration more difficult, but must not be corrected, because these changes may be of interest. This thesis will focus on type I misregistration. Type II and III misregistration may make corrections for type I misregistration more difficult, but will not be studied in this thesis.

To rectify a central perspective photograph is to make the information in the photograph - cultural, physical, and temporal - available for spatial analysis. Orthophotographs have been recognized sources of information for geographers since methods were developed to create them from aerial photographs. The many uses for this imagery include pollution detection and monitoring, environmental impact assessment, storm damage assessment, crop identification and inventorying, urban and rural planning, resources management, range management, erosion studies, watershed management, watercourse monitoring and water quality analysis (Light, 1993). This thesis seeks to extend this usefulness by analyzing their use as a source of ground control points to rectify other aerial imagery, in particular slides taken to check for program compliance by the Farm Services Agency of the U.S. Department of Agriculture. Full photographic registration of these images is not possible because they were not taken with the precision equipment required for removing camera and terrain distortions and registering stereo pairs. Aerial images that are simply registered without regard for relief displacement as a result of topography can be useful in environmental studies (Cairns et al., 1997; Gao and O'Leary, 1997) and multitemporal resource management studies (Guo and Psuty, 1997). In effect, management of land resources is a job that can be facilitated by aerial images in a GIS/LIS

(Bronsveld et al., 1994). Improved modeling of natural processes can be affected by better spatial data. These spatial data are rare, and cost effective additions from remote sensing can facilitate studies for multi-objective land use management.

Current methods of georeferencing small-scale aerial imagery (e.g., FSA 35mm slides) require locating an adequate number of ground control points in the image (Novak, 1992). The intersections of linear features such as roads, railroads, and rivers are commonly used as control points, since they can be accurately located in a digital orthophotoquad (DOQ) or other georeferenced display of the same scene. This investigation will use the existing DOQs as a source of ground control points for the images to be rectified, and will use GRASS software (United States Army Corps of Engineers, 1993) both for acquiring ground control points, and performing the transformations.

Unfortunately, the FSA slides have poor photogrammetric quality. The cameras have no calibration and the slides have no fiducial marks. The lack of well-controlled principal points and inconsistent overlap make the existence of stereo pairs very unreliable. Although stereo pairs can be created from the slides with a good deal of effort (Roberts and Griswold, 1986; Huberty and Anderson 1990), this research takes a pragmatic point matching approach for registering the photos and testing the limits of low order polynomial transformations. The effects of terrain elevation are also examined to test their influence on the effectiveness of the image registration approach.

The time taken to establish an accurate set of control points can be a significant cost in the process of image rectification. Therefore, an efficient method of choosing control points could effect considerable savings. For the purposes of error analysis, this study concentrates on scenes containing as many easily identifiable control points as possible, but the information gained and methods used should be extensible to all aerial scenes.

Error Analysis

Some of the critical issues to be addressed by this research are the efficiencies to be gained and the pitfalls to be avoided in the rectification process. Efficiency is measured against existing methods; errors are measured by comparing rectified image locations with known locations from a different source (i.e. DOQs). Not only do errors result in flawed mapping products, but the effect of these errors can be compounded in subsequent analyses (Walsh et al., 1987; Lunetta et al., 1991; McGwire, 1996). An important aspect of error analysis is the principle that a thorough understanding of error is critical in judging fitness of use for geospatial data (Chrisman, 1991).

The process of generating aerial imagery and processing it for use in an analytic environment (like a GIS) involves six steps. The steps are described below, as are errors and distortions that can result at each step in the process.

- Imaging: Errors in imaging affect the images used in this thesis and include excessive tilt, cloud cover, incorrect altitude, flight angle, sensor calibration and the like. Some of these are correctable as type I errors using the procedure presented here. However, because of the imprecise nature of the 35mm photos, the effects of these errors will not be analyzed separately. In the absence of error, aerial photographs are by nature center perspective. Away from the nadir, objects tend to lean outwards from the vertical. Elevation changes in the terrain also cause distortions in distance on the photograph.
- Cataloging: This involves identifying the area of the earth that the images represent. With the incredible volume of images available, this requires a large investment in time, effort, and storage media, and the possibility of errors is considerable. Errors in cataloging are usually more catastrophic than subtle, hence making detection of these errors more likely. These errors will not be assessed, except to note that the process of cataloging entails a substantial investment in time and money. Perhaps future airborne missions will use global

positioning systems to register scenes as they are flown (Schwarz et al., 1993; Curry and Schluckman, 1993). The cataloging of imagery used in this research is being done by the Center for Remote Sensing and GIS at Michigan State University, and funded by the NRCS (Enslin et al., 1995).

- Conversion to digital form: Remotely sensed information is either recorded directly in digital form as in satellite scanners, or recorded with analog sensors (i.e. photographic cameras) and later scanned or digitized. In either process, errors can occur in brightness value or position. Scanning is a critical step in building an information system. For this thesis, the process used was proprietary to Kodak and error was assumed to be a constant, but unknown, from image to image. Therefore scanning errors were outside the scope of the thesis, although the research of Kolbl and Bach (1996) is informative.
- Registration/rectification: It is presumed that registration effectiveness (i.e., accuracy) is a function of the number and placement of control points, and to a lesser extent, the spatial transformation used. The research in this thesis will attempt to measure the relationship between number and pattern of control points and the amount and pattern of error in the transformed image. It is assumed that some amount of error will occur in the acquisition of ground control points, but that this error will not have a systematic influence on the results, and that these errors are small relative to the other described errors.
- Storage/compression: To manage large files, it is efficient to compress the files, yet this compression can cause loss of information. These effects are outside the scope of this thesis, but Novak and Shahin (1996) is instructive. GRASS software has optional compression schemes, but they are not used for this research.
- Printing: The range of positional and intensity errors possible during printing, and degradation post-printing due to environmental and handling factors, will not be considered because the images are all digital.

This research is concerned with the errors in registration and rectification. The emphasis was on an analysis of error produced by different numbers of and patterns of ground control points, as well as different types of spatial transformations used in the rectification.

McGwire (1996) offers the opinion that the proper placement of ground control points is poorly defined in texts describing the rectification process. Previously, the guiding principal for both the correct number of control points and their placement has been determined by criteria such as the amount of distortion in the scene, the areas of interest (those areas that must be corrected properly), and the type of transformation needed to convert the scene to Earth coordinates.

Once the control points are located, a numeric transformation is used to correct the distortion in the image. Traditionally, this transformation has been a linear or affine transformation using first-, second-, or third-order polynomials (Novak, 1992). Fogel (1996) takes issue with the tradition of polynomial transformations, preferring instead to use radial basis functions, such as multiquadrics, thin plate splines and variations of these methods. Some reservation about these methods has been expressed because of the extreme computing complexity (Fonseca and Manjunath, 1996). Only polynomial methods are investigated in this thesis, but other spatial transformations remain as alternatives for further study. It is hoped, however, that the methods of analyzing error developed in this thesis can be applied equally to other rectification methods.

The primary objective of this research is to investigate the effects that the number and position of control points have on the ability to correct and georeference a digital scene, and to create an optimal procedure for rectification of FSA slides. It is also one of the objectives of this thesis to determine if the effects of relief can be safely ignored on a digital scene with 400 meters of relief.

Focus of the Study

In analyzing the rectification process, four questions were addressed:

1. What is the optimal number of control points to correct a digital scene?
2. What is the optimal placement of those control points?
3. To what extent does relief affect the rectification?
4. To what extent does transformation type affect the rectification?

Objectives

Five objectives were pursued:

1. Develop a method for comparing the relative precision (overall and spatially differentiated) of multiple rectifications of an image. The method will use control and test points obtained from a digital orthophotoquad (DOQ) and the rectified image.
2. Using this method, measure the positional accuracy and pattern of errors of multiple test points for different rectifications of the multiple images (selected to represent relatively flat and relatively variable terrain.)
3. Compare the value of an error measure calculated from the transformation equations versus a similar measure calculated with independent test points.
4. Evaluate overall measures and spatial patterns of locational accuracy to determine the influences of numbers of control points, and order of polynomial transformation.
5. Evaluate the differences in accuracy obtained when rectifying an image over flat terrain versus an image over variable terrain.

CHAPTER II

BACKGROUND

Introduction

Consideration of error in image registration begins with the feature recognition and matching process. For this investigation, ground control points will be interpreted from digital orthophoto quads (USDA-NRCS, 1995). The geometry of rectification will be considered next. The spatial transformations to be considered consist of first-, second-, and third-order linear and piecewise linear transformations (White and Griffin, 1985). Previous studies will be examined for the effect on error of the number and disposition of control points used in image rectification. Finally, the literature will be reviewed to describe error studies and metrics used in describing errors in image registration.

Feature Identification and Matching

Feature matching can be separated into two categories: point mapping with feedback and point mapping without feedback (Brown, 1992). Feedback involves the use of matched points to find more points. Excellent results can be obtained (Derenyi, 1996) using point mapping in an iterative process to register an image area by area. Automated feature identification is an evolving science, and the literature details several methods (Schenk and Toth, 1992; Al-Garni, 1995; Fonseca and Manjunath, 1996), but the method has limited application at present. One method to accomplish feature detection of points uses coordinate retrieval from the Global Positioning System (GPS) (Cook and Pinder, 1996). This method is increasingly of interest, both because of its relatively low cost and because of its availability. This is not to say it is a panacea. Not only is GPS accuracy suspect in urban areas (Brown, 1994), but the results are marginal in areas of the world without differential correction of the selective availability (Kardoulas et al., 1996). The method of feature identification this thesis will investigate involves manual recognition from an orthophotograph and employs a program within the GRASS system which enables manual feature matching between split screens (United States Army Corps of Engineers, 1993; Reisen and Stinson, 1996).

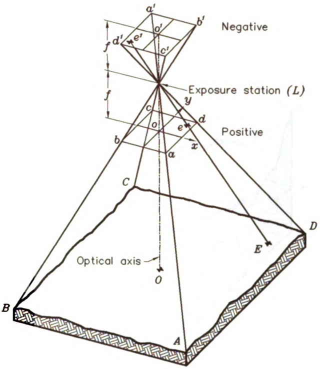

Figure 1 Geometry of Aerial Photography

Geometry

As early as 1949 (Clark, 1949), the geometry of aerial photography was well known, and various methods, all analog and optical, had been proposed to rectify them. Clark "develop(ed) a single consistent and easily comprehensible theorem of such universal application that it may serve to explain the principles of presently known methods of rectification and to establish simple criteria by which the validity of suggested procedures may be examined" (p. 288). The geometry of aerial photography is dominated by the scale factor of flying height to focal length of the camera (Figure 1), assuming the camera is perfectly vertical (Lillesand and Kieffer, 1994).

The earth scene below is converted to a scale image (i.e., one unit on the image = H/f units on the ground, where H equals the flying height, and f equals the focal length of the camera. The misregistration of aerial images is influenced by differences in the attitude of the platform and the irregularities of terrain (Lillesand and Kieffer, 1994).

