

**Evaluation of Photographic Properties for Area Estimation**

by

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(ABSTRACT)

From the known image positional errors on aerial photographs, this thesis computes and evaluates acreage estimation errors. Four hypothetical tracts were used in simulating aerial photographs with 104 different camera orientation combinations. Flying heights of 4000 and 6000 feet, focal lengths of 24 and 50 millimeters with and without lens distortion, and tilts of 0, 3, 6, and 12 degrees were simulated. The 416 photographs were all simulated with the camera exposure station centered above the midpoint of the respective tract's bounding rectangle. The topographic relief of the tracts ranged from 19 feet in the Coastal Plain to 105 feet in the Piedmont.

It was found that lens focal length did not have an independent effect on the acreage estimates. Relief error, the lowest, averaged -0.080%. In comparison, small errors in calculating scale were shown to be larger than relief errors. Tilt was recommended to be limited to six degrees, averaging +1.6% error at six degrees tilt. Because of its positive exponential nature when the tracts are centered, tilt can induce large biases. Including tilts from zero to six degrees, the average was 0.634%. Lens distortion error averaged -0.686%. Overall, the average acreage error was 0.363% for simulations up to and including six degrees of tilt with and without lens distortion. This result is for centered tracts, and it was felt many of the errors were compensating given this situation. In conclusion, the photographic images can estimate areas to  $\pm 1\%$ , however, additional errors are imparted during actual measurement of the photographs.

# Acknowledgements

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# INTRODUCTION

Aerial photography has been studied and applied for several years, especially 9-inch metric photography. For example, the U.S. Geologic Survey uses 9-in stereo imagery to produce topographic maps. Additionally, private forestry companies and public forest services use 9-in photographs for stand mapping and analyzing forest damage. Nevertheless, photographs have inaccuracies that must be understood. If one assumes map properties hold true on photographs, serious errors may be committed. Topographic elevation changes (relief), tilt of the camera axis, and lens imperfections all affect the accuracy of photographs, and dictate how closely photos represent precise maps. Extensive literature is available on individual image positional errors; however, this literature has not studied the combination and interaction of these errors when measuring areas. Area measurement from photographs is a common practice; in fact, Mead and Rasberry (1980) rated it third of all photointerpretation skills, second only to determining scale and measuring distances. Therefore, it is important to know and understand the effect of positional errors on acreage estimates made from photographic images.

Three film sizes are predominantly used in aerial photography. The largest format, 9 in by 9 in, is used in precise photogrammetric mapping, and Clegg and Scherz (1975) regarded it as the format necessary for correctly mapping extensive areas. The next smaller format, 55 mm

by 55 mm, is used in Canada for forest inventory and tree identification. By integrating the 70-mm camera system with radar altimeters and tilt indicators, the results were within desired accuracy limits (Meyer 1982). The smallest commonly used format, 36 mm by 24 mm, is a relatively simple, inexpensive, and flexible system. For this reason, 35-mm systems are beginning to be used more often on smaller projects. This 35-mm format has the least operational and initial investment costs, can be used with various camera mounts, and designed to increase the professional capabilities of the field resource manager (Meyer and Grumstrup 1978). Even though it was reported as having the worst metric accuracy (Dalman 1978), only limited research has evaluated these inaccuracies and their impact on management decisions. In fact, although much is known about the errors of a single point on all of the formats, no literature was available analyzing the accumulation and combination of these point errors when calculating areas.

The objective of this project was motivated from the lack of knowledge on the accuracy of area estimates from aerial photography. Focusing on 35-mm (the assumed worst case), the results of this study will be applicable to the other more accurate formats. Specifically, the objective of this study was to evaluate and compare the individual and combined effects of topographic displacement, camera tilt, and lens distortion upon the accuracy and precision of area estimates made on 35-mm aerial photographs.

# **LITERATURE REVIEW**

## **ADVANTAGES AND DISADVANTAGES OF 35-MM**

In comparison of the 9-in, 70-mm, and 35-mm formats, several authors have earnestly tried to determine the appropriate niche for each format. These comparisons have evaluated many aspects, a few of which are reiterated below to highlight the major points, and to provide a basis for applying 35-mm to this study.

Speed and flexibility are strong advantages of 35-mm photography. Klein (1970) stated that rapid, quality stereo images have been obtained with the 35-mm format. Additionally, camera systems with smaller formats are much simpler to use, and are adaptable to any type of aircraft which is available at the time photography is needed (Spencer 1978). This flexibility takes advantage of small openings in cloud cover to allow flying during the appropriate season (Meyer and Grumstrup 1978). Nine-inch camera systems require larger airplanes with bellypan hole camera mounts, target viewing equipment, and integrated operating systems permanently fastened in the aircraft. Seventy-millimeter cameras are more flexible and can be mounted in other locations on the aircraft. Thirty five-millimeter camera mounts range from simply hand holding the camera, to constructed window mounts, and elaborate bellypan

mounts similar to those used with 9-in cameras. Most importantly, no modifications to the airplane are required (Meyer and Grumstrup 1978). Furthermore, film acquisition and processing problems of the larger formats are alleviated by using normal color 35-mm film.

The cost of photographic systems can greatly influence which system is selected. The equipment and film traditionally employed for mapping are expensive. Clegg and Scherz (1975) compared the initial investment cost, and the cost for two photographs of the three systems and found that for:

- 9-in cameras, the initial investment was \$101,000, and the cost for two photos was \$17.51;
- 70-mm cameras, the initial investment was \$7,500, and the cost for two photos was \$2.85;
- 35-mm cameras, the initial investment was \$6,000, and the cost for two photos was \$0.80.

Clegg and Scherz also noted that the cost of 9-in camera systems can run higher than the cost of an airplane. Both of the smaller formats were considerably less expensive than the 9-in system, and furthermore, Roberts and Griswold (1986) found 35-mm to be twice as economical as 70-mm. As a result of this lower cost, flights for individual projects were feasible with 35-mm systems rather than compromising with general purpose photography (Roberts and Griswold 1986). Although it is obvious that 35-mm is less expensive per picture, one must also consider how many pictures are necessary to cover the study area. Sixty 35-mm photos are required to cover the equivalent of one 9-in photograph at the same scale (Spencer 1978), and, 150 photos are essential for stereo photography of an equal area covered by one 9-in stereo pair (Roberts and Griswold 1986).

Besides greatly increasing the number of photographs, viewing and handling are two other problems associated with the small format. To alleviate the viewing problem, size is increased either by slide projection or enlargement with paper prints. Paper prints also help solve the problem of handling small slides. Needham and Smith (1984) presented some of the possible problems associated with paper prints including, decentering, loss of area due to

cropping, and loss of conjugate images. Furthermore, enlargement causes all light rays to pass through a second lens assembly subjecting them to additional distortions and displacements.

Photographic resolution of the three formats was compared by Clegg and Scherz (1975). Several different sizes of targets were photographed at three elevations. They found that at flying heights of 1,000 feet, the smallest targets (1 ft<sup>2</sup>) were fuzzy on all formats. At heights of 3,000 feet, there was little difference between the 35-mm and the 70-mm formats, although most of the targets on the 9-in format were one step sharper, and at 5,000 feet, the 9-in format was superior. Additionally, Clegg and Scherz (1975) had two sets of experts, four in vegetation and three in soils, compare the three formats. The vegetation experts all said the 35-mm "provided good color rendition and resolution," and the four experts picked 35-mm as the format they would use. The soils experts, on the other hand, preferred the 9-in format because of the sharper resolution. However, when the pictures were concealed, so that the format was unknown, the soils experts could not correctly pick the 9-in format from the others.

In addition to photographic resolution, positional accuracy of an image is important. Accuracies of metric cameras approach 0.0001 times the flying height (Clegg and Scherz 1975). For example, with a flying height of 1,000 feet, one can measure correct ground positions of an object to within 0.1 foot, or approximately one inch. Clegg and Scherz (1975), in a comparison of the three formats, published some surprising results about 35-mm accuracy. The study measured 30 photo distances and compared these distances to a base map. The photographs were rectified in a tightly controlled area of 600 feet with a flying height of 5000 feet. 35-mm had the least error of the three formats: 35-mm = 1.39%; 70-mm = 1.97%; 9-in = 1.77%. To verify these results, a second test was conducted in which a scale factor was calculated for 30 lines. Again, 35-mm came out with the least error: 35-mm = 1.49%; 70-mm = 2.02%; 9-in = 1.54%. A third test compared the positions of points outside of the tightly controlled section and used the rectified 9-in photo as the base. Using four control points on the 9-in photo, the smaller formats were rectified to match these four points. Using this procedure,

35-mm photography had an error of 11 feet, while 70-mm had an error of 6.5 feet. Since some users of 35-mm photography do not have expensive rectifiers, a standard 35-mm carousel projector was then used. With this method Clegg and Scherz achieved accuracies of 8 feet relative to ground positions calculated from the 9-in format. In another study, Roberts and Griswold (1986) achieved accuracies of 0.0002 times flying height using 35-mm stereo imagery. Both studies concluded that 35-mm photography was accurate enough for environmental mapping which requires accuracies to tens of feet.

## **APPLICATIONS OF 35-MM**

Numerous publications have been written on projects utilizing 35-mm aerial photography. Klein (1970), Olson (1983), Miller and Meyer (1981), Shafer and Degler (1986), and Spencer (1978) are some examples of applications from simple overviews to map generation. These uses can be broken into two categories of qualitative and quantitative applications.

### ***QUALITATIVE APPLICATIONS***

Several authors have written about the advantages of small format aerial photography used for general overviews without stringent mapping and measurement goals in mind. For example, Shafer and Degler (1986) wrote, "When precise geographic positioning is not required or when it can be obtained by correlating features on conventional photogrammetric images, a great deal of data can be derived from hand-held photographs. . . . Hand-held photography offers the advantage of flexibility when qualitative, rather than quantitative, data are required." 35-mm photography is often used in conjunction with preexisting maps, or older 9-in photography that are now out of date due to changes in the area. Duncan, Meyer, and Moody (1984) found that National High Altitude Photography (NHAP) could estimate areas ac-

curately to 0.5 acres, but they needed supplemental 35-mm photography to get details of specific areas.

Meyer (1982) presented several applications of small format photography used in conjunction with preexisting photographs, one of which was the Minnesota forest peat lands survey. Black and white 9-in resource photography of the 145,000 acres was available at a scale of 1:15,840, but was inadequate for the task. Three levels of 35-mm color infrared photography furnished the desired information at a reduced cost. Scales of 1:120,000, 1:80,000, and 1:11,000 were flown in two stages, and a third flight acquired low oblique photographs of difficult vegetation boundaries. Meyer concluded, "Field verification in difficult classification areas indicated that the basic resource photography, used in conjunction with the supplemental coverage, provided very good classification accuracy." (Meyer 1982)

Supplemental photographs have also been beneficial in identifying images on current orthophotoquads. Mead and Gammon (1981) applied this technique for wetland vegetation mapping of North Carolina. 35-mm color infrared photographs were used as a supplement to recent 7.5 minute black and white USGS orthophotoquads. Only five percent of the area was photographed at a scale of 1:6,000, yet all cover types were photographed because the flight lines were keyed to high variation areas. The minimum mapping unit was four acres, in which all species type boundaries were those as identified on the orthophotoquad, and the supplemental aerial photographs were used only for type identification. Mead and Gammon concluded through field checks that the results were acceptable.

Thirty-five millimeter film has also been used as a primary source for qualitative information, rather than used as a supplement to other sources of spatial data. Weih, Nord, and Meyer (1982) evaluated film and filter combinations for 35-mm aerial photography at a scale of 1:20,000 to provide a low cost method for determining and mapping aspen regeneration stocking levels. Aspen regeneration was separated into three classes, and stand maps were then drawn using a rear projector screen. This allowed a more detailed analysis to be made

of how harvesting methods affected regeneration. The photography also provided a permanent record of the stand for future use and management evaluation.

A fourth application of qualitative photography is tree identification. Needham (1983) used large scale photos (1:650) to sample two forest stands during leaf change in the fall. Tree presence and species were tallied for the sample plots on the ground for comparison to the results of the photographs. The dominant and codominant trees could be identified with 95% accuracy. Some of the factors affecting accuracy were tree spacing, whether or not a distinct image appeared on the photo, and dominance of the tree.

## **QUANTITATIVE APPLICATIONS**

Quantitative applications of 35-mm photography do exist. However, a majority of the research has been on qualitative applications, and several authors have stated that one must be cautious in using 35-mm without metric control. For example, Dalman (1978) stated, "precision measurements cannot be taken from 35-mm SAP (supplemental aerial photography) due to distortions from: lens aberrations; displacement of objects on the photos; exaggeration of heights; and an unlevel camera platform." Furthermore, Zsilinsky (1969) pointed out, "hand-held photographs will generally not provide quantitative data except in gross terms. The qualitative data that are easily collected, however, far surpass any disadvantages of lack of control for mapping purposes." Quantitative uses can be divided into three areas, x,y position, height, and area calculations. Image position, although not specifically stated, is probably the most important factor in any mapping or interpretation project. The accuracy at which a system records images on film and subsequently projects and measures them is directly correlated to the accuracy of the project's results. The location of an object on a photo affects the comparison of the identified object to the ground, measurement of distances between objects, and measurement of heights.

One example of using single photo coordinates is measuring flame attributes. Clements, Ward, and Adkins (1983) used a 35-mm camera to measure flame height and distance of fire line travel per unit time. Camera tilt created some unavoidable errors. Because tilt remains constant for each picture, the ideal tilts for both height and distance calculations could not be met at the same time. Flame height error is two percent at ten degrees tilt, and distance error is six percent at twenty degrees tilt.

Goodrich (1982) conducted a study on the applicability of using terrestrial 35-mm stereo photography to monitor glacier movements. The analysis included tests of the camera and the system. In calibrating the camera, the side of a building was photographed with the test camera and with a calibrated terrestrial camera. Window corners were then compared on each picture to calibrate the 35-mm camera lens. Goodrich found the differences between the actual location and photogrammetric location of test targets on the 35-mm picture to be accurate enough for the application. The results, at distances of 100 and 200 feet, with and without corrections for parallax from the camera calibration, are presented in Table 1 (Goodrich 1982). Goodrich concluded, "The results indicate that a 35-mm camera can be used in the system described for obtaining stereo pairs without fear of significant distortion errors being introduced by the camera." Stereo pairs analyzed using a parallax correction graph provided the desired accuracy to within one foot for the glacier photography at a distance up to 110 feet. (Goodrich 1982)

A third application of quantitative data derived from photographs is production of topographic maps. Roberts and Griswold (1986) used 35-mm photography to create a topographic map, and compared this to a base map. A microcomputer was used to analytically remove distortions with nine parameters; focal length, flying height, absolute stereoscopic parallax, height of three ground control points, distance between two ground control points, and the measured coordinates of one ground control point. No lens distortion correction was used in the measurement procedure. In two of the stereo models they found no significant difference between the model and the ground. The third model did show minor significance, although

**Table 1. Difference between the actual location and photogrammetric location of test targets.**

Percent of discrepancies within one foot (Calculated - Actual)				
Dist (ft)	Yd	Xd	Zd	Parallax Correction
100	65	100	100	NO
100	100	100	100	YES
200	00	68	100	NO
200	68	100	100	YES

(Goodrich 1982)

note: X,Y, and Z are referenced in the ground coordinate system.

the average error was still 0.0002 times flying height. "The results indicate that practical photogrammetry can be done using 35-mm aerial photography and a microcomputer controlled analytical stereo plotter. Although some systematic errors are present in the plotted values, the magnitudes of the errors are low. These accuracy levels are acceptable for many photogrammetric purposes." (Roberts and Griswold 1986)

Research studies on acreage calculation from 35-mm photography are extremely limited. The only publication found analyzed the impact of transmission lines on agriculture production in the mid-west (Grumstrup et al. 1980). 500 miles (805 km) of seventeen power line segments were photographed at a nominal scale of 1:1,400. Dot grids were used to compute the acreage affected by each tower; each dot represented 0.0006 ac. (0.00024 ha). The acreage was adjusted if the calculated scale (using the cross arm distance) deviated from the nominal scale. From this study, Grumstrup found that agricultural practices and the affected acreage varied with the tower type. Relationships could then be formed between the amount of land withheld from production and the type of tower. Acreage calculation accuracy was concluded to be within the desired 10% level, in which three types of errors were found.