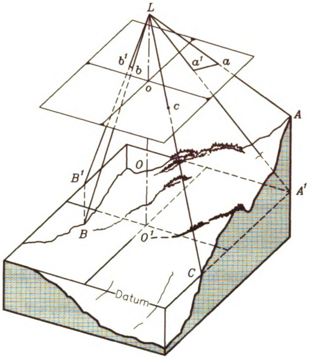

Figure 2 Distortions due to Elevation

In multitemporal studies this is partly due to changes in look angle. In particular, the slides taken annually by the Farm Services Agency, U.S. Department of Agriculture will not be in alignment from one year to the next.

Even if the look angle were perfectly vertical, the effect of terrain can cause distortion on center perspective photographs, as shown in Figure 2 (Lillesand and Kieffer, 1994). Points on the earth which are significantly higher will appear farther from center than they should. Tall structures appear to lean out from the center. For 35mm slides it is important to determine what terrain height would cause significant distortion. From an earth satellite in geosynchronous orbit nothing would appear to have significant altitude. From the perspective of airborne photography meant to check compliance with agricultural programs, most scenes of Michigan farmland, by virtue of their low relief would not have any significant relief displacement. Since these are low altitude aerial photographs, unlike the images investigated by Mather (1995), Ford and Zanelli

(1985) and others, some consideration will be given to the effect of terrain on the process. It is suspected that terrain in Michigan will show minimal effect on error, since El-Manadili and Novak (1996) report no effect for altitude ranges less than 1500 meters and a base-to-height ratio = 0.8, but this is for scenes recorded at SPOT satellite height. Other researchers conclude that flying heights greater than 12,000 meters can be considered high enough to ignore the effects of terrain. The Michigan slides are mostly flown at 6,000 meters, so the effect of terrain is unknown and subject to study. At some degree of relief, however, the effects of terrain will have to be considered.

If relief effects are correctly modeled, there are many more sources of error that cannot be adequately or exhaustively accounted for. The effect of distortion within the photographic field (Frasier and Shortis, 1992) is another source of error. Although the error contribution from lens distortion alone is minor, Frasier and Shortis admit the frustrations of mathematical models in describing that error and opt for an empirical approach in analyzing the error. With other sources of error, such as radiometric, atmospheric and growth, deformation or other temporal changes, an empirical approach to error analysis seems worth pursuing.

Spatial Transformation

The rectification process can be carried out globally or locally (Brown, 1992). This process follows two courses. Smaller images are corrected with global corrections, and these images are mosaicked to produced digital orthophotos in quadrangle format (Hood and Champion, 1989). On the other hand, any image may be differentially corrected (Novak, 1992) using small neighborhoods of the image and correcting each separately. This leads to surface discontinuities, but post processing and edge matching can create a smooth finished product (Hood and Champion, 1989). This thesis will investigate both a global, affine transformation and a local, piecewise linear transformation (White and Griffin, 1985).

The rectification process also includes an interpolation for grey scale assignment to each pixel. This process occurs after the projected pixel is created, by a resampling algorithm from the image to be rectified (Lillesand and Kieffer, 1994)

For some applications such as SPOT data, hybrid transformations can be created to model the effects of sensor alignment so that very good results can be obtained from as few as four control points (El-Manadili and Novak, 1996). It is noteworthy that error in the analysis by El-Manadili and Novak was reported as mean errors from 50 independent check points rather than transformation residuals. Also of note is the result that errors do not exceed one pixel for any of the (simulated) terrain with elevation differences less than or equal to 500 meters.

Fonseca and Manjunath (1996) report on 13 methods of automated feature identification/matching, and 11 of these methods used affine, polynomial or other combinations of rotation, translation or scaling. The other two reported no spatial transformation. In effect, any error detection/management scheme involving polynomial translations would still serve a wide audience. Mather (1995) reports on an exhaustive test of polynomial translations using an artificial scene, and found significant differences in the results from different types of polynomial algorithms.

Number and Position of Control Points.

Intuitively, the more ground control points that can be used, and the better their distribution, one would expect a better rectification result. Studies have shown that error surfaces are controlled by the pattern of ground control points (Ford and Zanelli, 1985). Stanislawski (1996) finds that error is inversely related to the number of control points up to about 20, and that more points beyond 20 do not consistently increase the accuracy. This observation was also made by McGwire (1996).

Mather (1995) showed, by addition of random error, the deleterious effect of error in ground control points. Of interest to this research is that his research shows improvement of spatial translation in terms of error reduction, through the full set of 40 control points. Other studies show that as few as four ground control points measured without error can produce well-rectified scenes (El-Manadili and Novak, 1996). The importance of error free control points was also noted in Clavet et al. (1993). The authors of this paper quantified this dependence by requiring 4 meter planimetric accuracy for control points to create an ortho-image meeting 10 meter accuracy at the 90 percent confidence level.

Error Analysis

Little error analysis is done for routine image rectification used for research. Sometimes the number of control points used for rectification is reported with residuals from the transformations (Hohle, 1996; Gao and O'Leary, 1997). Other researchers report on the number of control points used (Pope et al., 1996) and rely on visual inspection for analysis of the efficacy of the translation.

McGwire (1996) introduces a computational method (cross validation) for accuracy assessment that seems robust and should be included with new registration software. Cross validation iteratively removes a control point from the transformation equation and measures the error at that point. As a consequence, it requires more control points, but gives an estimate of error that is derived from measurements at known points. More importantly, McGwire illustrates the problem with reliance on RMSE of the residuals for an analysis of the error of the transformation. The RMSE is under-estimated for small numbers of control points, and over-estimated for large numbers of control points. This observation recurs in Cook and Pinder (1996) when the authors attempt to correct a translation by eliminating control points to "reduce the root-mean-square (RMSE) to 0.33..." (p.74). This would seem to be counter productive, since the real (global) error should be increasing as points are removed (McGwire, 1996). As important as McGwire's results are, cross validation takes a few more ground control points than the minimum, because improving error measurement requires a few extra points which become in effect check points. When those extra points are not available, or when the time to select them is not available, it would be useful to have information about error in rectifications done with few control points.

While Fogel (1996) reports greatly improved results for transformations other than polynomials, it is noted that error still exists no matter what method is used. It is also instructive to note that the error calculation is done on an independent set of check points, rather than on residuals. However, in many remote sensing applications, additional ground control points beyond those needed for the spatial transformation are frequently not available or too expensive to collect.

As Novak (1992) points out, while polynomials are easy to use, higher order polynomial transformations can be deceptive. That is, the error at the control points may be forced low, but because of the undulations between those control points, large errors may exist in the scene away from the control points. Much of the literature reports results of corrections using Landsat data which is essentially without relief because of the high flying height (Orti, 1981; Mather, 1995). Some investigators looking at the full range of correction by types of scenes and techniques (White and Griffin, 1985; Novak, 1992) seem to use visual inspection as evidence of the efficacy of the corrections. Williams (1995), created a 10 meter buffer around the "true" value for fencelines and used this buffer as a mask to determine the percentage of fencelines from corrected images that fell within the buffer as a quantitative measure of error in the image transformation. In Stanislawski's (1996) opinion:

> "A transformation model to a geographic reference system is an imperfect functional relationship between unknown parameters and coordinate observations. Imperfection arises from a lack of understanding of all

> contributing factors, or because the selected model is a simplification of the relationship. This imperfection can be referred to as bias which may produce systematic errors." (p. 430.)

This thesis will use several empirical tests, the root mean squared error measured at control points not used in the correcting transformation, an error surface for visual inspection, as well as histograms of that surface for quantitative analysis. Histograms, within the limits of the assumptions under which the error surface is made, will quantify the behavior of error and will enable a comparison to be made to the national map accuracy standard. This standard states that 90% of the points on a map, at 1:24000 scale, will be within 15 meters of the correct position (U.S. Geological Survey, 1997). Finally, a measure will be done of areas in the corrected images to test the effect on the field measurement of the different transformations.

CHAPTER III

METHODS

Introduction

Two digital images (i.e., scanned slides) were selected for desirable characteristics, cataloged, and converted to the tagged interchange file format (TIFF). Desirable characteristics included the appearance of many discernible physical or cultural features used for ground control points. Fifty-four of these features were selected in a stratified random manner for ground control points, half of those to be used for test points. For the first image, several rectifications were performed using three through twenty control points in various patterns. For each of these rectified images the 27 independent check points were used to assess the root mean squared error of each transformation. Using these point error samples, an error surface was created using inverse distance weighted interpolation. From the visualization of those error surfaces, from measures of the control point distribution and from histograms of the error surface, the spatial patterns of error were investigated for the effect of number and distribution of control points for the first and relatively flat image. For the second image, representative of Michigan's more hilly terrain, several first-order transformations using few control points were used to test the effect of terrain elevation on error patterns. Finally the best patterns of control points and order of transformation (as determined by the first image) were used to determine if equivalent results (in terms of overall accuracy) can be expected from hilly terrain.

Image Selection

For the first objective of this research (see end of Chapter 1), the primary task is to select two images for testing. The images should have many clearly identifiable features to be used as control points and test points distributed in a stratified random pattern throughout the image. The first image should be relatively flat, while the second should have as much relief as possible. In addition, the terrain will vary from having many obvious cultural and physical control points to nearly featureless terrain.

Since Michigan now has three counties covered by digital orthophotoquads (DOQs), there are many candidates for testing. The counties of Clinton, Kalkaska, and Otsego have DOQs available, and these represent varied terrain. Clinton County is primarily farmland, while Kalkaska and Otsego Counties are largely undeveloped. Kalkaska and Otsego Counties, in general, have more relief than Clinton County. A reasonable place to acquire a large number of control points is an urban scene. Consequently downtown Gaylord, Otsego County, was selected as a candidate for a sensed image with little or no relief. This was the image indexed as 79 (Figure 3) on the photo-CD.

Ortho Images

The ortho image matching Image 79 was on the Gaylord County quadrangle in its southwest quadrant. The disk storage for a DOQ is roughly 45 megabytes, a size that up to three years ago may have required some planning to accommodate on a desktop PC. Now, however, with disk sizes on the order of 4 to 9 Gigabytes common, the storage requirements for one DOQ are inconsequential, while county wide coverage may require some forethought. Primarily to save processing time, a piece matching the aerial image in Figure 3 was extracted from the DOQ (Figure 4). The subset area matching the image required less than 9 megabytes of storage.

Figure 3 Scanned Image of Downtown Gaylord

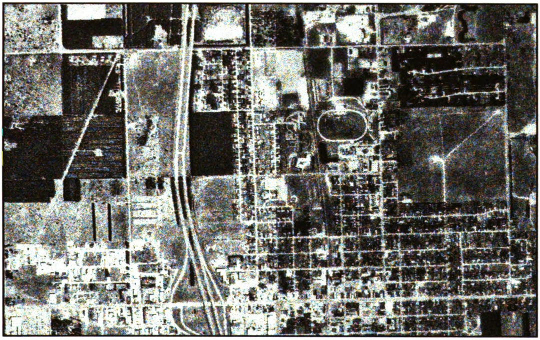

Figure 4 Ortho Image of Downtown Gaylord

Image Resolution

Two of the more important values in the digital image's resolution are the radiometric resolution (number of bits per pixel) and the spatial resolution of the pixel. The digital image for downtown Gaylord consists of 5,961,018 cells which are corrected to 7,136,864 cells, or 2,114 rows by 3376 columns. Since the scene covers an area approximately 2,000 by 3,000 meters, the resolution of the image is nominally one meter. The number of bits per pixel determines the number of possible colors that can be represented. One bit can represent one color, 8 bits can represent 256 colors, or one gray scale to 256 different values. More importantly, 24 bits can represent three different spectral bands to a level of 256, and the interaction can be used for realistic color displays and analyses of ground cover by spectral analysis. Thus, 24 bits, used for red, green, and blue wavelengths, yields true color in more than 16 million variations. 24 bit storage would work as well for Landsat Thematic Mapper or any other three band data. A drawback of the GRASS software used for this image processing is that it did not import the 24 bit color available in the TIFF files. Therefore the selection of control points was somewhat hampered by the nature of the display, and an implication of this drawback is that the results could be far better based, on Mather's (1996) observation that error in control point selection are very deleterious to the accuracy of the rectification.

Computer Hardware and Software

All image processing was done using the GRASS package of GIS software (United States Army Corps of Engineers, 1993). File manipulation routines, error computations, and display formatting routines were developed by the author from UNIX shell or awk scripts or native C code. The computer used was a SUN Microsystems Sparc-10 with 64 Mbytes of random access memory. Some additional processing was done on an AT&T Globalyst with a pentium processor and 32 Mbytes of memory.

Transformations

Among the common spatial transformations are linear, affine, projective and hybrid models (Brown, 1992, Novak, 1992). A transformation is linear if,

$$T(x_1 + x_2) = T(x_1) + T(x_2)$$

and affine if T(x) -T(0) is linear (Brown, 1992). For this thesis, transformations will be limited to transformations with these characteristics, i.e. a combination of translation, rotation and scaling.

With increasing numbers of control points, higher orders of polynomial transformations, can be defined. The minimum number of control points needed is:

$$(n + 1) * ((n + 2) / 2)$$

where n is the order of the transformation (Enslin et al., 1995), although other authors (Williams, 1995) recommend one additional point to avoid the distortion caused by a transformation with no degrees of freedom. These are global transformations; local transformations were also tested using piecewise linear transformations (White and Griffin, 1985).

Terrain With Relief

For an image with relief representative of a hilly area of Michigan, the image indexed as 81 on the CD was selected (Figure 5). This image is two air photos to the east of Image 79. Image 81 is a fairly hilly section (about 400 meters of relief) with no roads and few cultural features in the interior to use for ground control. The ortho image matching Image 81 was extracted from the southeast quadrant of the Gaylord quadrangle (Figure 6). The radiometric and spatial resolution were similar to Image 79.

Digital Elevation Models

To compare the patterns of error in corrected images with elevation patterns, the digital elevation models for the area matching Images 79 and 81 were printed (Figures 7 and 8).

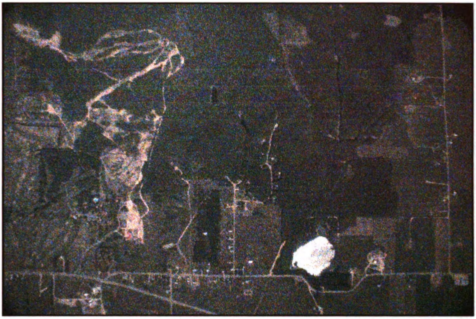

Figure 5 Scanned Image for Southeast Gaylord

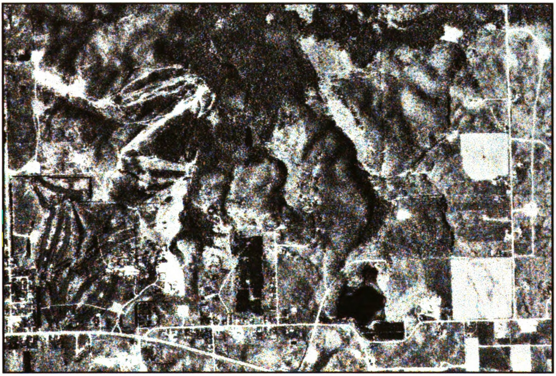

Figure 6 Ortho Image for Southeast Gaylord

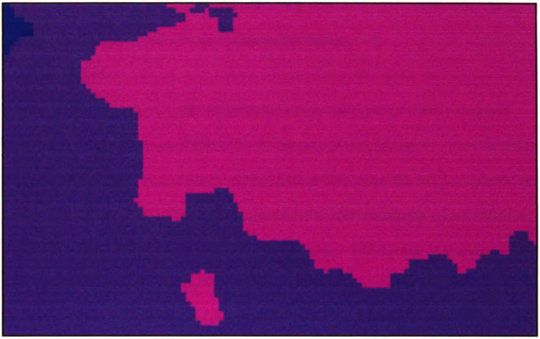

Figure 7 Digital Elevation Model for Downtown Gaylord (50 Meter Contour)

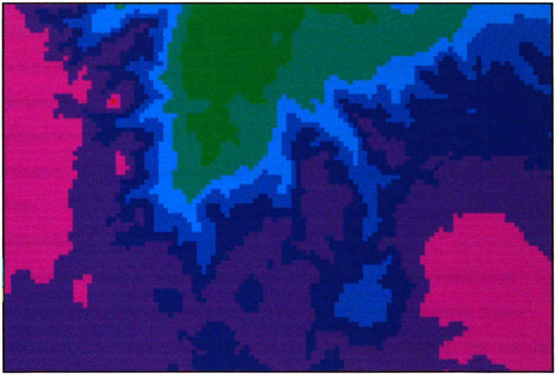

Figure 8 Digital Elevation Model for Southeast Gaylord (50 Meter Contour)

The models were imported from US Geological Survey data at 30 meter resolution. The elevations were reclassified into 50 meter contours for display.

Error Measurement

To measure error at test points, a GRASS sites file was created from the check points and displayed on the corrected image with the GRASS program d.sites (Figure 9). Then the GRASS program d.where was used to measure the easting and northing where the test point should have been. This measurement yielded a list of expected positions for identifiable points, and their actual position. To interpret this list, a program was written to read the file of actual positions versus the expected positions, and the RMSE, or the square root of the mean of the squared distances (errors) was calculated and reported.

Measures of Error

The root mean squared error (RMSE) was used as an acceptable global measure of error for the scene. RMSE is measured by taking the square root of the sum of the squared error at each test point divided by the number of test points (mean squared error). For each image rectification, twenty-seven independent control points were tested to find the RMSE for that image correction. The exact same points were used for error measurement for each different transformation. These check points were different points from those used to perform the correction.

Error Surfaces

Error surfaces were generated and displayed for each combination of control point pattern/transformation to visualize the patterns of error created by that combination. Since a global measure of error (RMSE) seems inadequate, even misleading, (McGwire, 1996), a display of local error should aid in determining the efficacy of the transformation.

A methodological assumption was made that the error surface can be modeled by inverse distance weighting. Since the test points are distributed in a stratified random pattern over the image there should be no clustering of sample points. Without clustering, inverse distance weighting can be assumed to give good results for a surface model (Isaaks and Srivistava, 1989). The inverse distance interpolation method used in this thesis is from the GRASS suite of software (United States Army Corps of Engineers, 1993) and uses inverse distance squared weighted from the twelve closest sample points.

Histograms were created from the error surfaces, so that quantitative measures of the numbers of cells with error in each one meter class could be calculated. Graphs were created using Excel© software from Microsoft Inc. to display the distribution of error from this histogram. The graphs of those histograms provided another visualization of the efficacy of the transformation. The graphs also suggested another measurement, a weighted average of the error at each cell which yielded a more representative version of RMSE.

Procedure

Image 79 (Figure 3) was converted from the Kodak Photo-CD, and 54 control points (6 rows by 9 columns) were chosen with 49 of the control points being cultural and 5 natural (Appendix A). Image 81 (Figure 5) was also processed and 54 control points were chosen of which 43 were cultural and 11 were natural (Appendix A). The ground control points were readily identifiable on the slide as well as on the DOQ and were distributed in a stratified random pattern over the scene. These points were also identified on the DOQ and their correct locations were saved. Half of the control points were reserved for transformations (the odd numbers) and the rest for check points for error testing. Twenty seven was considered to be an adequate number of check points (Figure 9) for an accurate assessment of the global error (McGwire, 1996; Reisen and Stinson, 1996).

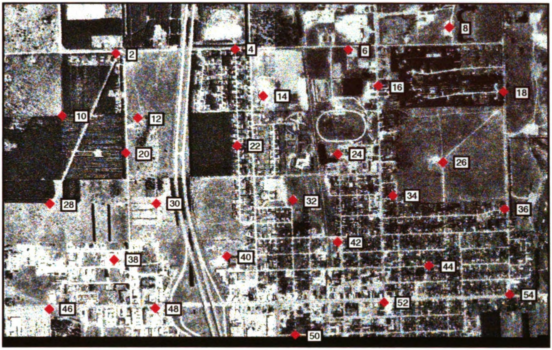

Figure 9 Check Points used for Error Measurements

For the first (flat) scene (Figure 3), a series of six different sets of three ground control points were selected from an initial total of twenty-seven available for corrections. For each of these sets, a first-order linear transformation was used to create a corrected scene. This set of six corrected scenes was used to test the effect of the pattern of ground control points on transformation efficiency, using the measures of error detailed above. For each set of ground control points, the area occupied by the points was reported. This area was calculated by the GRASS program d.measure. Next, patterns of four, five, and six points were selected, but for those sets, in addition to the tests done on the three point corrections, the tested RMSE from the control points was compared to the calculated RMSE of the transformation residuals. With no degrees of freedom for three control points, the reported error of the residuals is zero. For these corrected images, error surfaces were created as described above, and histograms and weighted averages were created to further analyze error. This established a baseline for the most efficient

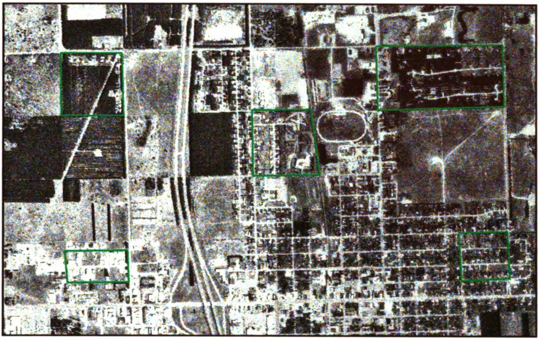

Figure 10 Field Boundaries for Area Test

(i.e., least time consuming) corrections.