- Positive systematic error, up to 3.7%, due to calculating the scale at the top of the transmission tower
- Random error of 1.6% due to error in measuring photo distance for calculating the scale
- Random error of 6.5% from dot grid estimates

This study looked at very small areas on level ground and one must be careful in extrapolating from these conclusions to larger areas over varying terrain.

## **LOCATION ERROR IN PHOTOGRAPHIC IMAGE**

The final section describes the causes and effects of image positional errors on photographs. By assuming photographs have properties equal to maps, three types of errors are disregarded (Spurr 1960, Wood 1949).

- The ground is not perfectly level, thus producing relief errors.
- The camera axis is not truly vertical, thus introducing tilt errors.
- Camera and photographic material fail to satisfy theoretical requirements completely, thus giving rise to what may be called instrumental errors.

In this section, image positional errors will be separated into these three categories, relief, tilt, and equipment.

### ***RELIEF***

Relief displacement often causes straight roads, fences, and utility lines on rolling ground to appear crooked on vertical photographs (Wolf 1983). This is especially true near the edge of a photo with severity dependent on terrain variation. Because displacement causes the tops of objects to register further from the principal point than the bottoms (Figure 1), trees appear to lean outward radially from the nadir, and displacement can cause some features to be obscured from view (Spurr 1960). All objects at the same elevation and equidistant from the nadir in any direction are displaced equal amounts due to relief (Spurr 1960). Furthermore, displacement is inversely related to flying height, and independent of focal length (Spurr 1960). Relief displacement may be reduced to any desired amount merely by increasing flying height (Figure 2) (Wood 1950). Wood (1949) noted relief errors are frequently 0.10 inch (2.54 mm) or more.

# Relief Displacement

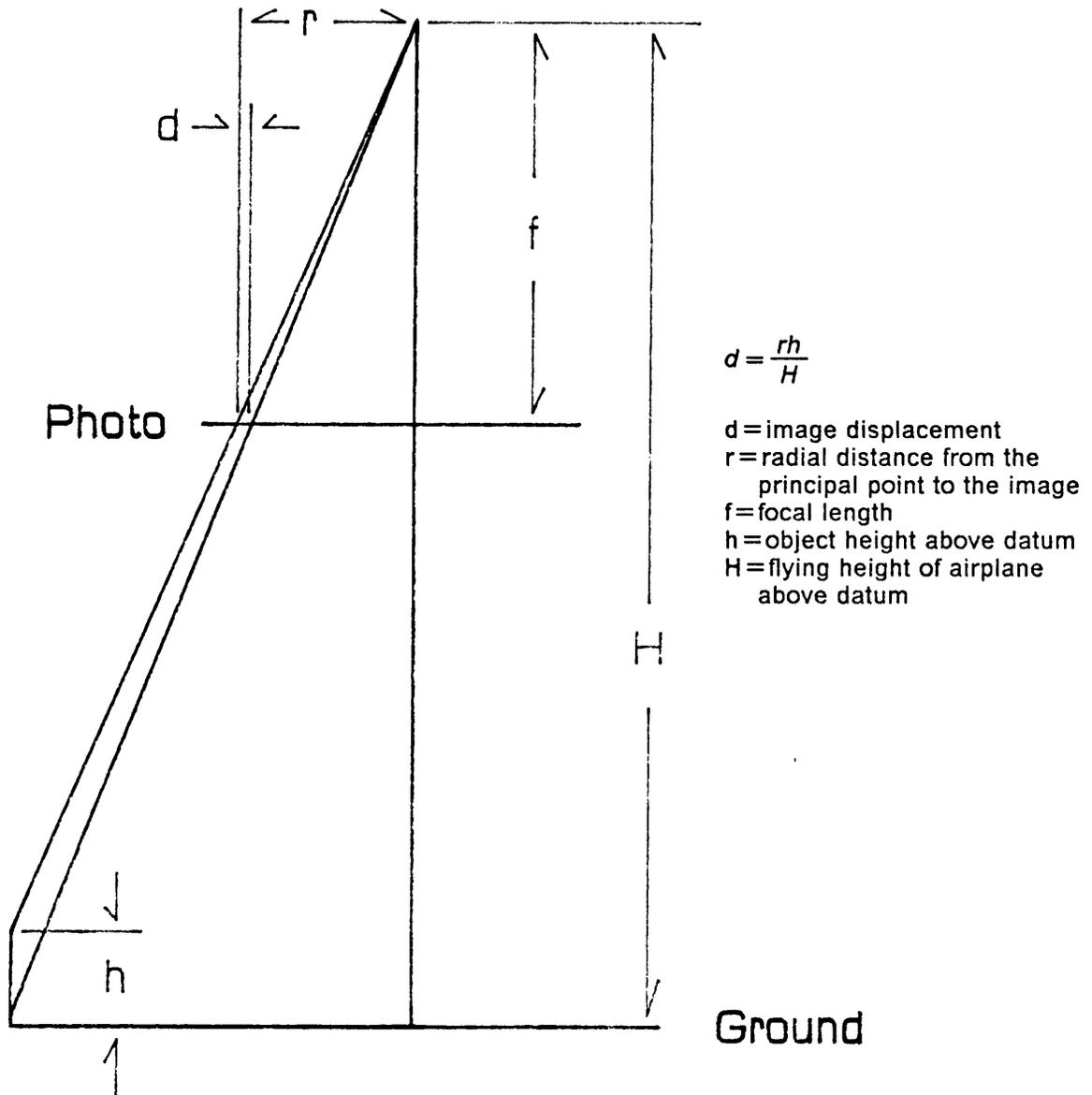


Figure 1. Drawing of relief displacement.

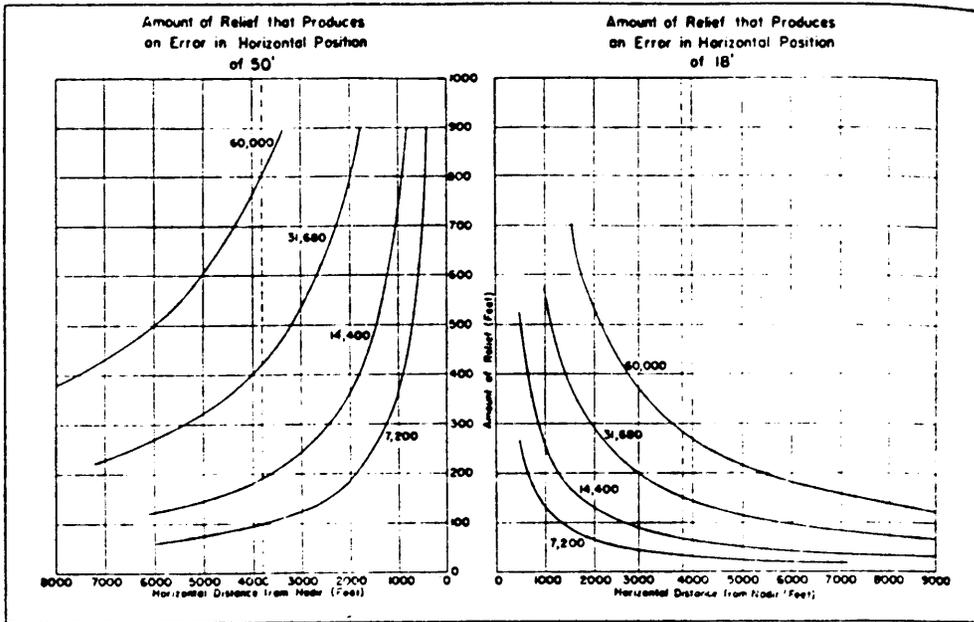


Figure 2. Displacement error at various flying heights and difference in topographic relief: (Wood 1950).

This value of 2.54 mm is for 9-in film, which is a much larger format compared to 35-mm film. Knowing relief error becomes more extreme outward from the principal point, a 35-mm photo will normally have less displacement at the edge of the format than a 9-in photo at the same flying height. To compute an example of relief positional error for 35-mm photography, the formula  $d = \frac{rh}{H}$  (American Society of Photogrammetry 1980) is used; where  $d$  is the displacement,  $r$  is the radial distance from the principal point to the displaced image,  $H$  is the flying height above the base, and  $h$  is the height of the object above the base. For example, with a flying height of 4000 feet, an object height of 100 feet, and an image 10 mm from the principal point, the image was displaced 0.25 mm.

The "Forestry Handbook " (Society of American Foresters 1984) gave a simple example of the effect topographic displacement has on area calculations. Two square parcels of land at different elevations and slopes, 91.8 acres each, are photographed vertically with one picture. The flying height for the photograph is 6000 feet above the nadir and the difference between the elevation of the highest and the lowest points is 1200 feet. With topographic displacement, parcel A on the photo was measured as 113.1 acres, an error of +23.2%. Similarly, parcel B due to relief was calculated on the photograph as having 67.9 acres, an error of -26.0%.

## **TILT**

Tilt of the camera axis is unavoidable, and therefore, must be studied to comprehend the magnitude of its affect on photographic measurements, and whether or not it can be ignored. As a result of tilt alone, images appear to be displaced radially toward the tilt isocenter on the upper side of the photo positive, and radially outward or away from the isocenter on the lower side (Figure 3) (Spurr 1960). The tilt isocenter is a point half way between the principal point and the nadir which together define the principal line. Along the isometric parallel (line through the isocenter perpendicular to the principal line) there is no displacement relative to an equivalent untilted photograph. Maximum tilt displacement occurs on the principal line,

# Tilt Displacement

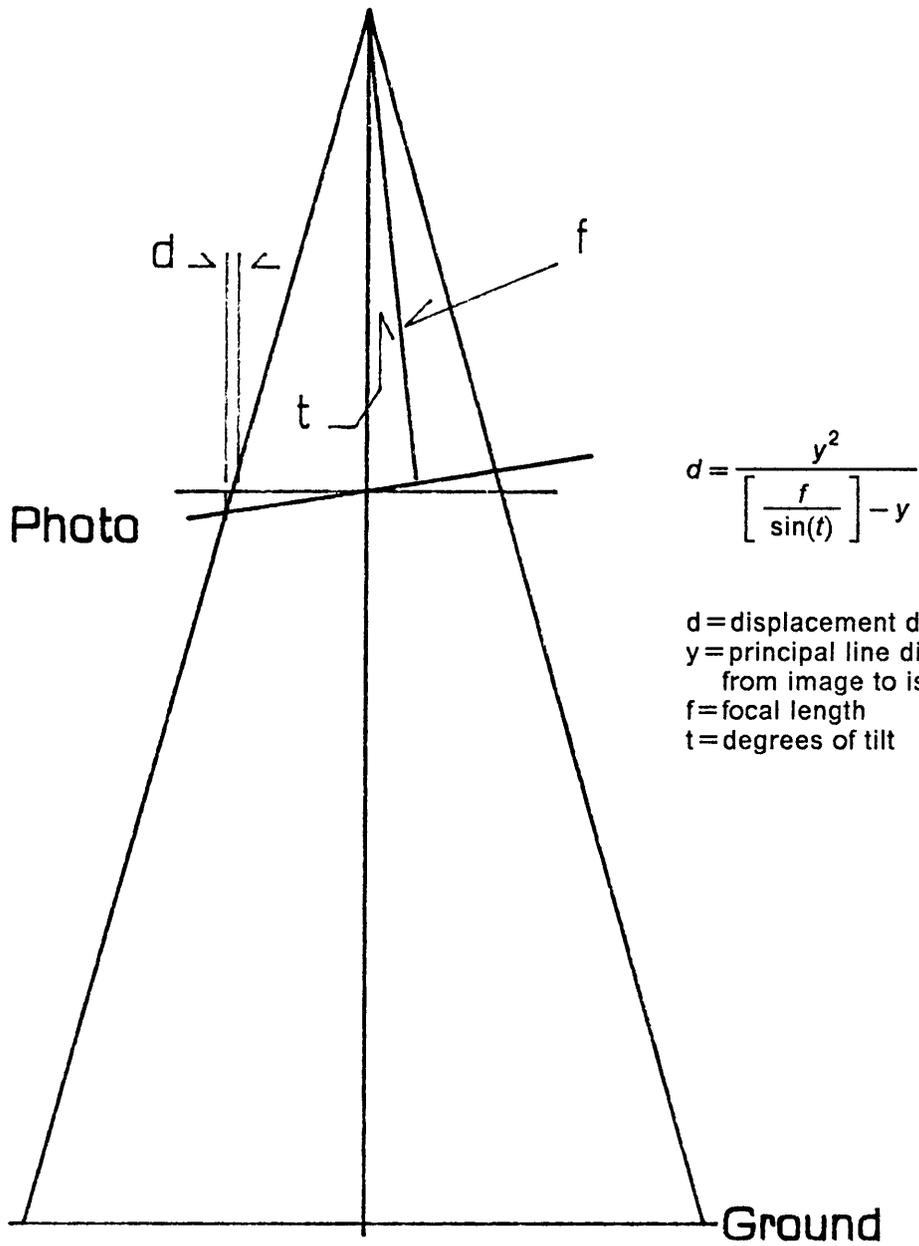


Figure 3. Drawing of tilt displacement.

and zero displacement occurs on the isometric parallel (American Society of Photogrammetry 1980). Figure 4 shows the affect of three degrees tilt on ground position. Carson (1985) showed that with tilts of 1.8 degrees, errors in x and y photo coordinates are several hundred microns on 9-in formats, and concluded that tilt should not be left out of collinearity equations to simplify linearization of these equations. Large errors in scale calculation, due to tilt, can be avoided by always measuring the distance between two points which are about the same elevation, the same distance from the center, and diametrically opposite the center, because this negates the effect of tilt (Spurr 1960, Wood 1949).

Again using the example for a 35-mm photograph, assume the camera platform is tilted three degrees. The formula used to compute tilt error for points on the principal line is from the "Manual of Photogrammetry" (American Society of Photogrammetry 1980).

$$d = \frac{y^2}{\left[ \frac{f}{\sin(t)} \right] - y}$$

where;    d = displacement due to tilt (mm),  
           y = distance on principal line from image to isocenter (mm),  
           t = the degrees of tilt (degrees).  
           f = focal length (mm).

Using a focal length of 50 mm, and an image on the principal line 10 mm from the isocenter, the error is 0.106 mm.

## **EQUIPMENT**

The accuracy and precision of the equipment used to record objects on film and the subsequent measurement of the images is directly related to the project accuracy and precision

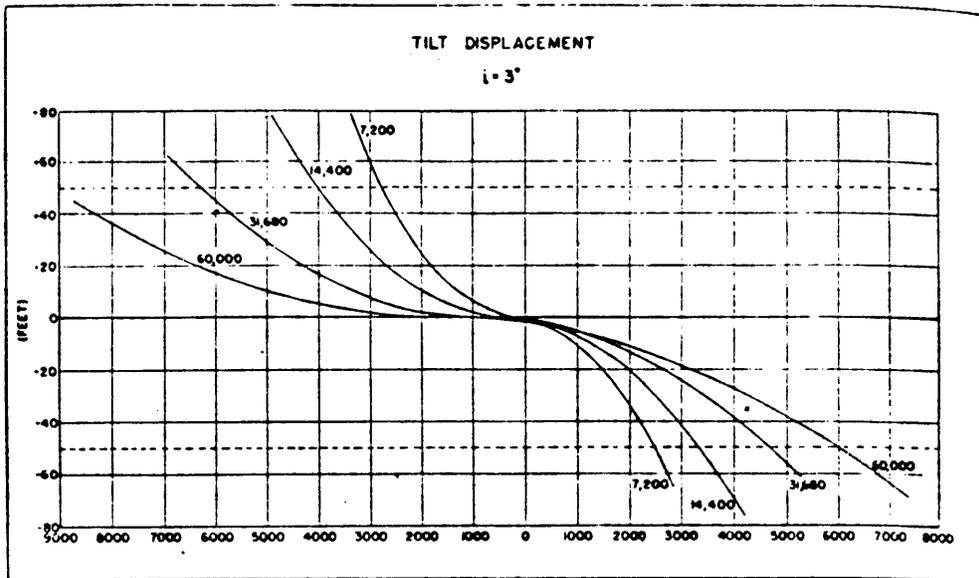


Figure 4. Curves showing error in horizontal position caused by tilt: Tilt of three degrees at various flying heights. The abscissa represents ground distances in feet from the principal point. (Wood 1950)

outcome. Factors involved in the photogrammetric accuracy include, camera and projector lens distortions, film flatness and stability, and precision of the measuring devices. The equipment can be divided into two operational objectives, initial recording of the light rays, and the use and measurement of the developed film.

Lens quality is very important because all light rays must pass through the assembly. Metric cameras have calibrated distortion curves, but few tests have been conducted on small format lenses. Spurr (1960) reported 9-in format camera lens have distortions of 10 micrometers at the edge. Goodrich (1982), in calibrating a 35-mm camera lens, found the residuals on the majority of targets measured to be below 20 micrometers, although some points had residuals in the 40 to 50 micrometer range.

In recording the images, films have two weaknesses stemming from the flexibility of the photographic material. First, film instability, shrinkage and stretching is present in all formats. However, the 9-in cameras record fiducial marks on the film which allows the instability to be computationally removed. Second, film flatness, since the material is flexible, the potential of bowing exists. Large format cameras hold the unexposed film flat with a vacuum. In both cases, 35-mm cameras do not have the capacity to correct or control the inherent weaknesses of the photographic material. Image blur can also be a problem. Excessive movement of the camera relative to the ground is the main cause, and it is therefore necessary to use fast shutter speeds to eliminate this image-motion (Spurr 1960).

A third shortcoming of 35-mm film is the smaller size of the photographs. Enlargement is often necessary for viewing and is especially necessary for measurement via several alternative methods. With all the methods though, the image rays must pass through a second lens assembly. Montgomery and Wolf (1986) found that with a tablet digitizer and an overhead projector, they could achieve measurement accuracies of 5 to 10 micrometers at photo scale. This system projects small formats, up to 2-inches square. The errors they found included:

- Tablet digitizer giving incorrect results (found tablet accurate to within .125 mm)
- Non-planar film surface
- Non-planar digitizer surface
- Projector lens distortion
- Non-parallelism of projector and digitizer
- Decentered cursor reference mark

Montgomery and Wolf (1986) reported surprisingly accurate results, from 5 to 10 micrometers, and are applying this system for several ongoing close range and terrestrial photogrammetric research projects, including applications in biostereometrics, traffic movement investigations, accident reconstruction, and positioning for hydrographic surveys.

## **SUMMARY**

It follows from the above discussion that topographic relief, tilt displacement, and equipment inaccuracies greatly affect image positions on photographs, and as such, a study was necessary to find the results of the singular and combined influences of image positional errors in area estimation. If an image had relief error of 0.25 mm, as computed in the example above, and tilt error of 0.106 mm in the same direction, and distortion error of 0.04 mm, the one point would be measured 0.396 mm from its correct location. All the points along a tract boundary each have independent values of relief displacement, tilt displacement, and lens distortion. It was theoretically known how and where location of images are changed before conducting this study, however, the combined effect of the displacements and distortions when calculating acreages was not known.

## **MATERIALS AND METHODS**

It was from this unknown error in area estimation from aerial photographs that this study was designed. There were two possible experimental designs; actual flights with targets and surveyed ground points to solve for flying parameters such as flying height and camera attitude, or analytic simulation to control these exterior orientation parameters. Due to the additional unknowns, lack of factor control, and measurement errors involved in actual experimental flights, the computational analytic simulation method was used.

Three steps were necessary to accomplish the analytical method. First, an appropriate number of sample tracts were selected and the boundaries digitized collecting x,y coordinates and elevations. Second, computer programs converting three dimensional ground coordinates into two dimensional photo coordinates with the correct adjustments for relief displacement, camera tilt, and lens distortion were written. Third, for each of the simulations, acreages were calculated directly from the photo coordinates, and the percent error was computed. From the percent error data, analyses were made to understand the effects of topographic displacement, tilt, and lens distortion on acreage estimation error.

## **DATA COLLECTION**

Because of the many combinations of the flight parameters to be simulated for each tract, only four test tracts were used. Ideally, the tracts should sample the range of topographic relief, tract sizes, and tract shapes. However, by limiting the number of sample tracts to four, the sampled areas were within regions where aerial photographs are often used and where the results would be most applicable. The Coastal Plain and the Piedmont physiographic regions both have large intensively managed agriculture and forestry land holdings and hence sampled for this study. Furthermore, the size of the sample tracts was limited to fit entirely on 35-mm film taken with normally used lenses and at normal flying heights. Actual tract boundaries were not necessary to complete this study for two simple reasons. First of all, this study was not undertaken to prove any particular point about a specific piece of land, but to produce some guidelines on flying height, lens choice, and tilt limitations. Secondly, because of the metes-and-bounds surveying in the East, tracts are irregular and dissimilar.

To acquire the data in the necessary ground coordinates, the four selected tracts were traced on 7.5 minute USGS topographic maps and digitized. The digitized coordinates were the intersections of the tract boundaries with the topographic elevation isolines. Two representative tracts were acquired from the Coastal Plain region and two from the Piedmont region. The Coastal Plain region is generally level, and was used as it was hypothesized there is little effect from relief in this area. These two sample tracts were from Murfreesboro, NC and Franklin, VA topographic maps, and have maximum topographic changes of 48 feet and 19 feet respectively. Rolling hills dominate the Piedmont area, and this area was chosen for study because both tilt and relief displacement could be better analyzed. The two sample tracts for this area were from Crewe West, VA and Keysville, VA topographic maps, and have maximum elevation differences of 105 feet and 60 feet respectively.

## PHOTOGRAPHIC SIMULATION

To simulate the photographs, ground coordinates were converted to photo coordinates via collinearity and lens distortion equations. The collinearity equations used seven parameters and the ground coordinates. Camera attitude (tilt, swing, azimuth), camera exposure station coordinates (X<sub>I</sub>, Y<sub>I</sub>, Z<sub>I</sub>) and camera focal length (f) were the seven parameters. The collinearity equations (Wolf 1983) automatically took into account and adjusted the photo image positions for topographic relief, camera tilt, and focal length.

$$x = -f \frac{[M_{11}(X_g - X_I) + M_{12}(Y_g - Y_I) + M_{13}(Z_g - Z_I)]}{[M_{31}(X_g - X_I) + M_{32}(Y_g - Y_I) + M_{33}(Z_g - Z_I)]}$$

$$y = -f \frac{[M_{21}(X_g - X_I) + M_{22}(Y_g - Y_I) + M_{23}(Z_g - Z_I)]}{[M_{31}(X_g - X_I) + M_{32}(Y_g - Y_I) + M_{33}(Z_g - Z_I)]}$$

where; x,y = photo image coordinates (mm)

f = focal length (mm)

X<sub>g</sub>, Y<sub>g</sub>, Z<sub>g</sub> = ground coordinates of object (ft)

X<sub>I</sub>, Y<sub>I</sub>, Z<sub>I</sub> = exposure station coordinates (ft)

M<sub>11</sub> = -cos(a)cos(s)-sin(a)cos(t)sin(s)

M<sub>12</sub> = sin(a)cos(s)-cos(a)cos(t)sin(s)

M<sub>13</sub> = -sin(t)sin(s)

M<sub>21</sub> = cos(a)sin(s)-sin(a)cos(t)cos(s)

M<sub>22</sub> = -sin(a)sin(s)-cos(a)cos(t)cos(s)

M<sub>23</sub> = -sin(t)cos(s)

M<sub>31</sub> = -sin(a)sin(t)

M<sub>32</sub> = -cos(a)sin(t)

M<sub>33</sub> = cos(t)

t = tilt (deg)

s = swing (deg)

a = azimuth (deg)

Flying heights of 4,000 feet and 6,000 feet, and lenses of 24 mm and 50 mm lengths were simulated. These values of flying heights and lens focal lengths represented commonly used values. For all of the simulations, the camera was located above the midpoint of a bounding rectangle which contained the tract, and was not horizontally shifted even with tilt of the camera axis. To implement tilt into the simulation, values of 0, 3, 6, and 12 degrees were used, with four repetitions of each value by changing the swing and azimuth angles. Tilts less than three degrees are commonly considered negligible and assumed zero. Tilts of six and twelve were used as representative values beyond the three degree limit. The four repetitions within each tilt level had azimuth values of 0, 90, 180, and 270. The respective swing was the azimuth plus 180 degrees to keep the top of the format oriented north. These four tilt directions, while not covering all possible directions, sampled each tract with a different portion of the tract at the low end of the tilted format. If the repetitions were all taken from the same quadrant, the same portion of the tract boundary would always be at the low end of the of the tilted format. It is also possible to move the camera exposure station to center the tract with tilt accounted for, however, this was not done in this study because an error in scale and new relief errors would be introduced. Lens distortion errors were applied to the computed photo coordinates for all of the simulations creating results both with and without distortion. The lens distortion curve published by Goodrich (1982) was used to adjust the photo coordinates in this study. Nineteen sample points were measured on this curve to recreate the specified model parameters and fitted through least squares regression techniques. The following equation and Figure 5 were developed through this procedure.

$$d = -5.96798r + 0.028053r^3 + 0.00019402r^5 + (-7.0935E - 07)r^7$$

where; d = displacement (microns)

r = radial distance to image (mm)

## LENS DISTORTION CURVE

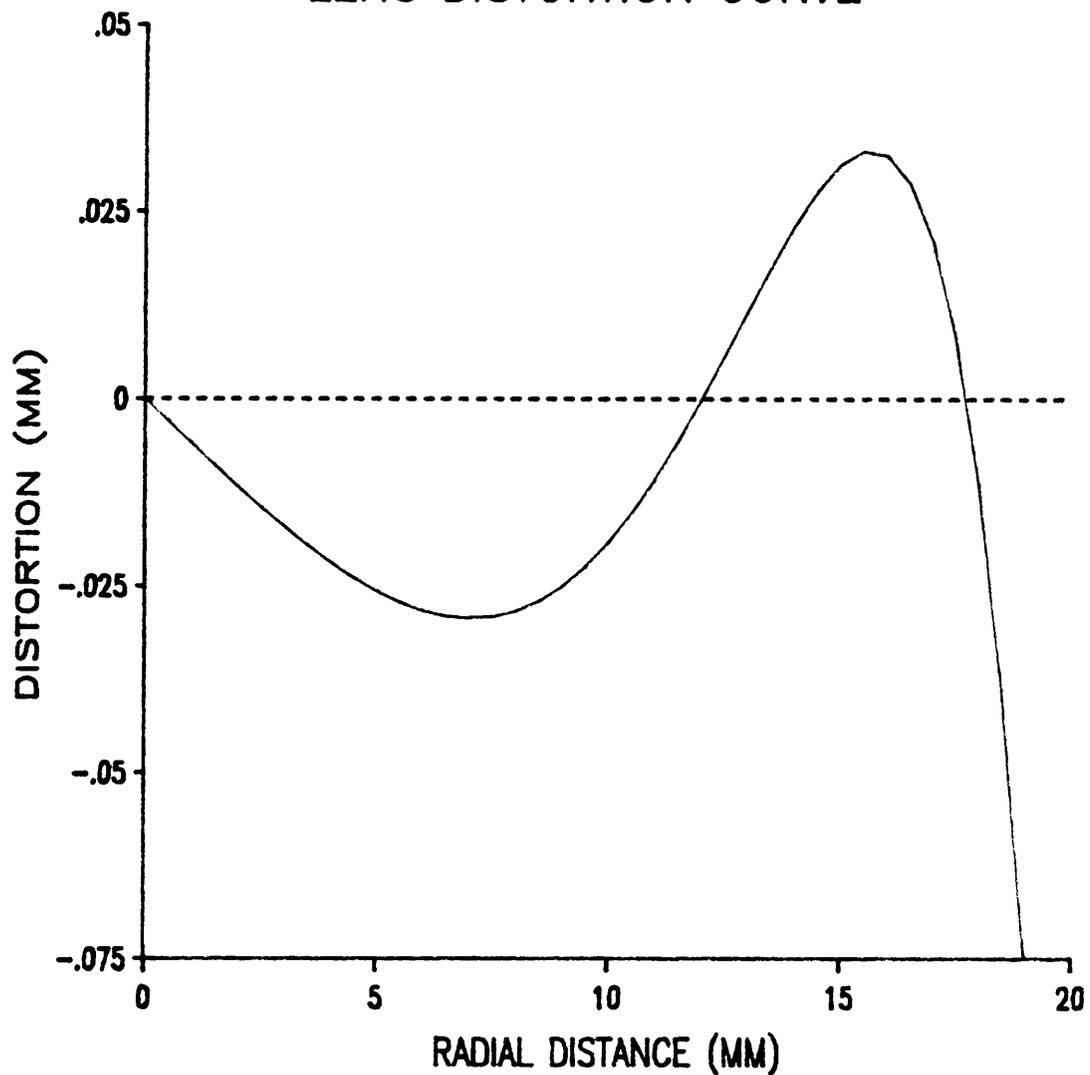


Figure 5. Example of lens distortion curve for 35-mm camera: Maximum radial distance is 21.6mm (Goodrich 1982).

Although this displacement curve is not expected to be the same for all 35-mm camera lenses, it is a known and published example. Since the lens distortion is radial, the photo coordinates were adjusted using the following two equations.

$$x' = x\left(1 - \frac{d}{r}\right)$$

$$y' = y\left(1 - \frac{d}{r}\right)$$

where;  $x'$  and  $y'$  = adjusted photo coordinates

$x$  and  $y$  = original photo coordinates

$d$  = displacement (mm)

$r$  = radial distance to image (mm)

## **METHODS OF ANALYSIS**

Two values of tract acreage were compared for the analysis. One of which was estimated from the simulated photographs, and the second was the true ground acres. The true ground acreage for each tract was calculated directly from the digitized ground coordinates. The photo acreage estimates, however, were more difficult to define. To begin, the photo area ( $\text{mm}^2$ ) was measured directly from the positive or negative transparencies. A conversion (scale) was then applied to convert the photo units of millimeters to the ground units of feet. This scale was linear and changed the units without affecting the comparisons. Scale was calculated by dividing the focal length by the flying height above the terrain elevation. However, the terrain was not level, and thus, the true scale fluctuates within the format. Therefore, an average scale (held constant) was used for the conversion, and was calculated by using the average elevation of the digitized points for each set of flying height and lens focal length

combinations of each tract. This is a commonly applied procedure during photo interpretation projects.

Acreage calculation was the primary data needed to reach the goals of this project. The photo coordinates of each tract perimeter were used in the following equation to compute the area (Brinker and Wolf 1977).

$$AREA = \frac{1}{2} \sum_{i=1}^n [x_i \cdot (y_{i+1} - y_{i-1})]$$

where; AREA = absolute value

x = x photo coordinate

y = y photo coordinate

i = point number

n = number of points

if i=1 then i-1 = n

if i=n then i+1 = 1

From the area calculations, percent error was calculated by dividing the change in acres, photo estimated minus true, by the true acres and then multiplied by 100.

Visualization of the positional errors was also important for understanding the results and making recommendations. Actual drawings of the simulated photographs helped in the visualization. These plots duplicated the simulated photographs with enlargements to easily discern the errors. Overplotting, for a better comparison, was also available. An example plot contained one plot without any positional errors, and a second and third plot with displacement influences of 3, and 6 degrees tilt. This type of analysis showed the general location of the positional errors, reproducing what would actually be seen when projecting the photographs on top of a correct base map.

These results of change in acres were best presented in a tabular format. Tabular form facilitates empirical comparisons and the creation of guidelines from the many available combinations of the data. Three example comparisons are explained below, and are only a sample of the comparisons to be examined. For example, in looking at the two tracts from the Piedmont region, one observes the impact flying height had on the relief displacement error as flying height increases from 4,000 feet to 6,000 feet. Secondly, constructed graphs show specific trends of tilt. It was unknown how acreage error changed as influenced by tilt, possibly linearly or exponentially. A graph helped explain and set guidelines for limitations of tilt. The third example analysis covers the hypothesis that lens distortion has minimal influences on acreage calculation. It was known that lens distortions causes minimal errors of a single point (0.04 mm), but the summation of these errors was unknown. By comparing different simulations with and without lens distortion, an average error due to lens distortion was computed.