Then the error surfaces from this quickest approach were compared to the error surface for 7, 8, 9, 10, 15 and 20 ground control points still using first-order linear transformations. The error at the 27 check points was again measured for each corrected image, and RMSE was calculated. Error surfaces were created and analyzed for error patterns. Calculated error from the transformations residuals was reported and compared to the RMSE from test points. Third-order linear transformations were also investigated for 10, 15 and 20 control points. It was assumed that as additional ground control points were added, that this added new information to the rectification process. RMSE was calculated from the 27 test points for each correction, and error surfaces as well as histograms were again created and the results reported.

Twenty-three different combinations of number and pattern of points (Appendix B) were used in all to create corrected images for Image 79. For each of these patterns, first-order linear transformations were used. From patterns with at least six points, second-order transformations were used, and for 10 or more points, third-order linear transformations were used.

For six or more point ground control patterns (Appendix B), a discontinuous, or local transformation was used, and measurements were made in the same manner as the global transformations.

Area Measurements

Areas were measured for several representative fields and street bounded areas to test the limits of the effects of global errors to be found in the rectifications. Five areas were chosen for measurement, one in the center and one in each of the four quadrants (Figure 10.) Each of these areas was measured for each corrected image. Each of the five areas was then compared to similar measurements taken from the DOQ (the assumed correct image), and the square root of the mean of the squared errors (RMSE) was reported as error.

Statistical Tests

The error in area measurement may be strongly correlated to the error in image rectification measured by RMSE. To test this relationship, an analysis of variance was performed using the Minitab statistics package from PWS-Kent Publishing (1992). To test the relationships between image rectification error and the number and area of control points, several simple linear regression models were constructed, also using the Minitab statistics package.

CHAPTER IV

RESULTS

Introduction

The results are presented first as qualitative observations of the corrected images for simple three point linear transformations. Error surfaces were created and used to further describe the error. These qualitative observations continue through greater numbers of ground control points, and higher orders of transformations.

For each of the orders of transformations, tables of measurements were presented which showed root mean squared error (RMSE), both calculated residuals (when possible) and measured. The measurements in the tables also include a measure of error in the area of representative fields, area of control points, and a weighted average of error in the error surfaces. Similar measures are reported for image corrections done with piecewise linear transformations.

Visual Observations of Corrected Images

Since the flight path was skewed from north, the image was transformed at an angle, leaving wedge shaped borders at the four edges. The amount of disagreement between image transformations was indicated by the size and shape of the borders. The size and shape of those borders were early clues to differences between transformations. Figure 11 is an example of a three point first order linear transformation using ground control point pattern 3.1 (Appendix B). For these images, the check points are superimposed on the image. An inspection of the location of those check points in the image (compared with where they should be) can give a qualitative indication of error at those points. A quick comparison of the correction using ground control pattern 3.1 (Figure 11) with ground control pattern 3.2 (Figure 12) shows a difference in error patterns. Check point 18, a road intersection (Appendix A), is quite removed from that intersection in Figure 11, and well positioned in Figure 12. Similarly, check point 4, another road intersection (Appendix A) is well positioned in Figure 11, but is disturbed in Figure 12. Comparison to the pattern of ground control points (Appendix B) shows that, as expected, the error that check points 4 and 18 exhibit is consistent with the distance of these check points from the ground control points. This error pattern seemed to continue to higher numbers of control points, in that when areas of the northeast and east that are not covered well by control points, they are consistently distorted (Figures 13, 14, and 15 - ground control patterns 4.3, 5.3, and 6.3). Unfortunately, this response to ground control was limited to the northeast and east area of the digital image. Distinctive response to ground control in other areas of the image were harder to visualize (e.g. Figure 16 - ground control pattern 5.2).

Second and higher order transformations can show extreme distortion in curved edges, (Figure 17). Figure 17 is a correction using a second order linear transformation with ground control pattern 6.1 (Appendix B). Despite a good distribution of control points, the quality of the corrected image is clearly unacceptable. The correspondence of error with control points in the northeast and east is even more pronounced with some check points that are entirely off the image (Figure 18 - control point pattern 6.3).

Piecewise linear transformations, on the other hand, usually give indication of being nearly planimetric corrections of the image. This is because the transformations are local. The triangular regions were each corrected independently and mosaiced together providing a

Figure 11 Corrected Image for Ground Control Point Pattern 3.1

Figure 12 Corrected Image for Ground Control Point Pattern 3.2

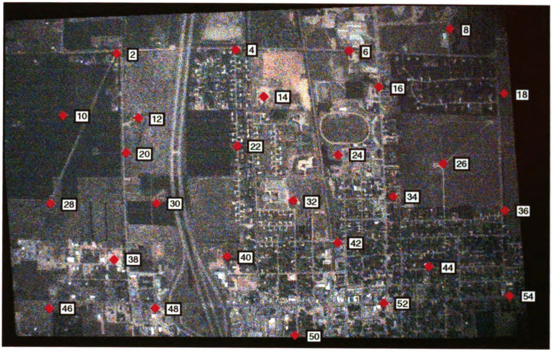

Figure 13 Corrected Image for Ground Control Point Pattern 4.3

Figure 14 Corrected Image for Ground Control Point Pattern 5.3

Figure 15 Corrected Image for Ground Control Point Pattern 6.3

Figure 16 Corrected Image for Ground Control Point Pattern 5.2

Figure 17 Corrected Image for Ground Control Point Pattern 6.1 (Second Order)

Figure 18 Corrected Image for Ground Control Point Pattern 6.3 (Second Order)

correction that is more sensitive to non-linear variation in image distortion (Figure 19). Figure 19 was created with ground control point pattern 10.1 (Appendix B).

Observations of Error Surfaces

The error surfaces showed, first, that error is lower near ground control points (Figure 20 - ground control pattern 3.1), as expected. In Figure 20, the areas of lower errors (areas colored yellow) were found in the northwest, southwest, and southeast regions of the corrected scene, as was anticipated from inspection of Figure 11. This pattern held up when using ground control patterns that avoided correcting the northeast, as in Figure 21 (ground control pattern 4.3) and Figure 22 (ground control point pattern 5.3). Inspection of more error surfaces, however, showed evidence again of systematic error in the northeast, or more generally the eastern part of the corrected scene. If ground control points were shifted to cover the northeast as in ground control pattern 3.2, instead of an inverse of Figure 20 (with high errors in the southwest), a more complex pattern resulted (Figure 23) that seems to distribute the northeastern error over the entire scene. Including points in all areas, including the center, did not seem to improve the overall pattern of error. Examples of patterns that include the center as well as the northeast are Figures 24 and 25 (ground control point patterns 5.1 and 6.2).

Effect of Elevation

There seemed to be no relationship between error and elevation (Figure 7). The northeastern corner of the image is more nearly flat than other areas of the image. This alone makes it difficult to use elevation as an explanation for systematic error within a relatively flat image. Yet as shown above, every pattern of ground control that avoided the northeast, such as 4.3 (Figure 21) and 5.3 (Figure 22) seemed to have lower error over more of the image. The patterns of error are probably better controlled by the numbers and patterns of ground control points than by elevation. The systematic error may be better explained by camera tilt, or

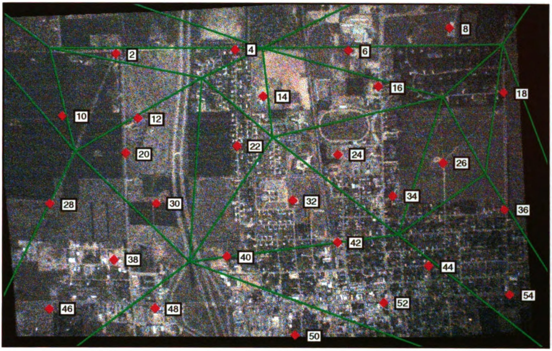

Figure 19 Piecewise Linear Transformations with 10 Ground Control Points

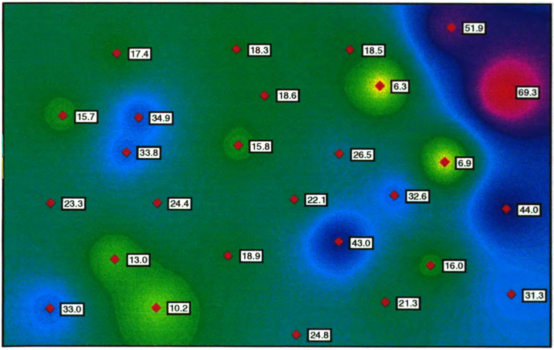

Figure 20 Error Surface for Ground Control Point Pattern 3.1 (yellow=low; red=high)

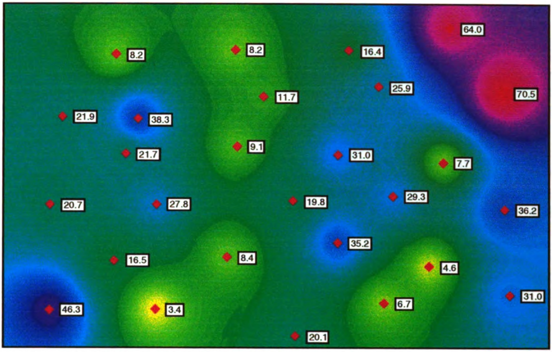

Figure 21 Error Surface for Ground Control Point Pattern 4.3 (yellow=low; red=high)

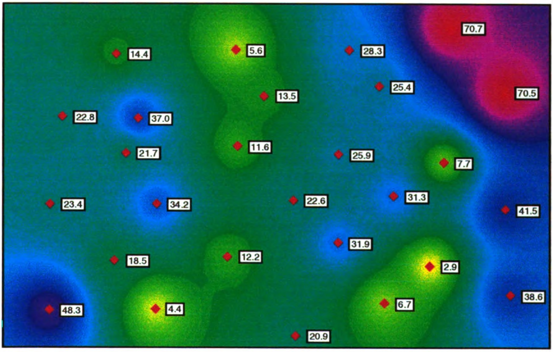

Figure 22 Error Surface for Ground Control Point Pattern 5.3 (yellow=low; red=high)

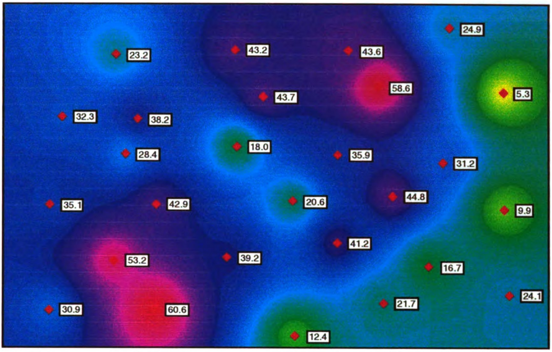

Figure 23 Error Surface for Ground Control Point Pattern 3.2 (yellow=low; red=high)

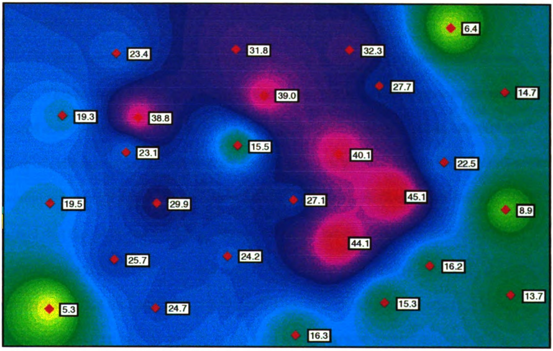

Figure 24 Error Surface for Ground Control Point Pattern 5.1 (yellow=low; red=high)

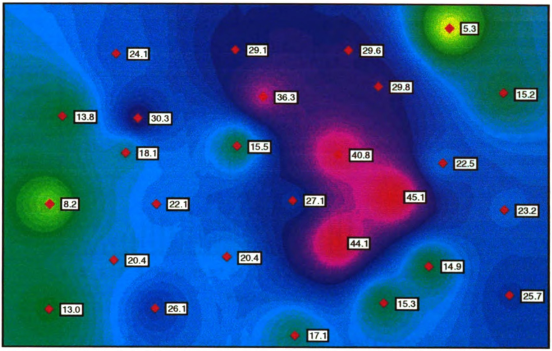

Figure 25 Error Surface for Ground Control Point Pattern 6.2 (yellow=low; red=high)

distortion within the camera itself. This relationship and the effect of elevation on image correction error in images with more relief are discussed below.