## **COMPUTER PROGRAMS**

For ease of computation and for future applications, computer programs were written to perform the steps described above. The four programs, one, digitized the ground coordinates, two, calculated the true acreage, three, simulated the photographs and calculated the photo acreage, and four, plotted the desired photographs (Appendixes A, B, C, D). The digitizing program was written on a Data General Desktop Model 30 using MPBASIC programming language to interface with a Calcomp 9100 Table Digitizer. The other three programs were written in Borland Turbo C for use on an IBM PC/AT to run on any IBM compatible personal computer. The plotting program was written to interface with an HP7475a plotter.

The first program, Mapper (Appendix A), recorded the digitized coordinates and elevations to an ASCII file. The program first initialized the table to output State Plane Coordinates and the

keyed-in elevations to the nearest foot. Before digitizing, the topographic map was secured to the table and the origin was set near the lower left hand corner of the map. The digitized points were the tract boundary corners and the points where the boundaries intersected the elevation contours. Although there were always small errors in digitizing, these errors were irrelevant for this study, and the recorded X and Y coordinates became the true coordinates for acreage calculation and for the photographic simulations. The coordinate file for each tract was then transferred to an IBM PC/AT file for photographic simulation.

The program Acreage (Appendix B) calculated the control acres from the digitized ground coordinates. These acres were not the true ground acreages, due to digitizing errors. However, since the same ground coordinates were used in both this program and the simulation program, this procedure accurately assessed the errors due to photographic properties. This acreage program utilized the Brinker and Wolf (1977) acreage calculation formula explained in the methods section. Acreages were recorded to three decimal places, although the computed acres were significant to five decimal places. More explicitly, as the smallest unit recorded during digitization was one foot, an area of one foot square divided by 43560 square feet per acre is approximately 0.00002 acres.

Photosim (Appendix C) was the main program for this project. Photosim computed the photo coordinates from the ground coordinates with the given camera orientation and location parameters. This program utilized the collinearity equations of Wolf (1983). Focal length was specified in millimeters and flying height was specified in feet. Tilt, swing, and azimuth, in degrees, controlled the amount and the direction of tilt. By adding 180 degrees to azimuth when specifying the swing the camera was always oriented north. Exposure station coordinates were in feet, and could have been specified in three ways. The first, and the simplest, was the center of the bounding rectangle. The program defaulted to these coordinates unless new coordinates were manually entered, which was the second option. The third option was available to recenter tracts on tilted photographs by off-setting the exposure station coordinates appropriately. An eighth parameter, topographic relief factor, allowed flattening out or

intensifying the topographic relief. The final step of the program wrote the the input parameters, the resulting photo area ( $\text{mm}^2$ ), the scale, and the calculated acres to the screen for each simulation. Photosim output photo coordinates to a specified file name. An extra coordinate was added to the end of the file which was the location of the tract center on the format.

The final program, Slide (Appendix D), plotted a simulated photograph on 8.5x11 paper. The plots could have been overlaid in any combination to show exactly how the photographs of the tracts appeared if enlarged to the same size as a base map. The base map, in this case, was a photo without positional errors. Since Photosim could also compute photo coordinates without any positional errors, Slide could plot respective photos with and without errors over top of each other.

## RESULTS AND DISCUSSION

To systematically evaluate the results of this project, discussion of the errors will be divided into three sections: topographic relief error, camera tilt error, and lens distortion error. A final section will then integrate the results and make several recommendations. This introduction section is necessary to highlight and discuss results pertinent to all three sections. It is also important to reiterate that this was a case study with the camera centered over the tract and with only four tracts used in the simulation. First of all, the error values compared are the change in acres, photo acres minus the ground acres, divided by the ground acres then multiplied by one hundred (percent acreage error). As can be seen from Table 2 through Table 5 the range of the percent acreage error is from -1.723 to 10.233 percent. A negative value exists if the photo computed acres was less than the true ground acres, and positive if the photo errors increased the tract size. Secondly, focal length did not change the acreage errors of relief and tilt when lens distortion error was not included and flying height was held constant. This fact is very important to aerial photography. At a given flying height, the distortion of the same images imparted from two different focal length lenses at the same flying height are proportionately equal, and consequently cancel out when computing acreages. Thus, the 35-mm format itself did not create or impart more error due to the focal length or the format size. Finally, at twelve degrees of tilt, the images could not be completely photo-

**Table 2. Results of the simulations for Crewe West, V.A.**

CREWE WEST 50.412 acres					
PERCENT ACREAGE ERROR					
HEIGHT		4000ft		6000ft	
LENS		24mm	50mm	24mm	50mm
T I L T	00 wo	-0.052	-0.052	-0.040	-0.040
	00 w	-1.032	-0.177	-1.145	-0.784
	03 wo	0.714	0.714	0.613	0.613
		0.470	0.470	0.440	0.440
		0.067	0.067	0.157	0.157
		0.282	0.282	0.315	0.315
	03 w	-0.220	0.631	-0.462	0.071
		-0.482	0.458	-0.645	-0.161
		-0.905	-0.081	-0.938	-0.524
		-0.682	0.204	-0.774	-0.319
	06 wo	2.386	2.386	2.136	2.136
		1.863	1.863	1.773	1.773
1.073		1.073	1.212	1.212	
1.476		1.476	1.521	1.521	
06 w	1.565	1.942	1.141	1.994	
	0.990	1.982	0.750	1.561	
	0.167	0.772	0.169	0.819	
	0.583	1.508	0.488	1.236	
12 wo	8.716	8.716	8.024	8.024	
	7.464	7.464	7.191	7.191	
	5.915	5.915	6.056	6.056	
	6.641	6.641	6.655	6.655	
12 w*					

w = with and wo = without lens distortion.

\*Lens distortion calculations are incorrect at 12 degrees of tilt because part of the tract image is off of a 35-mm format.

**Table 3. Results of the simulations for Franklin, V.A.**

FRANKLIN 29.612 acres					
PERCENT ACREAGE ERROR					
HEIGHT		4000ft		6000ft	
LENS		24mm	50mm	24mm	50mm
T I L T	00 wo	0.078	0.078	0.051	0.051
	00 w	-0.966	-0.324	-1.077	-0.824
	03 wo	0.797	0.797	0.665	0.665
		1.185	1.185	0.925	0.925
		0.209	0.209	0.274	0.274
		-0.179	-0.179	0.017	0.017
	03 w	-0.209	0.588	-0.439	-0.034
		0.199	1.091	-0.169	0.301
		-0.824	-0.176	-0.844	-0.534
		-1.233	-0.672	-1.114	-0.868
	06 wo	2.398	2.398	2.141	2.141
		3.188	3.188	2.664	2.664
1.206		1.206	1.344	1.344	
0.415		0.415	0.817	1.817	
06 w	1.483	2.445	1.104	1.874	
	2.317	3.411	1.655	2.560	
	0.230	0.959	0.270	0.841	
	-0.604	0.000	-0.280	0.159	
12 wo	8.480	8.480	7.879	7.879	
	10.161	10.161	8.996	8.996	
	5.937	5.937	6.180	6.180	
	4.258	4.258	5.062	5.062	
12 w*					

w = with and wo = without lens distortion.

\*Lens distortion calculations are incorrect at 12 degrees of tilt because part of the tract image is off of a 35-mm format.

**Table 4. Results of the simulations for Keysville, V.A.**

KEYSVILLE 16.486 acres					
PERCENT ACREAGE ERROR					
HEIGHT		4000ft		6000ft	
LENS		24mm	50mm	24mm	50mm
T I L T	00 wo	-0.346	-0.346	-0.230	-0.230
	00 w	-1.371	-0.698	-1.353	-1.080
	03 wo	0.097	0.097	0.194	0.194
		0.867	0.867	0.704	0.704
		0.061	0.061	0.170	0.170
		-0.691	-0.691	-0.328	-0.328
	03 w	-0.904	-0.182	-0.910	-0.522
		-0.103	0.849	-0.382	0.115
		-0.952	-0.164	-0.934	-0.564
		-1.723	-1.225	-1.450	-1.183
06 wo	1.407	1.407	1.474	1.474	
	2.978	2.978	2.511	2.511	
	1.322	1.322	1.425	1.425	
	-0.182	-0.182	0.412	0.412	
06 w	0.479	1.256	0.425	1.116	
	2.129	3.294	1.516	2.469	
	0.376	1.383	0.370	1.055	
	-1.177	-0.934	-0.673	-0.255	
12 wo	6.800	6.800	6.757	6.757	
	10.233	10.233	9.008	9.008	
	6.618	6.618	6.654	6.654	
	3.506	3.506	4.543	4.543	
12 w*					

w = with and wo = without lens distortion.

\*Lens distortion calculations are incorrect at 12 degrees of tilt because part of the tract image is off of a 35-mm format.

**Table 5. Results of the simulations for Murfreesboro, N.C.**

MURFREESBORO 43.713 acres					
PERCENT ACREAGE ERROR					
HEIGHT		4000ft		6000ft	
LENS		24mm	50mm	24mm	50mm
T I L T	00 wo	-0.059	-0.059	-0.041	-0.041
	00 w	-1.047	-0.236	-1.150	-0.800
	03 wo	0.643	0.643	0.565	0.565
		0.798	0.798	0.661	0.661
		0.101	0.101	0.194	0.194
		-0.048	-0.048	0.103	0.103
	03 w	-0.306	0.595	-0.517	-0.018
		-0.142	0.773	-0.416	0.112
		-0.874	-0.112	-0.903	-0.489
		-1.031	-0.295	-0.999	-0.611
	06 wo	2.232	2.232	2.031	2.031
		2.554	2.554	2.227	2.227
1.130		1.130	1.278	1.278	
0.835		0.835	1.095	1.095	
06 w	1.377	2.188	1.020	1.861	
	1.724	2.431	-0.999	2.113	
	0.217	0.816	0.233	0.890	
	-0.094	0.503	0.041	0.656	
12 wo	8.305	8.305	7.761	7.761	
	9.023	9.023	8.193	8.193	
	5.957	5.957	6.160	6.160	
	5.358	5.358	5.781	5.781	
12 w*					

w = with and wo = without lens distortion.

\*Lens distortion calculations are incorrect at 12 degrees of tilt because part of the tract image is off of a 35-mm format.

graphed on the 35-mm format. Thus, the percent error for simulations with lens distortion at twelve degrees of tilt were invalid because the tracts could not be photographed completely. Because the lens distortion is undefined for points off the format, these acreages were not used at anytime in the discussion. The results of twelve degrees tilt without lens distortion, however, were used, as the size of the imaging plane is ultimately irrelevant.

## **RELIEF**

Knowledge of relief displacement magnitude alone is the first building block necessary to examine the effects of the three photo-caused positional errors on area estimates. As camera tilt and lens distortion are added, relief displacement error becomes compounded with them. For this reason, only untilted simulations without lens distortions will be analyzed in this section.

The ranges of topography sampled exemplifies what is typically found in the Piedmont (Figure 6 and Figure 7) and in the Coastal Plain areas of the southeast (Figure 8 and Figure 9). As was expected, little error was caused by topographic relief displacement in area estimation (Table 6), although a more consistent difference between the Piedmont and Coastal Plain tracts was hypothesized. The average error was -0.167 and +0.007 for the Piedmont and coastal plain tracts, respectively. The range of the results was from -0.346 to +0.078, with the two Piedmont tracts having the lowest and the highest errors in absolute terms. Thus, tract boundary location in relation to the topography had more impact on the error than the maximum range of topographic variation. That is, the tract boundaries in the Piedmont have opportunity for greater relief displacement of a specific point, but there was a compensating interaction of these point displacements. Moreover, the Piedmont areas with the greater relief, did not conclusively produce the worst absolute error. In fact, the tract with the largest relief variation, Crewe West with 105 feet, had the lowest errors, -0.052 and -0.040,

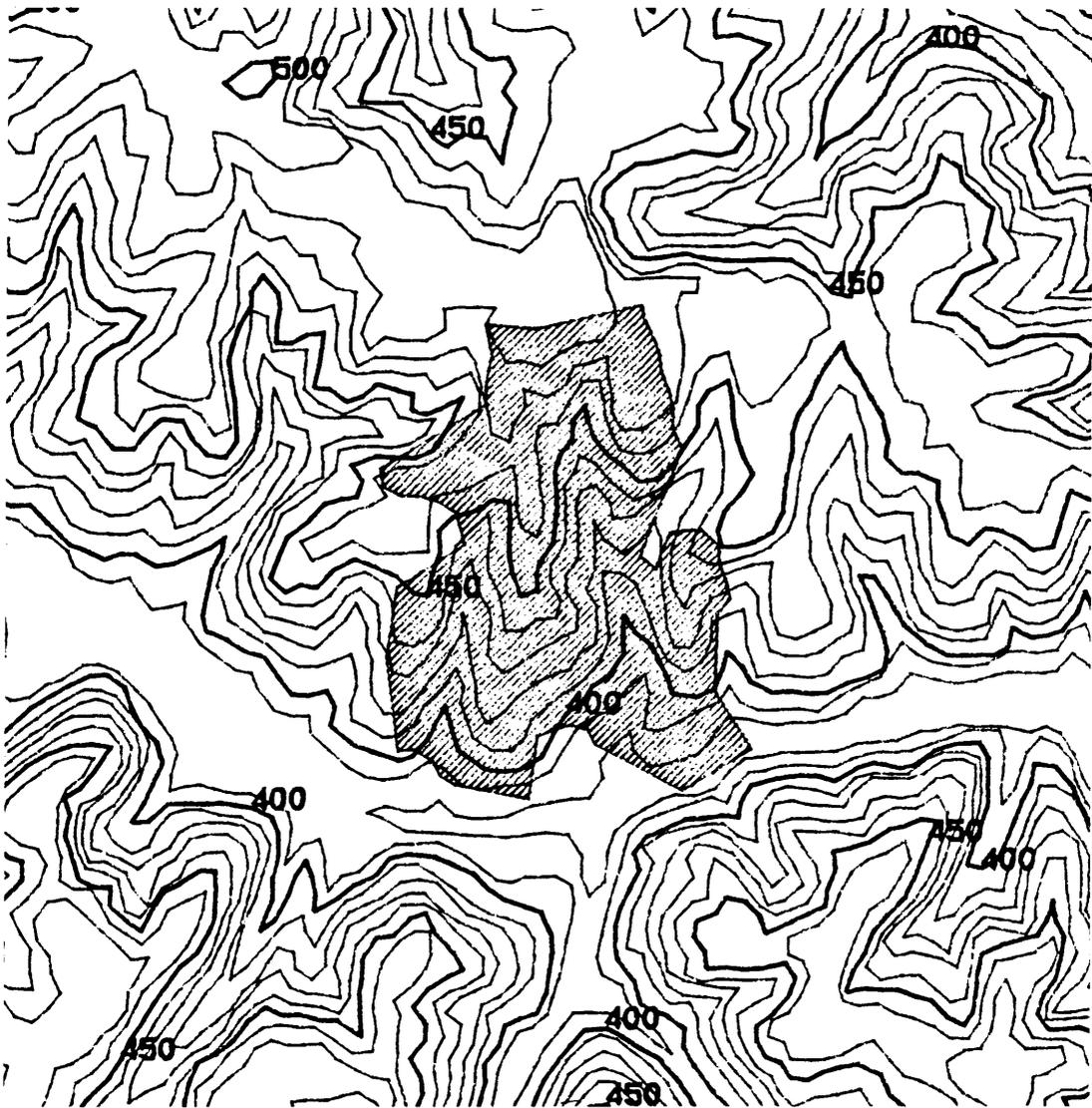


Figure 6. Topography of Crewe West, VA. area.

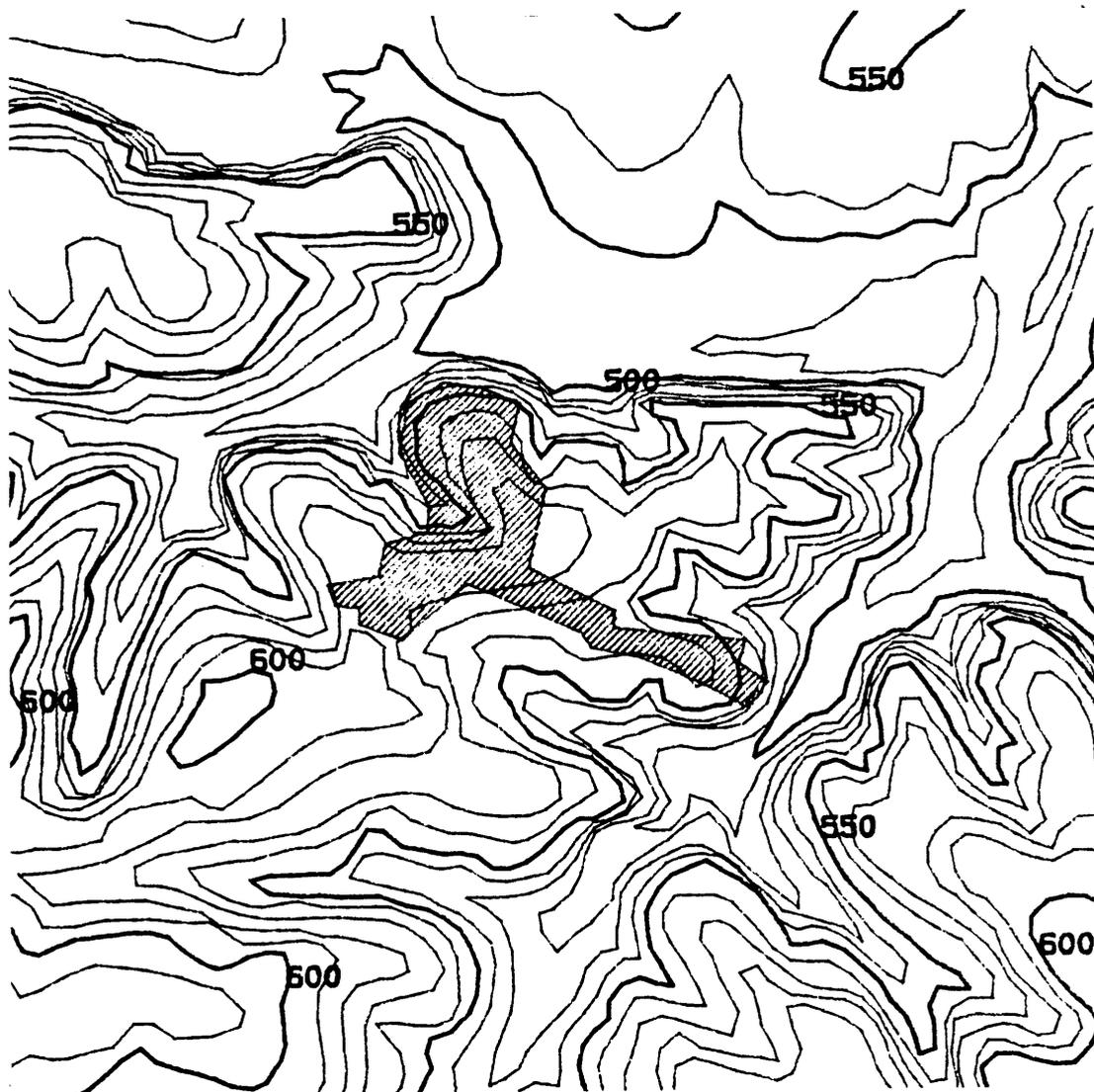


Figure 7. Topography of Keysville, VA. area.

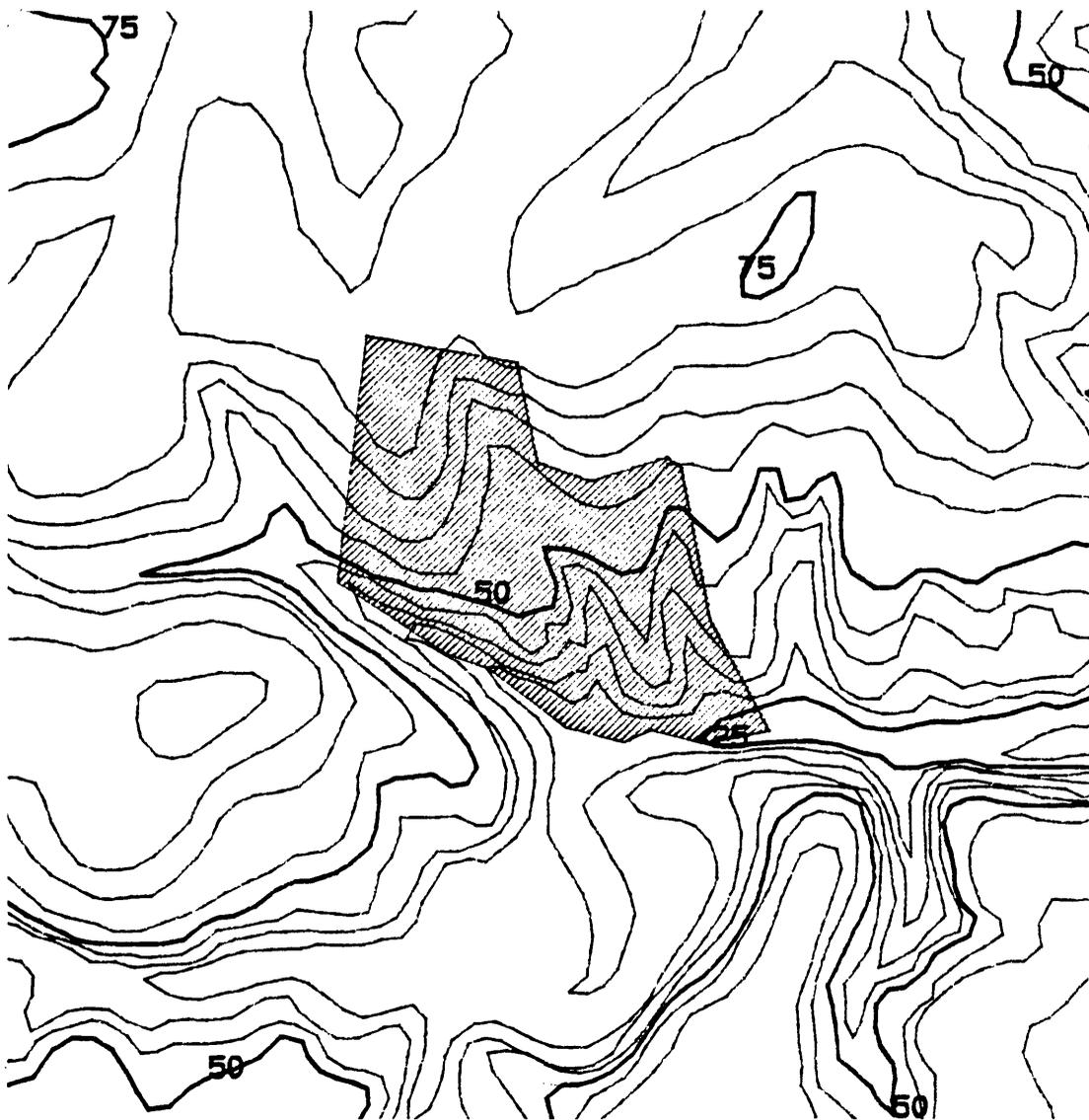


Figure 8. Topography of Murfreesboro, N.C. area.

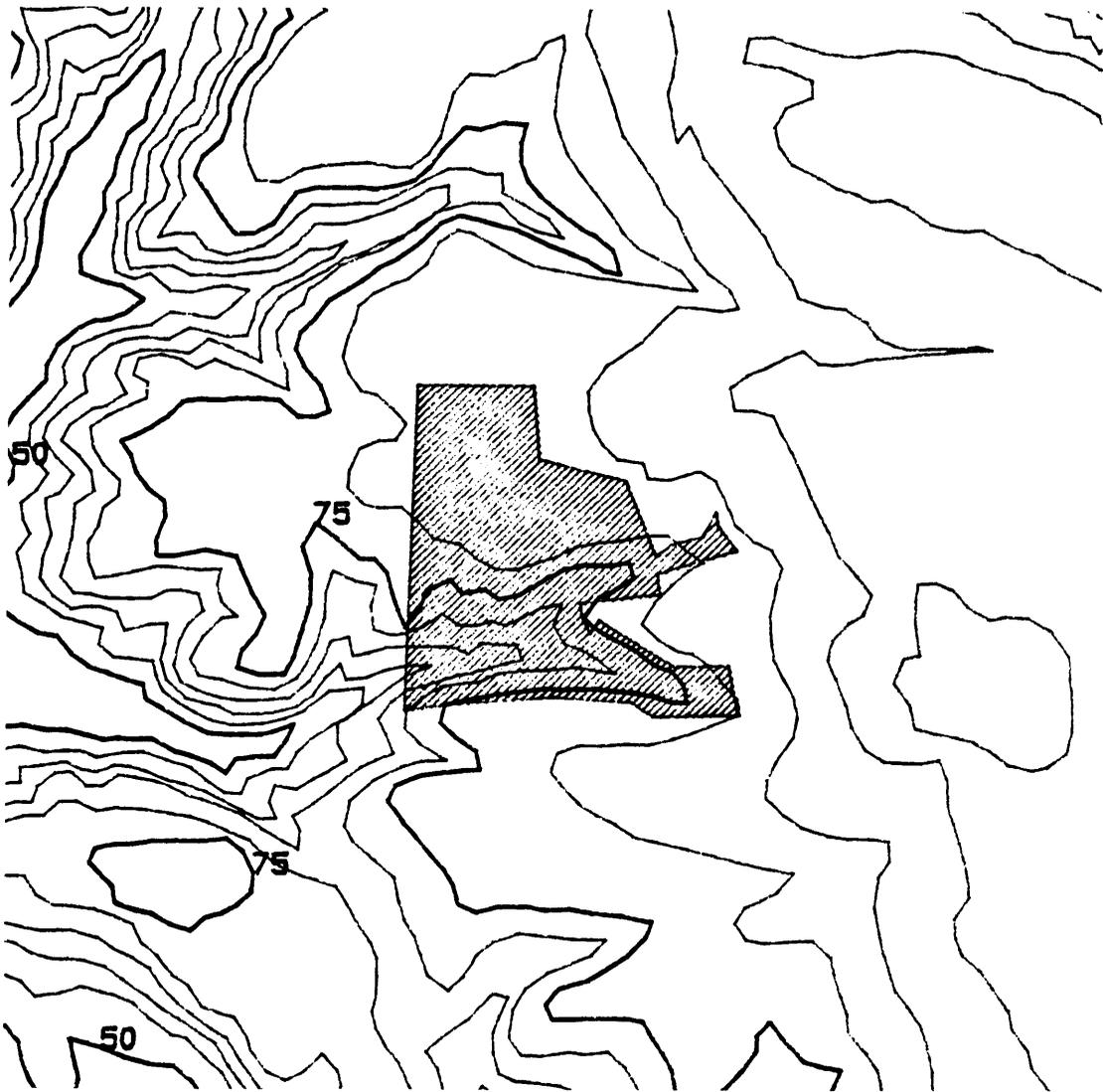


Figure 9. Topography of Franklin, VA. area.

**Table 6. Percent acreage error from relief displacement.**

TRACT	PERCENT ACREAGE ERROR			
	PIEDMONT		COASTAL PLAIN	
	CREWE.	KEYS.	MURF.	FRANK.
MAX. RELIEF	105 ft	60 ft	48 ft	19 ft
FLYING HEIGHT 4000 ft	-0.052	-0.346	-0.059	0.078
FLYING HEIGHT 6000 ft	-0.040	-0.230	-0.041	0.051
AVERAGE	-0.167		0.007	

at 4000 and 6000 feet flying height respectively. Although the averages seem to conclude that Coastal Plain tracts have less error, this average was closer to zero because one tract had negative errors while the other tract had positive errors. The following discussion presents possible reasons why the relief errors are inconclusive for area calculation, and why a more thorough sample is necessary.

An incorrect scale estimate easily changes the sign and magnitude of the errors. To illustrate the effect of scale on the resulting percent error, a hypothetical, level tract was created approximately the same size as the average of the four test tracts. Tract acreage was calculated for this fictitious tract with errors in flying height of one to five feet (Table 7). The scale was held constant throughout, while the true flying height changed, to show the consequences of an inaccurate flying height used in calculating a photo scale. For example, the third row of Table 7 assumes a flying height of 4000 feet and 6000 feet while in actuality the the flying height was 3998 feet and 5998 feet. The percent acreage error was then computed as 0.10 and 0.067 respectively. One can see that percent acreage error with a two foot error in flying height is larger than three out of four tract errors reported as relief error. Likewise, a 7 foot change in flying height, following the trend, would produce percent acreage errors worse than those of the fourth tract. Whether or not an error of seven feet is possible is dependent on the precision of determining scale. Aircraft altimeters are often incremented by ten or twenty feet, in which case the smallest significant unit is five feet. Furthermore, five feet is only 0.125 percent of the flying height at 4000 feet, and less at 6000 feet. The nominal focal length also imparts additional inaccuracies into the scale estimate. The lens used to calibrate the distortion curve for this study had a nominal focal length of 50 mm, but the true calibrated focal length was 51.21 mm, an error of 2.42 percent. This is equal to a flying height error of 96.8 feet at a nominal height of 4000 feet. A second alternative to the focal length flying height ratio is measuring the length of a known ground distance on each photo. This method is also susceptible to imprecisions in measurement. A distance of 1000 feet on the ground, with a 24 mm lens and a flying height of 4000 feet, would measure as 6.000 millimeters on the photo-

**Table 7. Effect flying height error has on percent acreage error, 4000ft and 6000ft are used in calculating respective tract acres.**

PERCENT ACREAGE ERROR FOR CHANGE IN ACTUAL FLYING HEIGHT					
ASSUMED HEIGHT 4000 ft			ASSUMED HEIGHT 6000 ft		
FLYING HEIGHT	COMPUTED ACRES	PERCENT ERROR	FLYING HEIGHT	COMPUTED ACRES	PERCENT ERROR
4000ft	35.000	0.000	6000ft	35.000	0.000
3999ft	35.018	0.050	5999ft	35.012	0.033
3998ft	35.035	0.100	5998ft	35.023	0.067
3997ft	35.053	0.150	5997ft	35.035	0.100
3996ft	35.070	0.200	5996ft	35.047	0.133
3995ft	35.088	0.250	5995ft	35.058	0.167

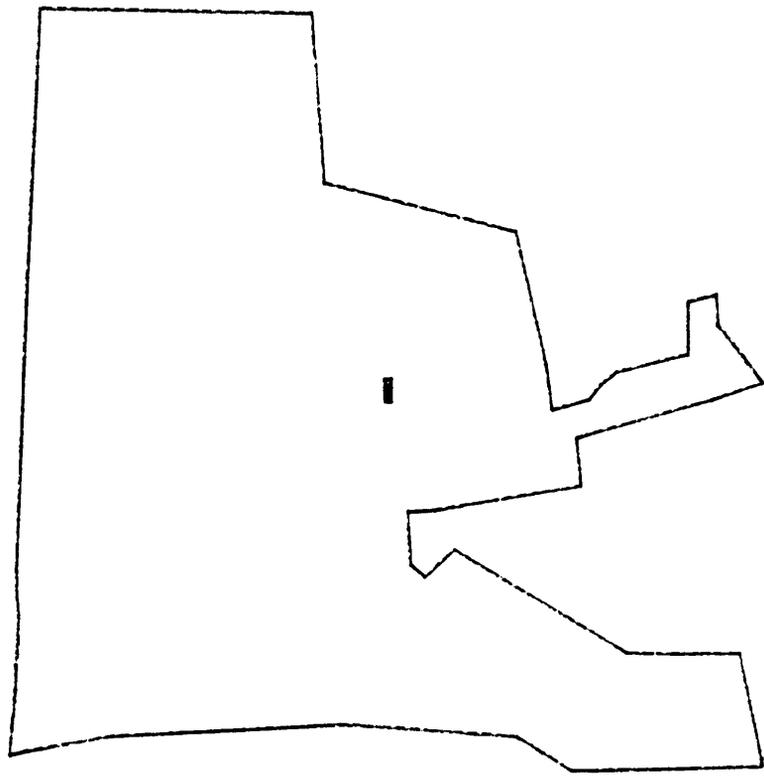
$$\text{computed acres} = \text{true acres} \times \left[ \frac{\text{actual height}}{\text{assumed height}} \right]^2$$

graph. With a flying height of 3995 feet, this same ground distance would measure as 6.0075 mm. The equipment commonly used to measure lengths on photographs is not accurate to seven micrometers.