Measurements

To better analyze error in corrected scenes, histograms were created from the error surfaces. This histogram gives graphic depiction of how many cells (i.e., how much area in the corrected scene) have particular levels of error. Such a graphic can be used to interpret the number of cells that exceed some arbitrary error level). For presentation, the histograms were converted to bar graphs in Excel©, from Microsoft. Earlier work (Reisen and Stinson, 1996) indicated that the variances of error across an image and between corrections with different patterns of control points decrease with increasing numbers of control points. With greater than seven control points the pattern of ground control points becomes less important. Visual evidence of this effect may be seen by comparing the histograms of error surfaces in Figure 26 and Figure 27. Figure 26 was created from histograms of the error surfaces derived from

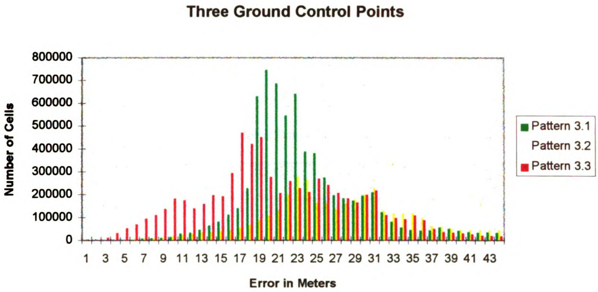

Figure 26 Histograms of Error for 3 Ground Control Points

corrections using first order linear transformations with ground control point patterns 3.1 through 3.3. Figure 27 was created similarly from ground control point patterns 7.1 through 7.3. The distribution of error in both sets of histograms is nearly normal, but in Figure 27 the population

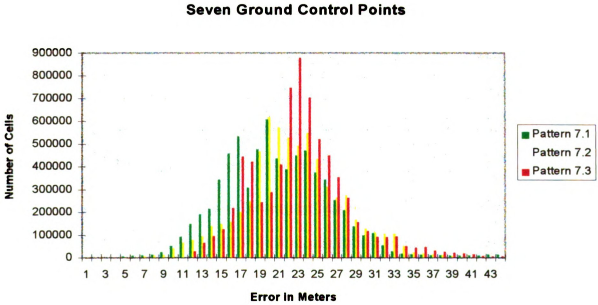

Figure 27 Histograms of Error for 7 Ground Control Points

means are nearly the same for the three different patterns. The error patterns converge at higher numbers of points, partly because, barring clustering, increasing numbers of points limit the differences in the number of patterns available.

First Order Linear Transformations

Table 1 Measurements for 3 Point First Order Transformations

GCP Pattern	ACP	RMSE	Wgtd Average	Field Area	Sq. Error
3.1	151	29.2	25.3	15.25	0.56
3.2	245	35.5	32.9	15.92	0.01
3.3	159	29.9	23.8	14.90	1.20
3.4	135	34.9	25.9	14.78	1.48
3.5	199	29.0	27.0	15.39	0.36
3.6	97	35.2	29.0	15.04	0.91

Table 1 reports the error measurements for the 6 simple 3 point linear transformations. Column one (GCP Pattern) is the ground control point pattern from Appendix B. Column two (ACP) is the area contained by the ground control points in hectares. Column three (RMSE) is the calculated root mean square error for the twenty seven test points in meters. The next column (Wgtd Average) is the average error of all cells weighted by the number of cells at each error level. $Wgtd\_Average = \sum_{i=1}^{M} error(i) * (N(i)/T))$, where M = the maximum error level, N(i) is the number of cells of error(i), and T is the total number of cells. The fifth column (Field Area) is the average area (in hectares) of five fields measured in the four quadrants and center of the corrected image. The last column (Sq. Error) is the sum of the squared difference between each field area and the "true" area (measured on the DOQ).

There was a lack of correlation between the area contained by the control points (ACP) and the root mean squared error (RMSE), (with a correlation coefficient of 0.09 calculated by Microsoft's Excel©).

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Table 2 reports average error measures for multiple transformations with three through seven ground control points and for a single example of a transformation using eight, nine, ten, fifteen and twenty ground control points. The first column (Number of Points) is the number of ground control points used in the transformation used to correct the image. The second column (RMSE) is the measured root mean square error for the twenty seven test points in meters. The third column (Residuals) is the reported RMSE calculated as the residuals for the control points used in the transformation (reported by the program i.points). The next column (Wgtd Average) is the average error of all cells weighted by the number of cells. The fifth column (Field Area) is the average area (in hectares) of five fields measured in the four quadrants and center of the corrected image. The last column (Sq. Error) is the squared difference between each field area and the "true" area (measured on the DOQ).

Table 2 Measurements for First Order Transformations

Number of Points	RMSE	Residuals	Wgt Average	Field Area	Sq. Error
3	32.28	0	27.3	15.21	0.70
4	31.0	11.8	26.7	15.40	0.48
5	27.3	20.4	24.2	15.50	0.16
6	27.1	21.8	23.4	15.50	0.40
7	24.5	25.9	22.6	15.50	0.39
8	22.8	26.5	21.2	15.53	0.27
9	24.6	22.2	22.9	15.50	0.30
10	22.1	20.8	20.0	15.40	0.42
15	24.6	22.4	23.1	15.43	0.38
20	22.4	22.2	20.2	15.40	0.43

Note that the squared error of field measurement for three points which is reported as 0.7 hectares, ranged from 0.0 to 1.4 hectares (Table 1). For these first order linear transformations, there seemed to be no improvement in field area error beyond 8 control points.

Second Order Linear Transformations

Table 3 Measurements for Second Order Transformations

GCP Pattern	Number of Points	RMSE	Residuals	Wgtd Average	Field Area	Sq. Error
6.1	6	54.4	0	48.1	14.86	1.28
6.2	6	26.5	0	24.6	15.71	0.08
6.3	6	59.1	0	34.6	14.20	3.22
7.1	7	44.9	11.6	27.8	14.92	1.16
7.2	7	24.2	14.8	21.4	15.56	0.19
7.3	7	25.5	15.9	21.3	15.30	0.21
8.1	8	23.7	18.9	19.9	15.47	0.27
9.1	9	22.1	12.6	18.3	15.61	0.15
10.1	10	28.1	9.5	23.8	15.35	0.41
15.1	15	19.2	19.1	18.9	15.53	0.21
20.1	20	18.5	18.9	16.3	15.52	0.22

The column definitions in Table 3 are the same as for Table 2, with the addition of column one (GCP Pattern) is the pattern of ground control points from Appendix B. Second order corrections are prone to distortion, especially for areas outside of control points (e.g. Figure 18). For these transformations the table shows a steady decline, both in RMSE and the weighted average measurement of the error surface, with increasing numbers of points through 20 points. Some results, as for control point pattern 6.2, however, can have a low RMSE. That suggests that factors other than the number of control points are significant at higher orders. For example, the transformation is probably much more sensitive to the pattern of ground control points at higher orders. Evidence for this can be based on the results in Table 3, where there is large variation in the error surfaces (as measured by the weighted average) for 6 point patterns and 7 point patterns.

Further evidence is shown by comparisons between error surfaces for images corrected with first-order linear transformations using 10 points and 15 points (Figures 28 and 29) and the error surfaces for second-order transformations with the same sets of ground control points (Figures 30 and 31). The error surface in Figure 28 is quite similar to the error surface in Figure

29. In first-order linear transformations, the additional 5 points created very little disturbance in the surface. In contrast, the error surface in Figure 30 shows a remarkably different pattern than the error surface in Figure 31. This disturbance in error pattern must have been caused by the introduction of 5 more ground control points.

Third Order Linear Transformations

Table 4 Measurements for Third Order Transformations

Number of Points	RMSE	Residuals	Wgtd Average	Field Area	Sq. Error
10	34.5	0	19.9	16.17	0.03
15	19.0	3.5	17.7	15.51	0.24
20	20.0	4.7	17.5	15.39	0.36

The column definitions in Table 4 are the same as in Table 2. Visually the third order transformations are the least satisfying (Figure 32) because of the high degree of curvilinear skew introduced into the image. However, the RMSE is somewhat better than first order transformations. With increasing numbers of points, the error of field measurements is greater (Table 4) with third order transformations, possibly because of the erratic behavior of third order surfaces between control points. Too few observations were generated to perform correlation or regression analysis on the third order transformations.

Piecewise Linear Transformations

Table 5 Measurements for Piecewise Linear Transformations

Number of Points	RMSE	Wgtd Average	Field Area	Sq. Error
6	31.2	24.2	15.58	0.17
7	27.7	21.5	15.86	0.12
8	17.4	14.9	15.87	0.02
9	20.2	16.9	15.60	0.15
10	18.2	15.2	15.87	0.01
15	14.4	12.3	15.87	0.02
20	13.5	9.7	16.02	0.00

The column definitions in Table 5 are the same as in Table 2. The piecewise linear transformation is the only discontinuous transformation tested. It took much longer in execution, on the order of 10 times as long, and this could have some impact on a large volume project. As measured by accuracy, it performed far better than linear transformations, probably due to the non-linear nature of error in central projection photos, and the ability of piecewise linear transformations to perform local corrections. The RMSEs, weighted average of error, and field area measurement error for these transformations (Table 5) were lower than for the continuous transformations.