For level tracts, the value of the flying height above the terrain is easily derived as the flying height above mean sea level, or some other datum, minus the elevation of the terrain above this datum. For tracts with terrain variation however, the scale of the highest point is larger than the scale of the lowest point. This variation in scale is the actual affect of relief. Points of higher elevation have a larger scale and are thus imaged further from the principal point. This discussion is to point out that selection of one scale for a tract or the whole format is difficult. If one uses the flying height above the highest tract elevation to compute scale, the estimated acreage would be too low. Likewise, if the lowest elevation was used to compute the scale, the tract acreage would be positively biased. The difference between the Piedmont and the Coastal Plain average errors could possibly be from a difference in computing the elevation in which the aircraft is 4000 or 6000 feet above.

In the scale calculation for this study, the specified flying height was defined as the height above the average terrain elevation. The average terrain elevation was further defined as the simple average of the digitized points. In the case of the Franklin tract, a disproportionate number of points were digitized at the lower elevations than the higher elevations. When, in fact, the majority of the tract was a plateau at the higher elevation. This caused the actual flying height to be slightly lower than the nominal height over a majority of the tract thereby increasing the true scale in these areas. By plotting the simulated photographs with and without relief error at 4000 feet using a 50 mm lens, one can see that the actual error is very small (Figure 10). Likewise, Figure 11 through Figure 13 show the displacement errors for the other three tracts. Notice for the Crewe West tract, the displacement error, although large, was compensating. Part of the tract was displaced outward, while an equal section was displaced inward.

# FRANKLIN, VA



—— NO DISPLACEMENT  
29.612 ACRES

----- WITH DISPLACEMENT  
29.636 ACRES

X-PRINCIPAL POINT

O-TRACT CENTER

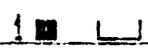


Figure 10. Franklin tract with and without relief displacement.

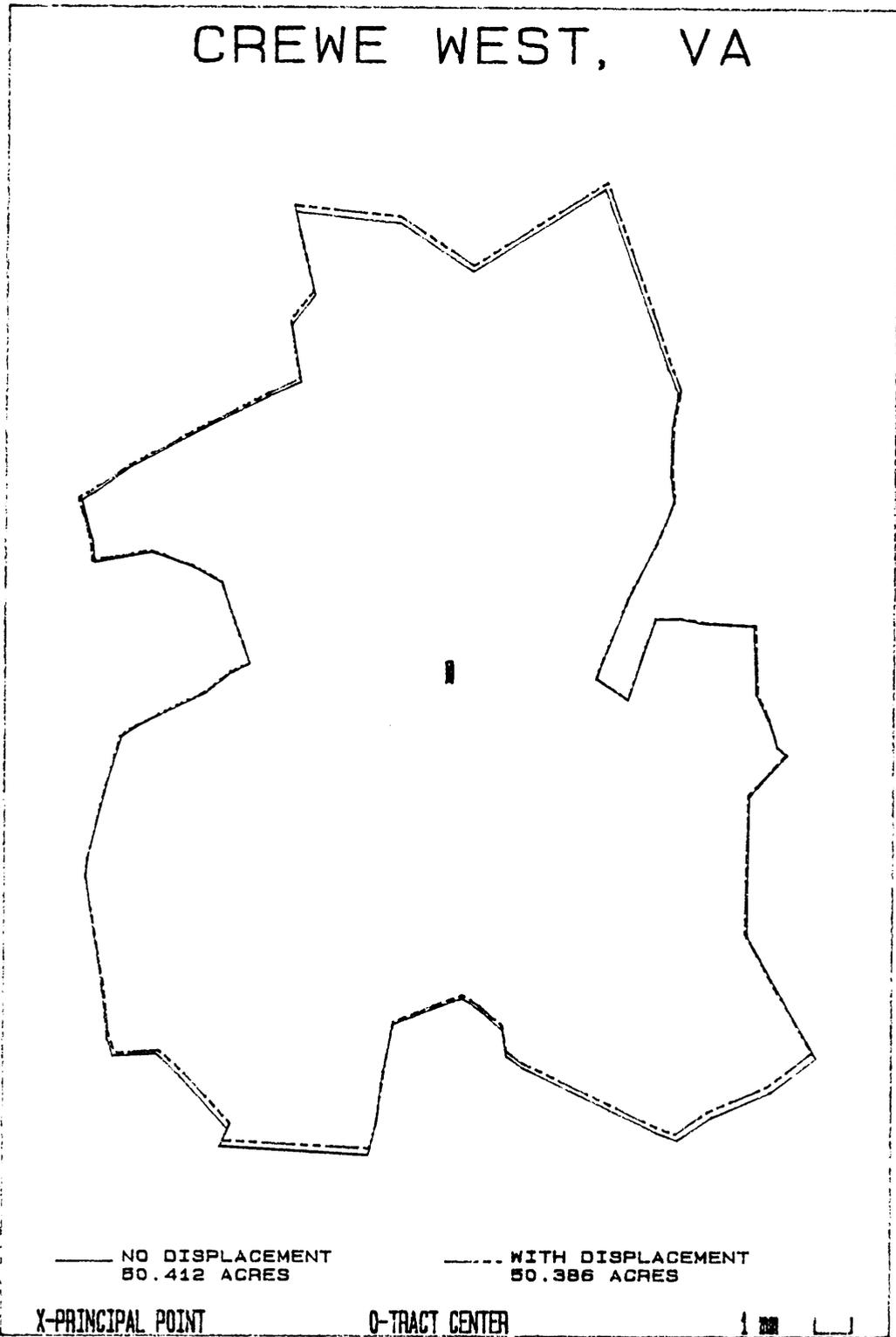


Figure 11. Crewe West tract with and without relief displacement.

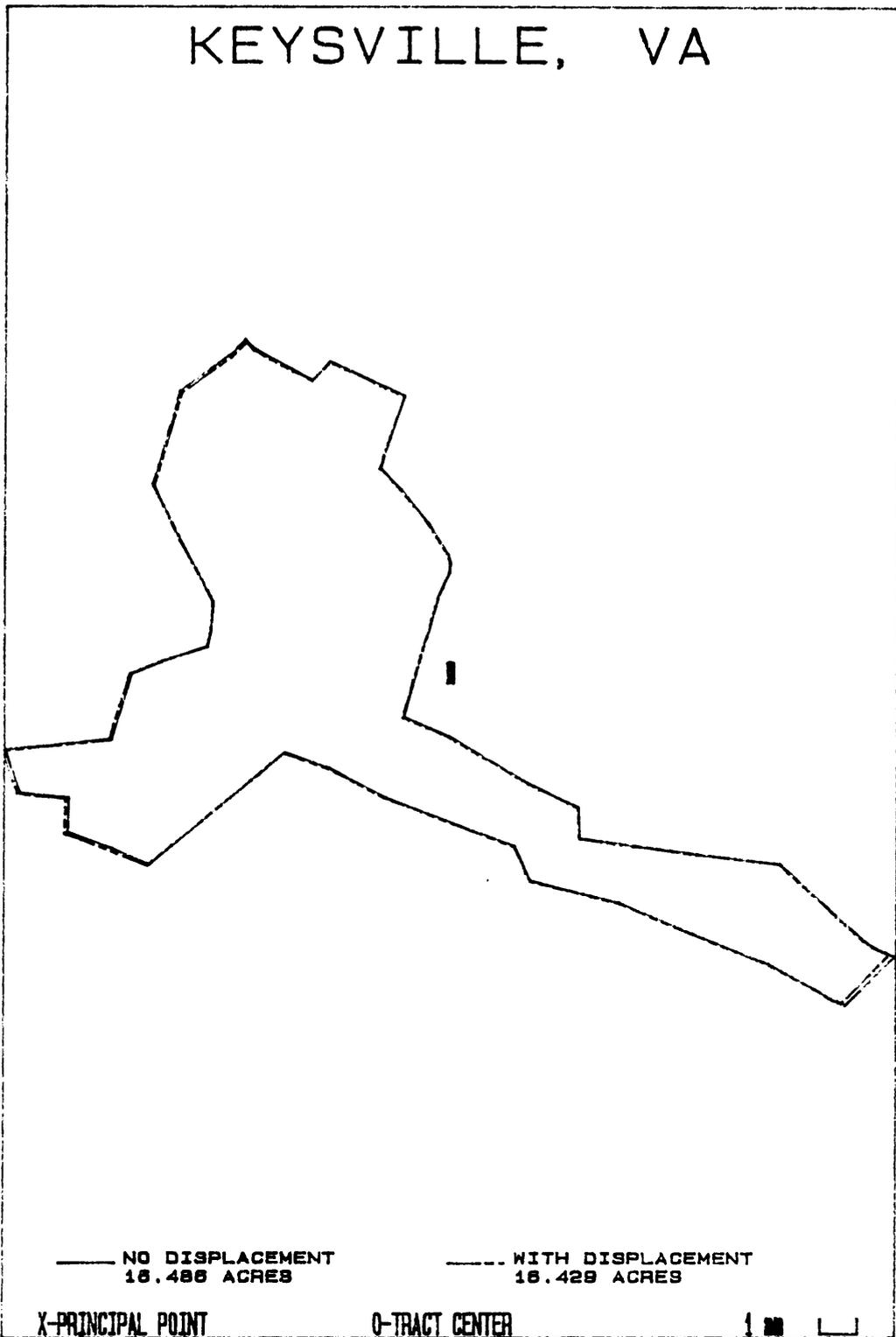


Figure 12. Keysville tract with and without relief displacement.

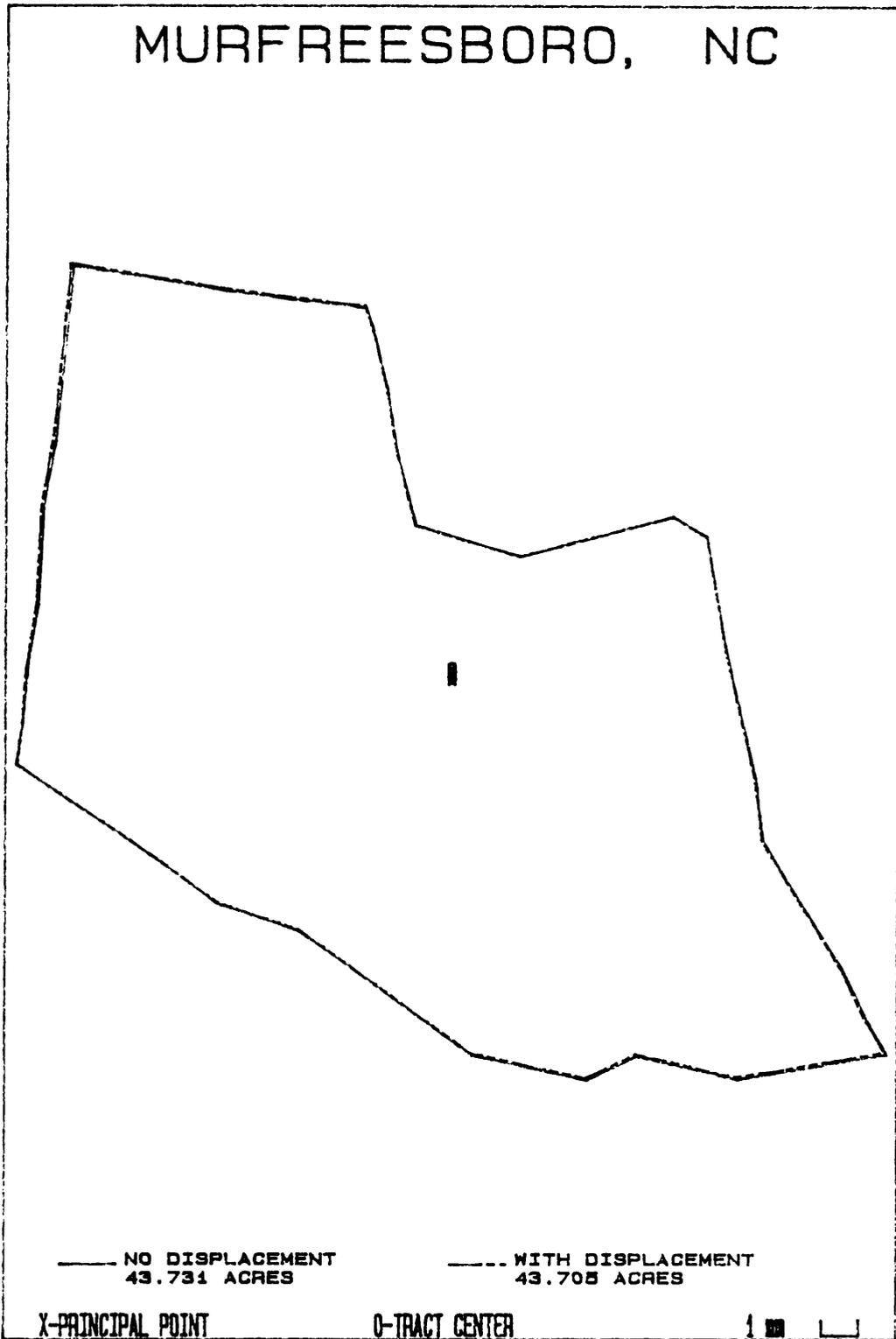


Figure 13. Murfreesboro tract with and without relief displacement.

No definite conclusions can therefore be drawn regarding whether or not the Piedmont has more or less relief error than the Coastal Plain, when calculating acreages because there are other factors involved. First of all, the compensating or additive influences of relief displacement is different for centered tracts than for off-center tracts. These off-center tracts were not simulated in this study, and the relief effects are unknown. Furthermore, from the discussion on scale, it is apparent that the imprecision of scale can overshadow relief error for either region. The variance, on the other hand, was obviously greater for the Piedmont region. This was supported by the fact that the two Piedmont tracts had the largest and the smallest absolute errors. Also, the variance of the movement of each point on the tract boundary was larger for the Piedmont than the Coastal Plain because of the greater terrain relief. The important observation here is the magnitude of the error. As will be brought out in the camera tilt and lens distortion sections, relief displacement was small in relation to the other positional errors.

The second important aspect of the investigation of relief displacement was observing the impact of flying height. By subtracting the absolute value of the percent error of the 4000 feet flying height simulation from the percent error of the 6000 feet flying height simulation, the magnitude of change due to relief errors for a change in flying height was computed. As was expected, an increase in flying height decreased the error due to topographic variation in all cases (Table 8). The average absolute error at 4000 feet was 0.134, while for a flying height of 6000 feet the error was 0.091 for the four tracts. Thus, the average improvement in the percent acreage error was 0.043. The results also show that in these four example tracts, the tract with the largest error improved the most when flying height was increased. Since the focal length of the lens had no effect on the relief error, selection of flying height could be increased to reduce topographic relief error to any desired level, and the focal length increased to retain a similar scale.

**Table 8. Improvement of percent error from relief displacement by increasing flying height.**

TRACT	PERCENT ACREAGE ERROR				AVG %e  *
	PIEDMONT		COASTAL PLAIN		
	CREWE.	KEYS.	MURF.	FRANK.	
RELIEF	105 ft	60 ft	48 ft	19 ft	58 ft
4000 ft	-0.052	-0.346	-0.059	0.078	0.134
6000 ft	-0.040	-0.230	-0.041	0.051	0.091
IMPROVE- MENT	0.012	0.116	0.018	0.027	0.043

\* AVG|%e| is the average of the absolute value of the four tracts.

## CAMERA TILT

The trends of tilt error were harder to quantify than those of relief. Compounded with the tilt error are the previously discussed errors of relief and scale. Adding to this is the heterogeneity of the tilt error variance. Figure 14 indicates that as tilt increases, the range of the observed error widens dramatically. The results of the four repetitions of tilt direction for the four tracts were averaged together for each of the tilts and flying heights to produce Table 9. Zero tilt was included in Table 9 as a reference base to compare the percent error effects of tilt. The average error at both 4000 and 6000 feet flying heights increased positively from -0.095 and -0.065 at zero tilt to 7.086 and 6.931 at twelve degrees tilt, respectively.

From Figure 14, it is apparent that the trend is increasingly positive at an increasing rate. To test the hypothesis that the trend was exponential, two simple models were fit using least squares techniques and the residuals were then plotted (Figure 15 and Figure 16). The two models were  $error = b_0 + b_1(tilt)$  and  $error = b_0 + b_1(tilt) + b_2(tilt^2)$ . As was evident in Figure 15 and Figure 16, the second model with the tilt squared term fit the increasing trend better. In Figure 15, aside from the increasing spread, there was still a curvilinear trend unaccounted for. The  $R^2$  for the simple model was 0.8414, while for the model with  $tilt^2$  the  $R^2$  was 0.8901. Because of the large variance, the  $R^2$  did not improve dramatically. However, it was obvious from the graphs that the increase in error was more than just linear.

An explanation of why the error is always increasingly more positive is necessary at this point. First of all, it is known that images below the isometric parallel are displaced radially outward from the isocenter. Secondly, because tilt causes the nadir (the tract center for this study) to be imaged on the lower side of tilt below the tilt isocenter, more of the tract is also imaged below the isometric parallel. Because more and more of the tract is imaged below the isometric parallel as tilt increases, the size of the imaged tract is increasing as well. This is

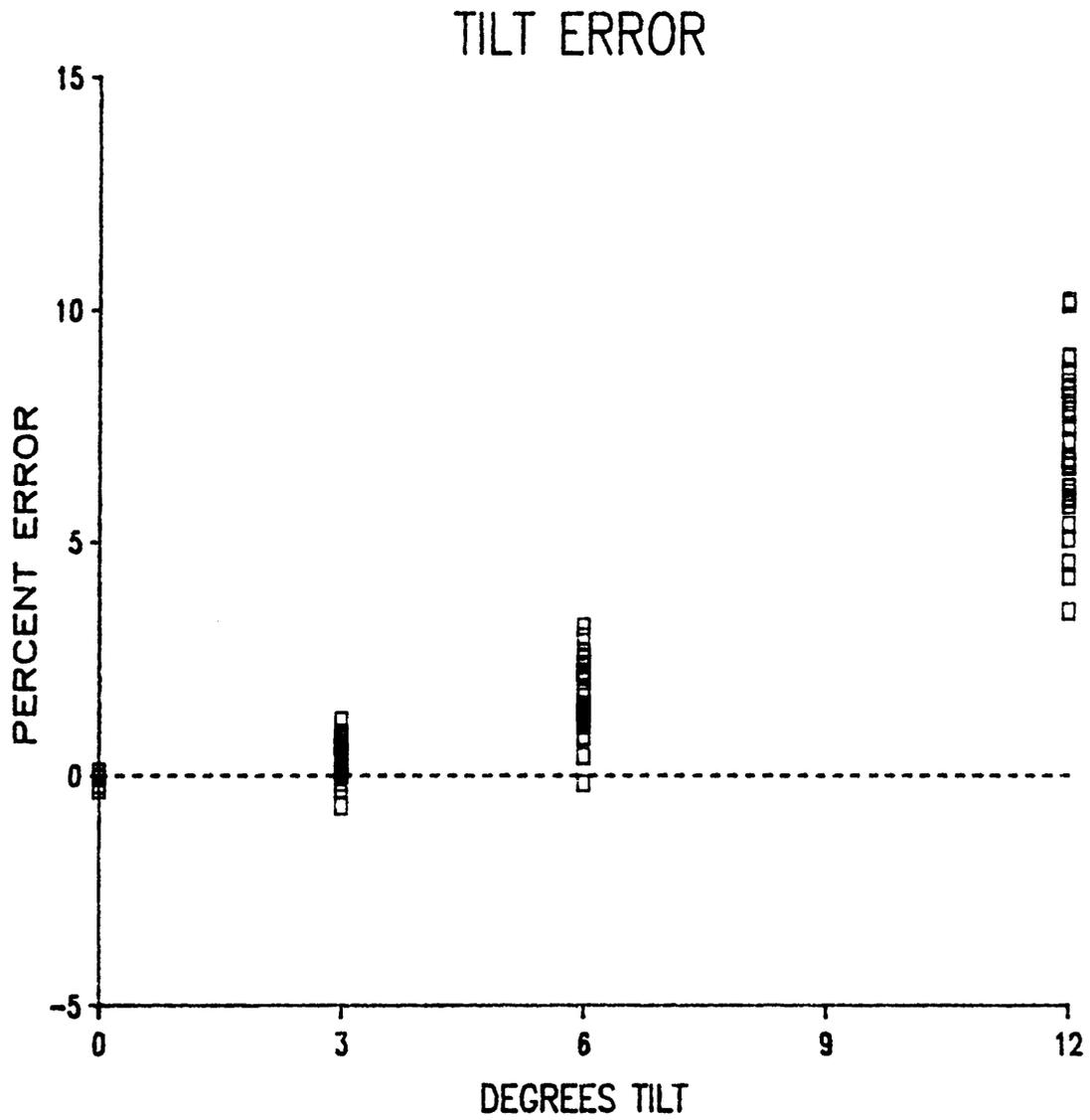


Figure 14. Scatter plot of percent acreage error and degrees of tilt

**Table 9. Result of simulations for increasing tilt and all four tracts averaged together.**

PERCENT ACREAGE ERROR					
TILT DEG.	HEIGHT FT.	MIN	MAX	AVERAGE	VARIANCE
00	4000	-0.346	0.078	-0.095	0.032
00	6000	-0.230	0.051	-0.065	0.014
03	4000	-0.691	1.185	0.336	0.228
03	6000	-0.328	0.925	0.354	0.102
06	4000	-0.182	3.188	1.643	0.865
06	6000	0.412	2.664	1.629	0.386
12	4000	3.506	10.233	7.086	3.842
12	6000	4.543	9.008	6.931	1.711

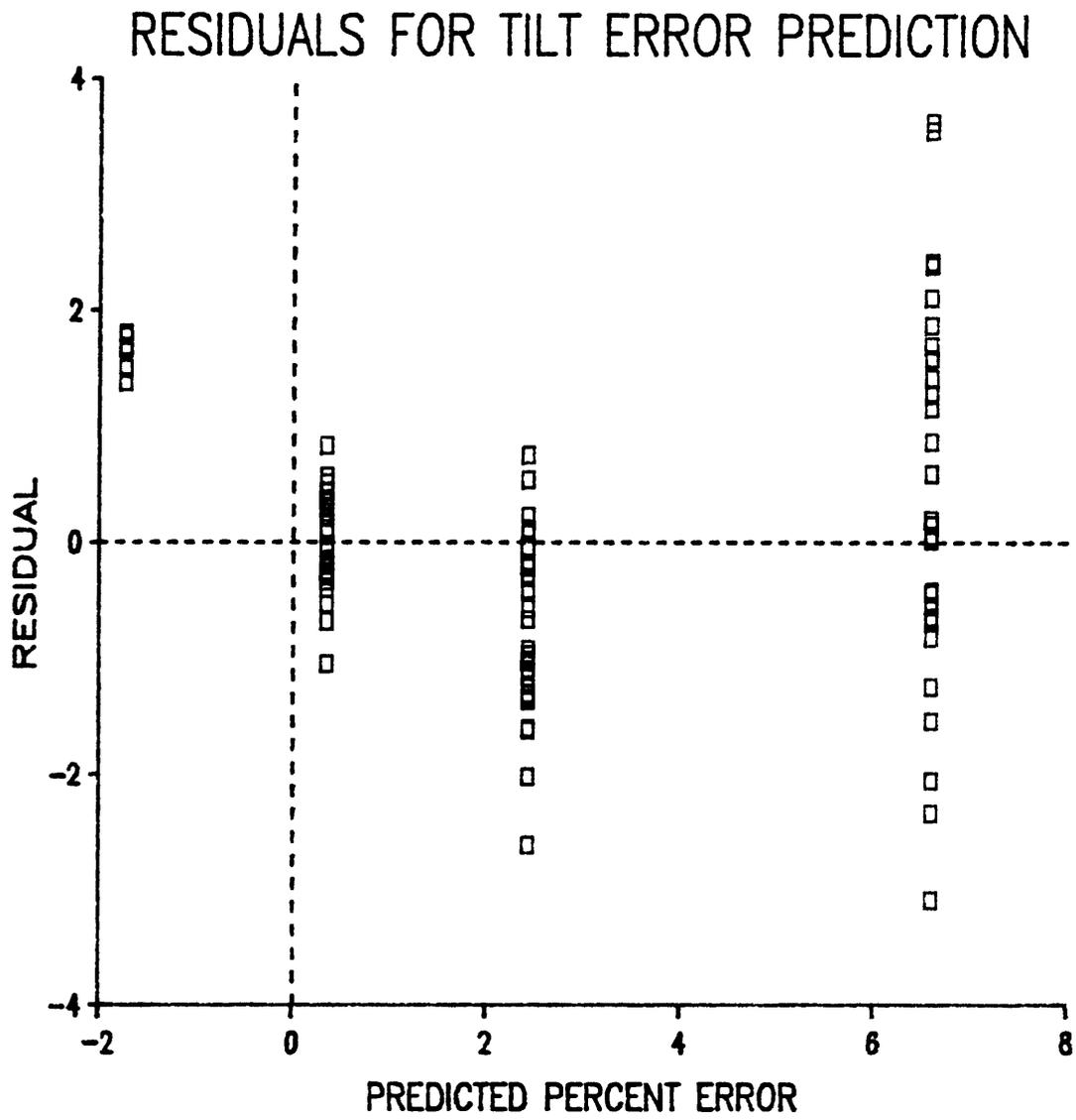


Figure 15. Plot of residual and predicted values of percent error for model  $error = b_0 + b_1(\text{tilt})$ .

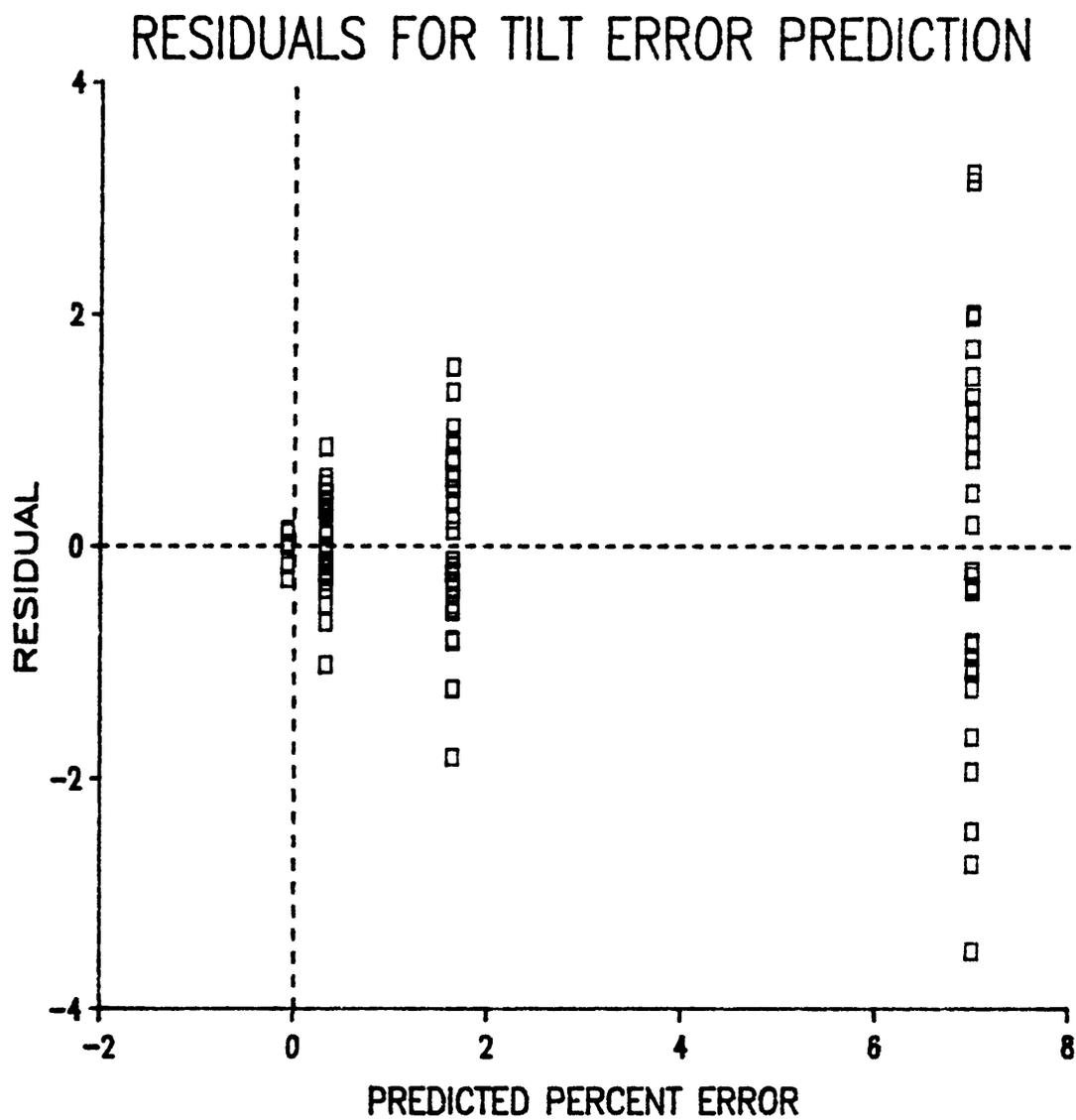


Figure 16. Plot of residual and predicted values of percent error for model  $error = b_0 + b_1(\text{tilt}) + b_2(\text{tilt}^2)$ .

apparent when investigating the trends of the three tilt simulations. How off-center tracts compare area-wise is unknown from this study.

Furthermore, a pattern of the percent error existed within the four repetition of each tilt dependent on the tract shape. As the tilt direction rotated from north, to east, to south, and to west, relations between the tract shape and tilt direction were formed. When the camera was oriented in such a way that a long narrow section of the tract was in the lower half (downhill portion) of the tilted format, the area estimate was less than if the narrow section was located in the upper half (uphill portion) of the frame. Keysville has a long section in the south-east corner and is an example of this relationship. The percent error at six degrees tilt and 4000 feet flying height was -0.182 when the tilt was directed westward (uphill portion of the tilt toward the west), and 2.978 tilted eastward (uphill toward the east). Similarly, if the bulk of the tract was in the downhill portion of the format, the area estimate was greater than if the bulk was located in the uphill half of the frame. The Franklin tract is an example of this when the camera is tilted toward the east. Therefore, tilt error was related to the direction of tilt interacting with the shape of the tract. This is an example of where the limited number of tracts of a case study limits the inferences of the results. More tracts of different shapes are necessary to verify the tilt errors.

The question then arises whether or not flying height had an additional impact on the tilt error. The difference between the average error for 4000 feet and 6000 feet at the three tilts was 0.018% at three degrees, -0.014% at six degrees, and -0.155% at twelve degrees. The maximum difference between 4000 feet and 6000 feet elevation at any tilt was -0.155% error. However, the higher altitude error was not consistently better. At three degrees of tilt, the error at 6000 feet was larger than the error at 4000 feet by 0.018 percent. More simulations are necessary before one can conclude that 6000 feet has consistently lower or higher tilt error than 4000 feet. From these results, a change in flying height did not appear to change the acreage error due to tilt.