Terrain With Moderate Relief

Table 6 Summary of Measurements for 3 Points

Number of Points	Pattern	Wgtd Average	Transformation Order	RMSE
3	3.1	35.3	First	47.4
3	3.2	46.3	First	58.4
3	3.3	32.1	First	40.7
3	3.4	30.9	First	48.3
3	3.5	34.5	First	41.5
3	3.6	37.8	First	56.5
10	10.1	12.7	PWL	15.0
15	15.1	12.0	PWL	14.6
20	20.1	12.3	PWL	14.8

Table 6 reports the number of points, the transformation order and RMSE for corrected images created from Image 81 (Figure 5). Quantitatively, the RMSE for 3 points for Image 81 (Figure 5) is greater than for Image 79 (Figure 3). This may be due in some part to the difficulty in choosing control points (Mather, 1995). The pattern of error shown in Figure 33, however, is consistent with that found in Image 79 (Figure 20) taken with the same camera. This would not lead one to believe that the increased error is due to elevation differences. In fact, the error surface seems to have no relation to the digital elevation model for this scene (Figure 8). A discontinuous transformation, the piecewise linear transformation, does just as well on this scene as it does on the previous one (Table 6).

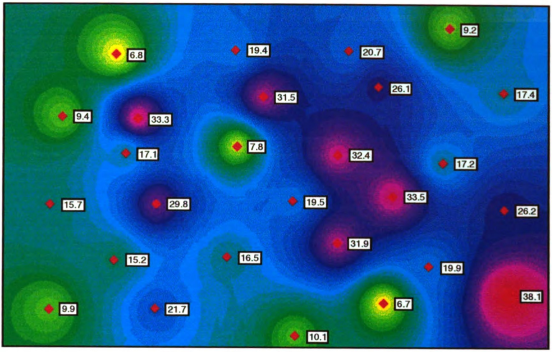


Figure 28 Error Surface for Ground Control Point Pattern 10.1 (First-Order)
(yellow=low; red=high)

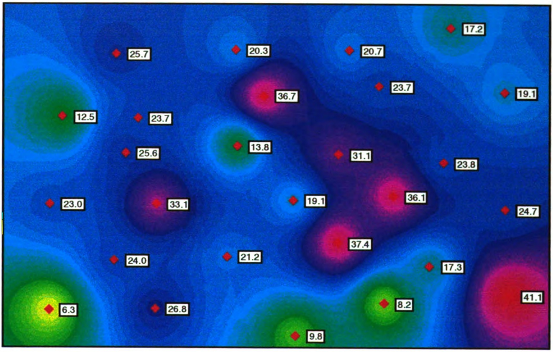


Figure 29 Error Surface for Ground Control Point Pattern 15.1 (First Order)
(yellow=low; red=high)

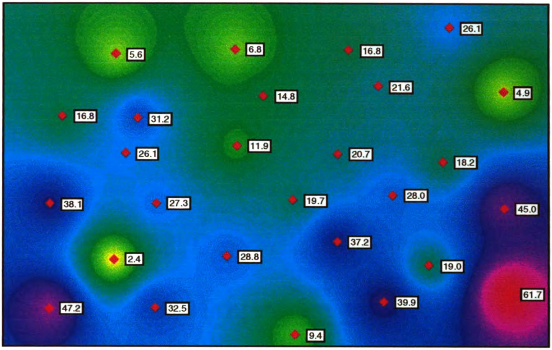


Figure 30 Error Surface for Ground Control Point Pattern 10.1 (Second-Order)
(yellow=low; red=high)

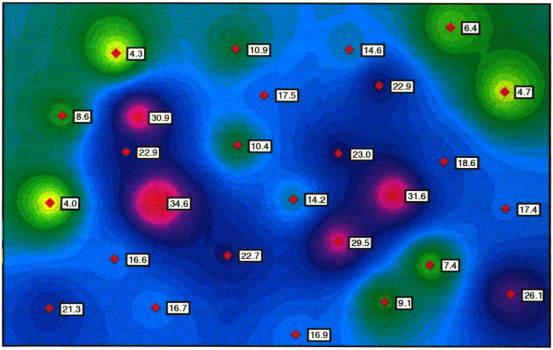


Figure 31 Error Surface for Ground Control Point Pattern 15.1 (Second Order)
(yellow=low; red=high)

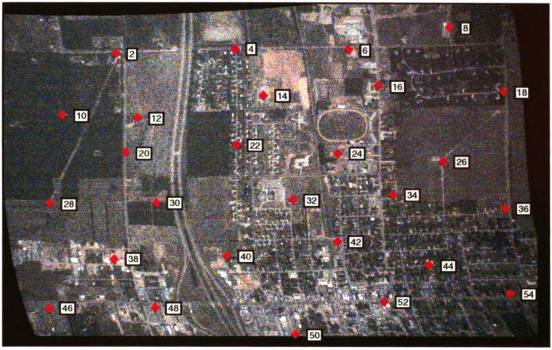


Figure 32 Corrected image using a Third Order Linear Transformation

Statistics

As expected from the tabular results, an analysis of variance test on root mean squared error by order of transformation (using piecewise linear as an order of transformation), showed the clear superiority (lower error) of the piecewise linear transformation over the first order linear transformation (Appendix C, Table 7). Overall, the piecewise linear transformation showed a root mean squared error (RMSE) of 22 meters, while the first order linear transformation showed an RMSE of 32 meters. Considering only first order linear transformations, a linear model showed that the number of ground control points was significantly related to the RMSE of test points ($p<0.00$), and predicts approximately 43% of the variation (Appendix C, Table 8). Errors in field measurement in turn can be predicted by RMSE (Appendix C, Table 9). The root mean squared error significantly ($p<0.00$) predicts about 62% of the variation in field measurement error.

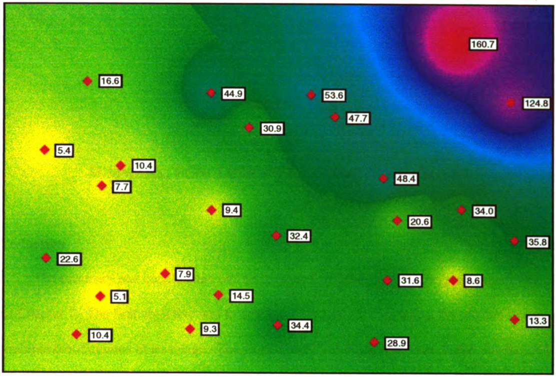


Figure 33 Error Surface for Ground Control Pattern 3.1 (Image 81)
(yellow=low; red=high)

CHAPTER V

SUMMARY, CONCLUSIONS & RECOMMENDATIONS

Introduction

The summary and conclusions will be presented as answers to the original objectives from Chapter 1. The first objective was to develop a method for comparing the relative precision of multiple rectifications of an image. The second and third objectives were to use this method to compare the sensitivity of an error measure calculated from the transformation equations (residuals) with a similar measure calculated from independent check points. The fourth objective was to determine the influences of numbers and pattern of ground control points, and order of polynomial transformations. As well as the order of the polynomial transformations, two types of transformations were evaluated, the continuous linear transformation, and a discontinuous (piecewise linear) transformation. The fifth objective was to evaluate the differences in accuracy introduced by moderate terrain.

A Process to Evaluate Image Corrections

Visual inspection of the corrected image can be a useful test of image quality when used with reference data, such as a corrected vector layer or ground control points, but is deceiving for the higher orders of linear transformations. For second order linear transformations the image may be well corrected for some patterns (ground control point pattern 6.2, Appendix B - Figure 34) and the RMSE can be acceptable (26.5 - Chapter 4, Table 3). But with the same number of

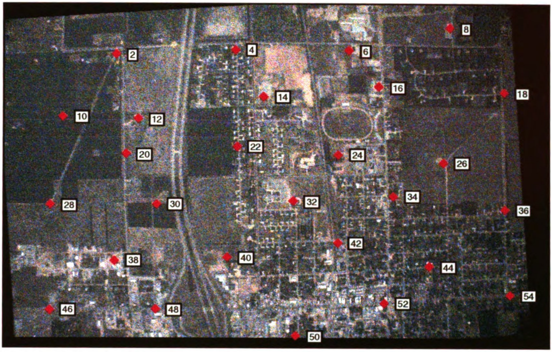


Figure 34 Corrected Image for Ground Control Point Pattern 6.2 (Second Order)

Figure 35 Corrected Image for Ground Control Point Pattern 6.3 (Second Order)

points and a different pattern (e.g. ground control point pattern 6.3, Appendix B), the results can seem quite poor (Figure 35), and yet have a large area that is well corrected. Visual inspection will become important for incremental methods (Derenyi, 1996), resulting in greatly improved accuracy, but visual inspection alone should be used with caution as an assessment of rectification accuracy. Error surfaces for the two different transformations, Figures 36 and 37, give much more information about the efficacy of the transformation. Visually, a relationship seems to exist between the position of control points and the low values on error surfaces. It is noted that the error in the correction using ground control point pattern 6.2 (Figure 36) is fairly uniform while the error pattern for ground control point pattern 6.3 (Figure 37) shows a large area of well corrected image.

The error surfaces show that for the most part, areas far from ground control points have a high level of error and, conversely, the position of ground control points coincides with areas of low error. Unfortunately, some areas of the digital image (and one has to assume the original slide) have areas of high error that are less easily explained. Some areas of the first test image, the north east in particular, exhibit systematic error. Adding control points to lower the error in that area simply distributes the error throughout the entire image. Perhaps this is because of a camera tilt in that direction or distortion in the camera lens. As a visual tool, error surfaces are good complements to global quantitative measures such as RMSE. Information about systematic error would be difficult or impossible to describe with global measures alone. The error surfaces created can be used to quantify error, either on a global, or regional basis. In addition, error surfaces make direct comparison of error in different images (such as image 79 and 81) possible.

The measurement of field areas, while adding more information about error, also tests how that error relates to secondary products. Sometimes this error may be less than expected. Relative error, the error in distance between points, is not always as high as absolute error

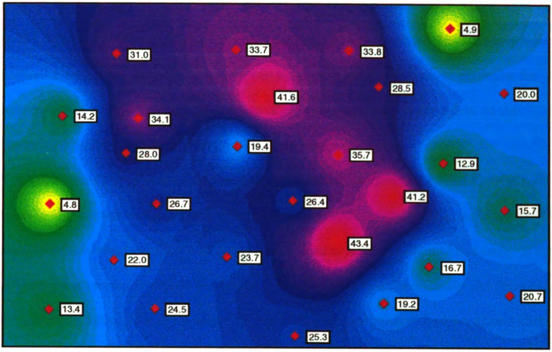


Figure 36 Error Surface for Ground Control Point Pattern 6.2 (Second Order)
(yellow=low; red=high)

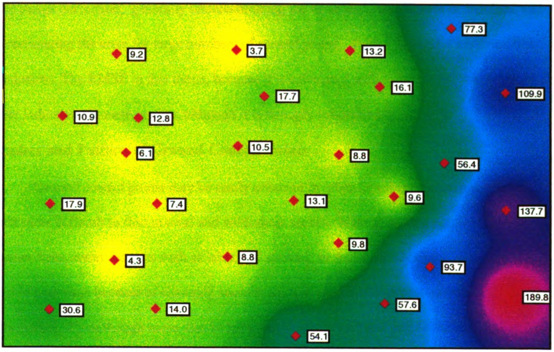


Figure 37 Error Surface for Ground Control Point Pattern 6.3 (Second Order)
(yellow=low; red=high)

(Stanislawski et al., 1996). For this reason, the precision of area measurements will sometimes be better than the root mean square error would suggest. An implication of this is that once their limitations are accepted, the corrected slides can be good management tools, in particular for measurements of natural resources. The effect of error on an analysis is dependent on the importance of relative versus absolute position in the analysis.

This method of testing check points and creating and examining the error surface, and measuring representative areas used in this thesis, while tedious, seems to be a useful method for accurately determining both the global mean error in a scene and the pattern of that error. If the RMSE from this empirical method were calculated using cross validation (Isaaks and Srivastava, 1989; McGwire, 1996), then cross validation, a strictly computational method, could be a cost-effective and more reliable method for assessing the average error in a rectified image.

Residuals Compared to Root Mean Squared Error

McGwire (1996) noted that transformation residuals give a poor measure of the accuracy of an image correction, generally underestimating the error with low degrees of freedom, and overestimating the error for large numbers of control points. Tables 2, 3 and 4 reinforce that conclusion. The RMSE in this thesis, because it is calculated with independent check points, is a better indicator of image quality, although it is strongly influenced by outliers.

Number and Pattern of Ground Control Points

Ground control points may be easily obtained in urban or suburban settings, but are much more difficult to find in rural and wilderness scenes. Natural ground control points, whether trees, water features such as lakes and streams, or rocks and clearings are much less reliable over time because of changing seasons and sun angles, movement growth or deformation. Even though more than twice as many ground control points were natural in Image 81, that was still only slightly more than 20% of the total points.

Where ground control points were not readily available, good results (~30 meters RMSE) may still be obtained with as few as 3 or 4 points. RMSE is only weakly explained by the number of control points unless the transformation type is held constant. Within a transformation type or order, more points reduce the average error, as measured by RMSE (Appendix C, Table 8). This suggests that the more points available, the lower the average error. Without some kind of discontinuity (i.e., a transformation such as piecewise linear), error in an image has to be distributed throughout the corrected image. The distribution of control points, as measured by the average area contained by them, is unrelated to RMSE with a Pearson correlation coefficient of 0.09. The distribution of control points, however, strongly affects the pattern of error, especially with small numbers of control points and even more at higher orders of transformation. The pattern of error is also strongly influenced, as evidenced by inspection of the error surfaces, by increasing the number of ground control points. As expected, error outside the control point perimeter is much greater than error inside, as in Pattern 3.4 (Figure 38), although, merely encompassing the scene with 4 points, as in Pattern 4.1 (Figure 39), leaves the error in the center very high.

Transformations

Order of transformation has a strong effect on image quality as measured by RMSE. Because of the non-linear nature of error in slides from non-metric cameras, probably no continuous transformation (and no first order transformation) will approach national map accuracy standards. The confidence intervals shown on the analysis of variance (Table 7, Appendix C) clearly show that a discontinuous transformation can accommodate the error to a much better degree. While second order and higher transformations can be forced to match with more and more control points, the errors measured at points in between and outside of control points can be very large.

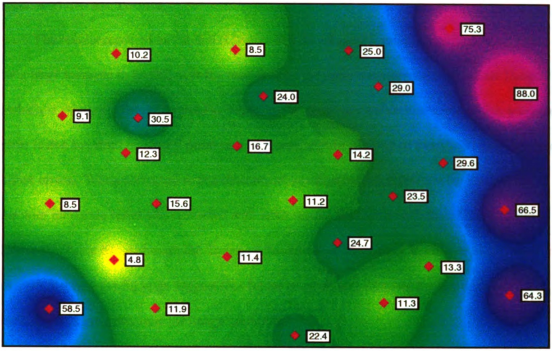


Figure 38 Error Surface for Ground Control Point Pattern 3.4 (yellow=low; red=high)

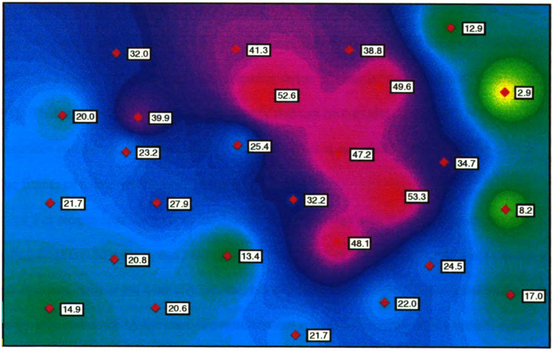


Figure 39 Error Surface for Ground Control Point Pattern 4.1 (yellow=low; red=high)

Effects of Moderate Terrain

The results reported in Table 6 (Chapter IV) for Image 81, an image with some relief, show a large increase in RMSE over the results from the same transformations used on Image 79, which is relatively flat, (Chapter IV, Table 1). While it is possible that some of this increase in error is due to errors in control point measurement, terrain is likely to have had some influence on those errors. When corrected with a discontinuous transformation (piecewise linear), the scene with moderate relief was corrected with error results approaching those of level terrain (Chapter IV, Table 6). Although the design of this study precludes any definitive conclusions in the effect of relief, the findings suggest that future work should focus on the application of discontinuous transformations for image correction.

Recommendations

The implications of this research are twofold. First, no matter how many control points are used, it is doubtful that a global linear transformation will produce results better than 20 meters RMSE, with some areas of much higher error. The other, and more positive, implication is that the slides contain a large volume of information, both physical and temporal, that can be rectified to a known level of error. The proper criterion of error is "fitness of use" (Chrisman, 1991). That is, error, rather than being an entity that can be completely avoided, is simply a measurable component of image quality. In effect, error is one quality that should be used to judge fitness of a data set for a particular use.

For simple rectifications of the 35-mm slides for large area studies, efficient results, yielding RMSE ~ 30 meters, can be expected from using 3 or 4 ground control points chosen in a simple pattern, neither too centrally located, nor too close to the edges of the digital image. The average area contained by the control points was not correlated to error for the control point patterns used in Appendix B. In an extreme case, however, a linear pattern of control points is reported to yield rectified images with high global error (Mather, 1995).

The practical implication of this research for the National Resources Inventory (NRI) is that a digital image rectification can be achieved with a global error of 30 meters RMSE, which is within the normal precision of measurement of features taken from an analog projection of the 35mm slide (Bowman, 1998). A linear transformation with 3 or 4 control points (which would have to be first order), is a procedure that requires relatively little operator effort. Hence, the results of this thesis suggest that digital image rectification may provide a cost effective replacement for analog methods. Rectified digital images of point sample units for the NRI, could be maintained conveniently on Photo-CD's with no loss of precision. These results reinforce the conclusions of Williams (1995), who, from rectified digital images of the ASCS(FSA) slides, produced results that were similar in precision to previous analog methods.

For those slides where many discernible features are available, using 10 to 15 well distributed ground control points and a piecewise linear transformation will yield an RMSE of 12 to 14 meters (14 to 16 meters in the more rugged terrain). This result suggests that in urban or suburban scenes, the little extra effort required to collect about 10 extra points can yield much lower error by allowing the application of the discontinuous (piecewise linear) transformation.

Opportunities for Future Research

Certainly more work could be done on the areas of unexplained error, such as in the northeast quadrant of downtown Gaylord. Perhaps clues exist in the radiometric behavior of the original slide that could be used to flag especially distorted portions of an image. Where such areas are identified, a discontinuous rectification method, such as piecewise linear transformations, could be indicated as the method of choice. Future research should test the effects of these transformations on derivative measurements, such as area measurements of features that cross boundaries.

A global measure of error could be tested to replace RMSE. A characteristic of RMSE is its sensitivity to extreme values. Used with a third order transformation and 10 control points (Pattern 10.1), RMSE is measured at 34.5 meters. By eliminating four of 27 test points the RMSE becomes 12.9. Clearly, much of the image is well rectified, nearly to National Map Accuracy Standards at 1:24,000 scale.

Calibrating the limits of terrain effects could be another area of study. From altitude, the real distance on the ground is the apparent distance divided by the cosine of the terrain elevation angle. Especially in regards to measurements of distance, more work needs to be done to find the terrain elevation angle, thus compensating for tilt and less than ideal camera optics. The work done in this thesis should be repeated on additional 35-mm slides to test whether the error patterns found here are symptomatic of small frame cameras in general, or the particular camera used for this plane for this day.

Finally, future research should test the influence of the methodological limitations of this study. One assumption was the use of inverse distance weighting to model the behavior of error surfaces. One tool to test the validity of this assumption would be semivariograms. Another important direction for further work would be better image processing tools that enhance resolution rather than resample to eight bit color from the original scanned image. Better color should make ground control point selection easier and more precise. Finally, much work remains to be done on the transformations themselves. With more computational power available for much lower prices, intensive transformations (such as thin plate splines) better point matching (such as incremental methods) and better validation (cross validation at a minimum) need to be examined.

APPENDICES

APPENDIX A

APPENDIX A

GROUND CONTROL POINTS

IMAGE 79 - DOWNTOWN GAYLORD

1. Northwest corner of house.
2. Acute corner of road intersection (northeast).
3. Center of turnaround
4. Center of road intersection.
5. North center of road intersection.
6. Northwest corner of building.
7. Center of road intersection.
8. Southeast corner of building.
9. Center of road intersection.
10. Field intersection.
11. Northeast corner of building.
12. Northwest corner of building.
13. Southwest corner of driveway intersection.
14. Center of roof ventilator.
15. Northeast corner of long shed.
16. East center of driveway.
17. North center of driveway.
18. Center of road intersection.
19. Center of road intersection.
20. East center of driveway.
21. Center of freeway turnaround.
22. East center of driveway.
23. East center of driveway.
24. East center of driveway.
25. Southeast corner of building.
26. Acute path intersection.
27. Object in field.
28. Southeast corner of woodlot.
29. North end of windbreak.
30. Northwest corner of woodlot.
31. Northwest corner of parking lot.
32. Pitchers mound.

33. Northeast corner of building.

34. Southeast corner of building.

35. Center of street intersection.

36. Southeast corner of driveway.

37. Northeast corner of woodlot.

38. Northwest corner of building.

39. North end of windbreak.

40. Northwest corner of windbreak.

41. Center of street intersection.

42. Northeast corner of roof air conditioner.

43. Center of road intersection.

44. Center of driveway.

45. North center of driveway.

46. North center of roadway.

47. Northwest corner of building.

48. Northwest corner of building.

49. Center of overpass.

50. Center of road intersection.

51. Southeast corner of woodlot.

52. Northeast corner of woodlot.

53. Center street intersection.

54. North center of intersection.

IMAGE 81 - SOUTHEAST GAYLORD

1. Northwest Corner of clearing.
2. East point of clearing.
3. South corner of clearing.
4. South tip of clearing.
5. Road intersection.
6. Center of clearing.
7. Road intersection.
8. South point of lake.
9. East center of driveway.
10. Road intersection.
11. Road intersection.
12. Point of road intersection.
13. West road intersection.
14. North tip of lake.
15. North tip of lake.
16. Tree line intersection with road.
17. East point of clearing.
18. Center of driveway intersection.
19. Center of sand trap.
20. Road intersection.
21. East end of tree clump.
22. North point of clearing.
23. East house addition.
24. Road intersection
25. Bare spot in field.
26. Rock in field.
27. Center of driveway intersection.
28. North edge of sand trap.
29. Road intersection.
30. Northeast edge of tennis courts.
31. Road intersection.
32. Center of driveway intersection.
33. Center of house.
34. Southern tip of clearing.
35. Center of driveway.
36. Center of driveway.
37. Center of sand trap.
38. Center of sandtrap.

39. Center of intersection.

40. Center of driveway.

41. Northeast corner of building.

42. Center of clearing.

43. Center of building.

44. Center of tree.

45. Center of building.

46. Center of driveway.

47. Center of driveway.

48. Center of driveway.

49. Northeast corner of building.

50. North center of intersection.

51. Center of intersection.

52. Center of driveway.

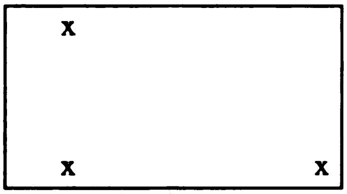
53. Center of silo.

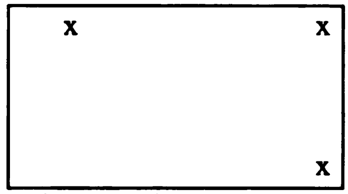
54. North center of intersection.

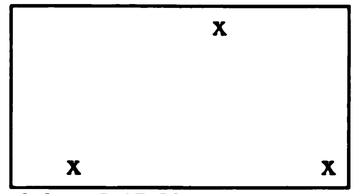
APPENDIX B

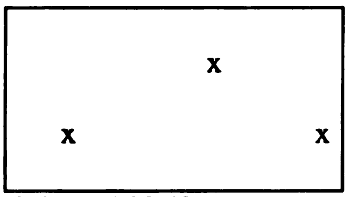
APPENDIX B

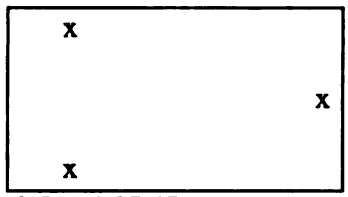
PATTERNS OF GROUND CONTROL POINTS

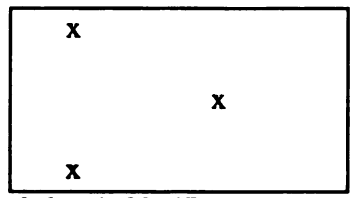

3.1 - 1,47,53

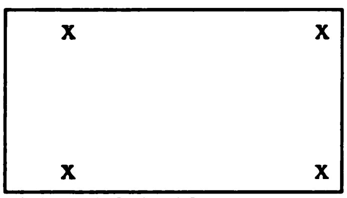

3.2 - 1,9,53

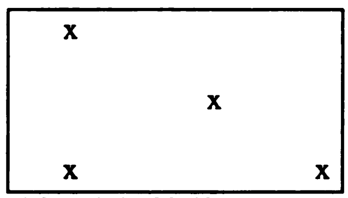

3.3 - 5,47,53

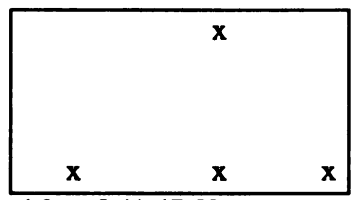

3.4 - 15,39,43

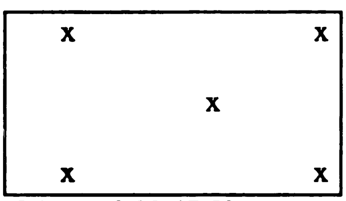

3.5 - 1,27,47

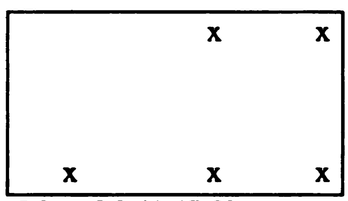

3.6 - 1, 23, 47

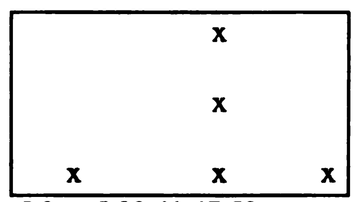

4.1 - 1,9,47,53

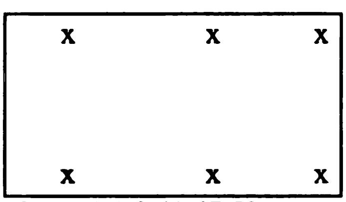

4.2 - 1,47,23,53

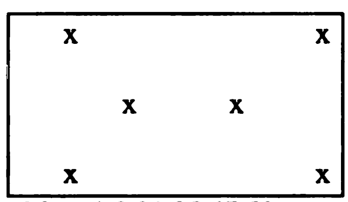

4.3 - 5,41,47,53

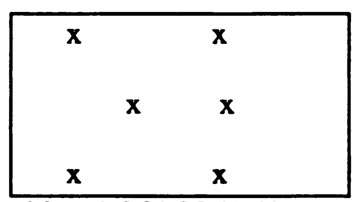

5.1 - 1,9,23,47,53

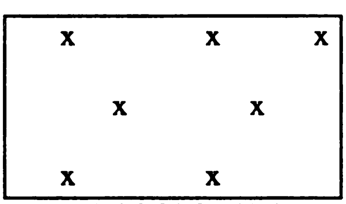

5.2 - 5,9,41,47,53

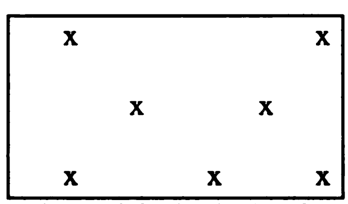

5.3 - 5,23,41,47,53

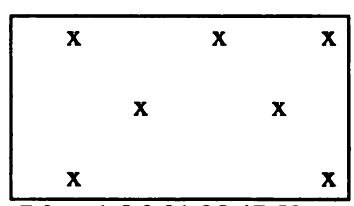

6.1 - 1,5,9,41,47,53

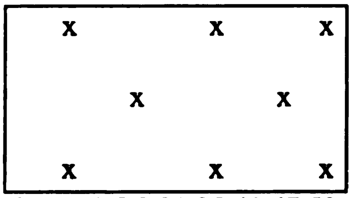

6.2 - 1,9,21,25,47,53


6.3 - 1,5,21,25,47,41

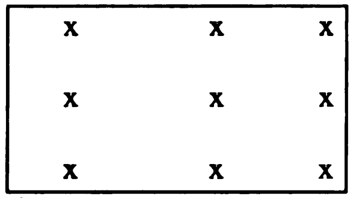

7.1 - 1,5,9,21,25,41,47


7.2 - 1,9,21,25,41,47,53

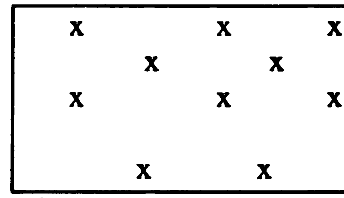

7.3 - 1,5,9,21,25,47,53



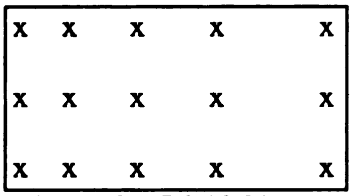
8.1 - 1,5,9,21,25,41,47,53



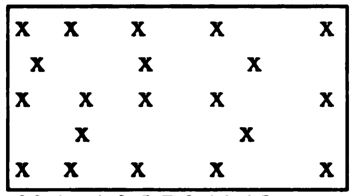
9.1 -
1,5,9,19,23,27,41,47,53



10.1 -
1,5,9,13,17,19,23,27,39,43



15.1 - 1,3,5,7,9,19,21,
23,25,27,37,39,41,43,45



20.1 - 1,3,5,7,9,11,15,
17,19,21,23,25,27,29,35,
37,39,41,43,45

APPENDIX C

APPENDIX C

STATISTICAL RESULTS

Table 7 Analysis of Variance for Root Mean Squared Error by Order of Transformation

ANALYSIS OF VARIANCE ON rmse

SOURCE	DF	SS	MS	F	p
order	3	1148	383	3.28	0.028
ERROR	53	6184	117		
TOTAL	56	7332			

```
                                          INDIVIDUAL 95 PCT CI'S FOR MEAN
                                          BASED ON POOLED STDEV
 LEVEL       N      MEAN     STDEV   ------+---------+---------+---------
+
     0      14     21.77      9.69         (------*------)
     1      29     32.16      9.91                        (----*----)
     2      11     31.46     14.36                    (-------*-------)
     3       3     24.50      8.67    (---------------*---------------)
                                     ------+---------+---------+---------
+
 POOLED STDEV =    10.80                  16.0      24.0      32.0
40.0
```

First Order Linear Transformations:

Table 8 RMSE Predicted By Number Of Ground Control Points

The regression equation is
RMSE = 32.1 - 0.680 numpts

Predictor	Coef	Stdev	t-ratio	p
Constant	32.135	1.225	26.24	0.000
numpts	-0.6802	0.1628	-4.18	0.000

s = 3.153 R-sq = 45.4% R-sq(adj) = 42.8%

Analysis of Variance

SOURCE	DF	SS	MS	F	p
Regression	1	173.62	173.62	17.47	0.000
Error	21	208.73	9.94		
Total	22	382.35			

Unusual Observations

Obs.	numpts	rmse	Fit	Stdev.Fit	Residual	St.Resid
23	20.0	22.400	18.531	2.317	3.869	1.81 X

X denotes an obs. whose X value gives it large influence.

Table 9 Errors in field measurement predicted by RMSE

The following is a linear model of errors in field measurement predicted by the RMSE of the 27 check points.

The regression equation is
error = - 0.972 + 0.0513 rmse

48 cases used 12 cases contain missing values

Predictor	Coef	Stdev	t-ratio	p
Constant	-0.9718	0.1701	-5.71	0.000
rmse	0.051308	0.005872	8.74	0.000

s = 0.3711 R-sq = 62.4% R-sq(adj) = 61.6%

Analysis of Variance

SOURCE	DF	SS	MS	F	p
Regression	1	10.514	10.514	76.34	0.000
Error	46	6.335	0.138		
Total	47	16.849			

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