A second part of tilt error, as flying height increases, was the variance of the error at a given tilt. As mentioned earlier, the variance of the error increased as tilt increases. However, the data suggest that the variance was lower at higher altitudes when stratifying the error by flying heights (Table 9). By increasing the flying height from 4000 feet to 6000 feet, the variance dropped more than half for all degrees of tilt tested. This was also evident by comparing the range of the percent errors. The columns labeled MIN and MAX contain the observed minimum and maximum errors for each tilt•height combination. The decrease in variance at higher altitudes could be the compounding effect of relief displacement. With an increase in altitude the topographic displacement decreased. The ratio  $\frac{h}{H}$  in the displacement equation was lower for the higher altitude and thus the images were displaced less causing the effect to be less in tilted photographs. This still holds true for tilted photographs, and therefore with the 6000 feet height, the topography contributed less to the compounded error. One could also hypothesize that the improvement was due to a change in scale. As scale decreases, the points were imaged closer to the isometric parallel and displaced less due to tilt. Thus, the tilt error and variance would decrease. Following from this conclusion, a shorter focal length lens would also have the same effect on the variance. However, focal length did not change the acreage error. Consequently, changing the scale, by using a shorter focal length lens, did not change the variance.

## **LENS DISTORTION**

From the above discussion, it was noted that a change in the focal length had no effect on the relief acreage error, or the tilt acreage error at a given flying height. The focal length, therefore, can be used to appropriately match the photographic scale at any flying height to the project without increasing or decreasing the error. This, however, was true only without lens distortion. By adding lens distortion, the derived errors were compounded with tilt, topography, flying height, and focal length. The distortion affect is radial, causing the imaged point

to be displaced inward or outward relative to the principal point. All summaries and conclusions of lens distortion effects are for this distortion curve only.

Overall, with lens distortion, the computed tract acres were reduced 0.686 percent (Table 10). This was calculated by subtracting the percent error without distortion from the percent error with distortion for each of the tracts. Negative values indicated the lens distortion caused a reduction of the imaged tract size. The results of twelve degrees tilt were withheld from the computations for Table 10 because the results with lens distortion of this tilt were invalid. Because tilt errors were mostly positive, lens distortion improved the area estimates for these tracts. However, for the photographs with zero tilt, lens distortion made all the area estimates less than the true acreage.

Image distortion is dependent on where the image's bundle of light rays pass through the lens, consequently scale most directly dictates the path of the rays. The other influencing factors were tilt and topography. Assuming tracts are fairly regularly shaped, that is, they are not convoluted, the points on the tract boundary have nearly the same radii from the tract center. Following this assumption, one could adjust the scale so that a majority of the tract boundary lines are imaged through the lowest distortion circumference of the lens. As one can see in Table 10, the lowest error was at 4000 feet with a 50 millimeter lens. This was because the image rays of the tract boundaries passed through the outer section of the lens where distortion was low. If error, and possibly biases, of -0.686 are too high, each lens should be calibrated. Then, depending on the size of the tract, flying height and lens focal length can be matched to allow a majority of the important light rays to pass through the low distortion area. The results of this procedure could possibly reduce the error from the worst average error of -1.073 percent for this lens, to the best average error of -0.183 percent. Again, these results are for centered tracts, radial lens distortion will affect off-center tracts in a different way.

To understand why the overall average was -0.686 for this lens, example errors were computed for a circle. A circle is the worst case because all points are displaced an equal positive

**Table 10. Average of change in percent error for with and without lens distortion averaged over all tilts and repetitions**

CHANGE IN PERCENT ACREAGE ERROR WITH LENS DISTORTION					
HEIGHT	LENS	MIN	MAX	AVERAGE	VARIANCE
4000ft	24mm	-1.054	-0.821	-0.953	0.004
4000ft	50mm	-0.752	+0.316	-0.183	0.048
6000ft	24mm	-1.131	-0.995	-1.073	0.002
6000ft	50mm	-0.885	-0.042	-0.534	0.060
OVERALL		-1.131	+0.316	-0.686	0.023

or negative amount. Figure 17 shows the percentage error for circles of radius 0.0 to 20 millimeters. Twelve millimeters is the largest circle completely imaged on the 35-mm format. From this curve, which is valid for this lens distortion curve only, one can see the range of error was -1.3 to +0.5. Also noticeable is the fact that a majority of the curve was negative. This supports the results of -0.686 change in percent error due to lens distortion.

Tilt also had a slight impact on the lens distortion error. By tilting the camera, the images of a circle are no longer equidistant from the principal point, and thus all images are not distorted identically. Table 11 shows this was true for the sample tracts also. As tilt increases, lens distortion has less of a compounding affect on the estimates. For the vertical simulations, the difference in percent error with and without distortion was -0.807. At six degrees of tilt the change in error was -0.603 for the average over all scales. Thus, lens distortion errors were maximum on vertical photographs and improved slightly as tilt increases.

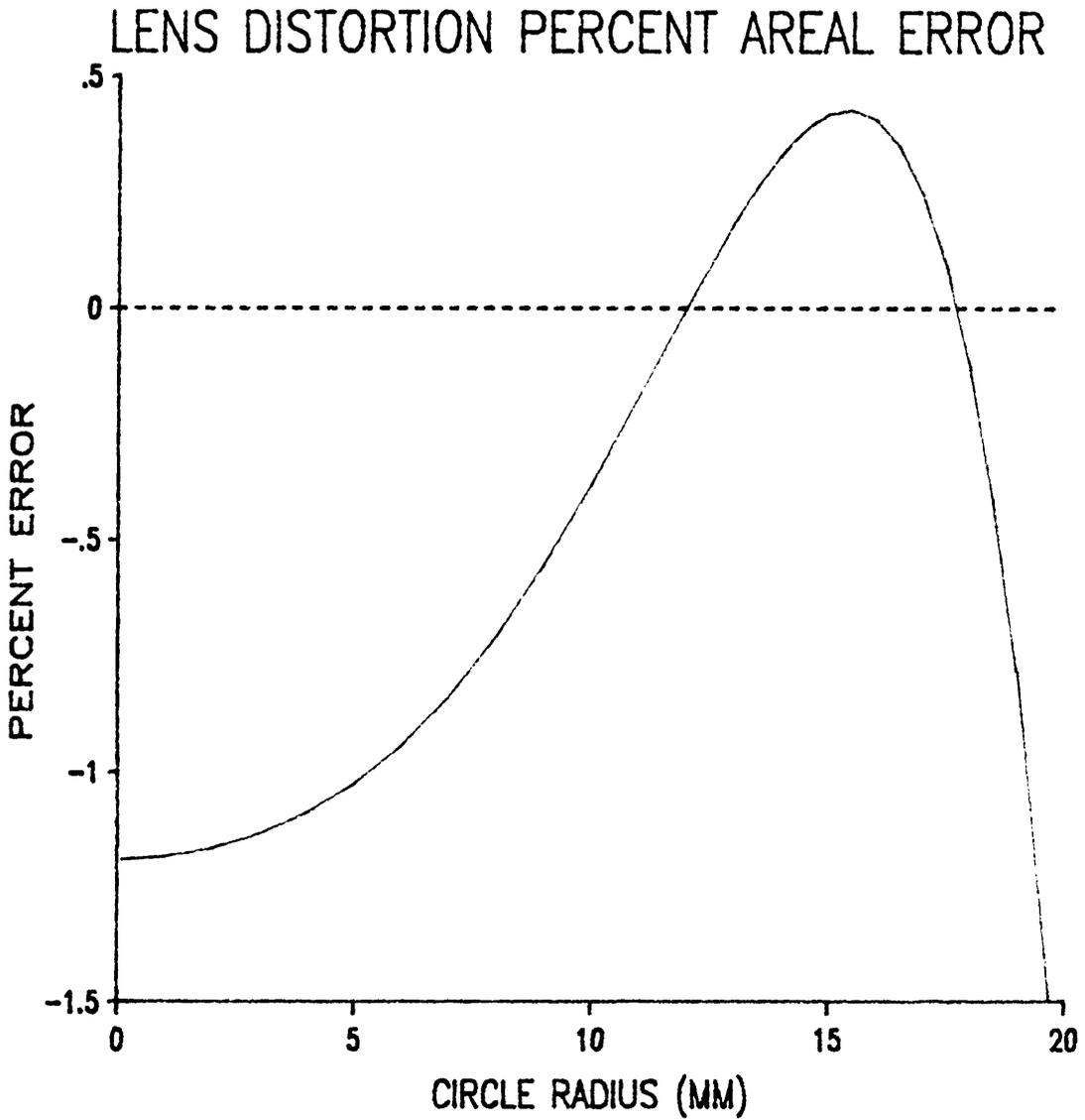


Figure 17. Graph of percent error for circles with lens distortion.

**Table 11. Average of change in percent error for with and without lens distortion for tilts of 0 to 6 degrees.**

CHANGE IN PERCENT ACREAGE ERROR WITH LENS DISTORTION					
TILT	4000ft 24mm	4000ft 50mm	6000ft 24mm	6000ft 50mm	OVERALL
00	-1.009	-0.294	-1.116	-0.807	-0.807
03	-0.985	-0.193	-1.097	-0.681	-0.739
06	-0.907	-0.145	-1.038	-0.320	-0.603

## **SUMMARY AND CONCLUSION**

Three major contributors in the positional errors have been discussed and analyzed. The worst error achieved was slightly over ten percent, and the best was zero percent error. Separating the acreage error into its component parts, relief averaged -0.080 percent error, camera tilt averaged +2.227 percent error, and lens distortion averaged -0.686 percent error. The overall average error incorporating all factors was 0.363%. This average included all simulations from zero to six degrees of tilt. The extent to which these results affect the use of aerial photography to compute areas is a function of how well the actual applications imitate the simulations performed in this study. Mainly, all simulations in this study had the exposure station directly over the midpoint of the tract's bounding rectangle. Given this situation, many of the image positional errors are compensating when computing areas. Figure 18 shows the correct Keysville tract without any positional errors overlain with a simulated photograph. The simulated photograph has a tilt of six degrees, flying height of 4000 feet and a 50 mm lens with distortion. At this scale the error is visible, and the actual difference in acres is 0.543, 3.294 percent of the 16.486 true acres.

Topographic relief has the potential to create large errors. However, the realization of this potential was dependent on the tract boundary location relative to the topography. Crewe West, with 105 feet elevation difference between the highest and the lowest points, had a lower

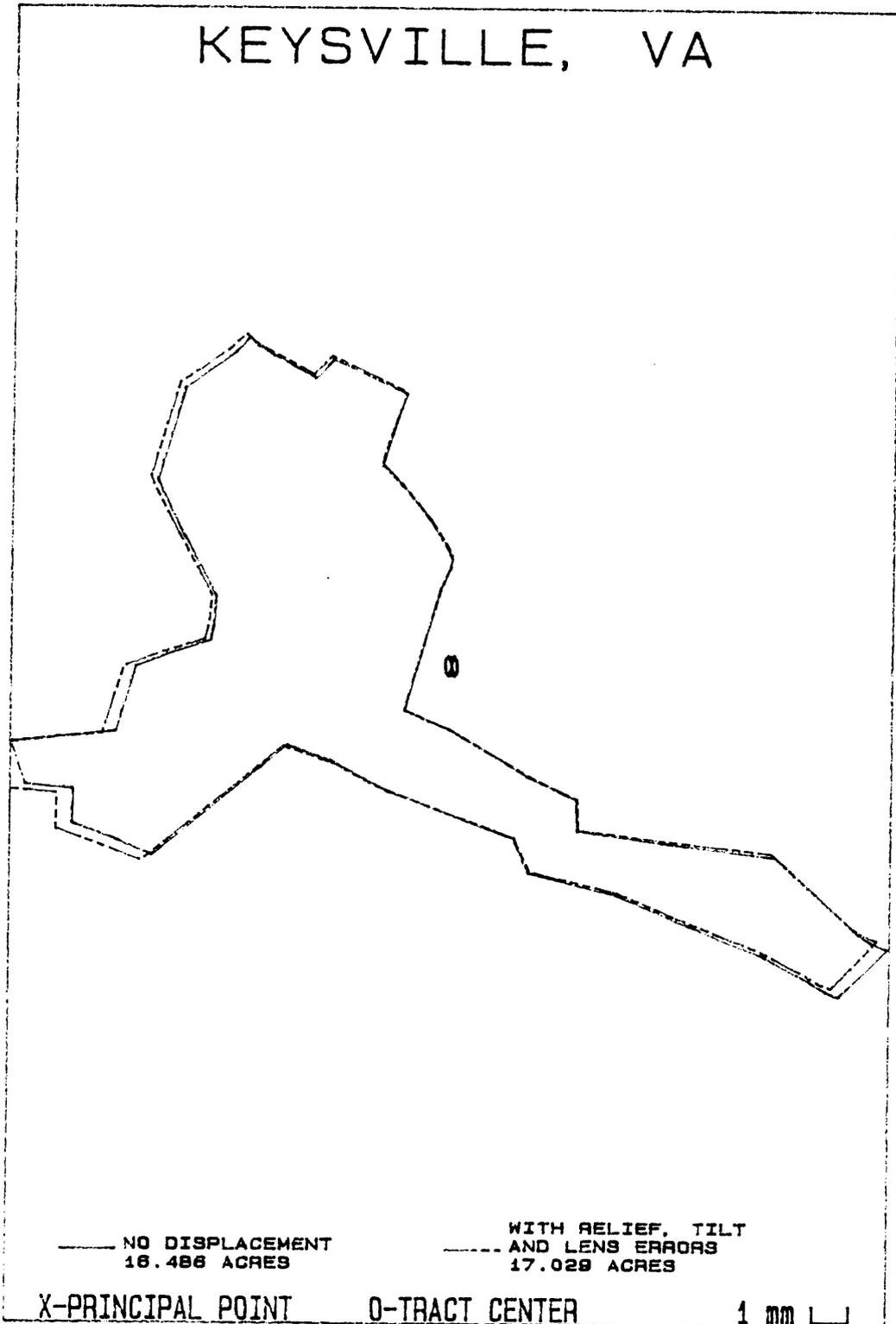


Figure 18. Plot of true Keysville tract overlain with photograph at 4000ft, 50mm, and 6 degree tilt east, with lens distortion.

absolute error than Franklin with an elevation difference of 19 feet. In the four sample tracts the largest error was -0.346%. The individual point relief errors can either be compensating, or additive. Crewe West and Franklin tracts are two examples of this, respectively. Topographic relief also introduced scale inaccuracies because photographs do not have one scale throughout the format. If it is necessary to compute a scale, a small miscalibration can produce acreage errors greater than relief acreage errors. From the observation of relief error of these four tracts, it was hypothesized that relief errors for acreage estimation are generally small, and would approach zero over the long run. Again, this hypothesis was for centered tracts only. It is unknown how relief errors would affect non-centered tracts.

Tilt errors had the greatest impact on the estimation accuracy. Unlike relief errors, the long run average of tilt error will always be greater than zero when the exposure station is centered over the tract. Because tilt is always occurring, this conclusion suggests a positive bias in acreage estimation exists. This project, however, simulated only one scenario of tilt. It is unknown how tilt effects off-center tracts. In actual applications, tracts are often not well-centered on photos. Additionally, by hand holding the camera, tracts may be centered relative to the principal point, but tilt has a greater feasible range. From the results, tilts less than six degrees are recommended. By limiting tilt to less than six degrees, the average error for these four tracts was limited to less than 1.6 percent, and, the average of the four tracts with 0, 3, and 6 degrees tilt was 0.643 percent.

Lens distortion, on average, caused the photo estimated areas to be underestimated by 0.686 percent. To show the high influence lens distortion error had on the area estimate, the average tract acreage error without lens distortion at zero, three, and six degrees of tilt was +0.643 percent. The same average, only with lens distortion was -0.366 percent. To limit the errors due to lens distortion, calibrating the lens and matching the scale appropriately to utilize the low distortion section of the lens can improve the area estimates. Furthermore, because lens distortion is fixed, the achievable accuracy is dependent on the quality of the lens.

In conclusion, the limiting factors for estimating area of centered tracts from small format camera system in the Piedmont and Coastal Plain regions were camera tilt and lens distortion. Hopefully, one can assume that the lens distortion errors over all 35-mm camera systems would be compensating and average to zero distortion. In this case, the remaining tilt errors of 0.643 percent are the controlling factor. However, only a few lenses are commonly applied by a user, and thus the generalization and conclusion that the properties of 35-mm aerial photography create area errors less than one percent in many cases. For land management applications, such as cover-type mapping and site-prep mapping,  $\pm 1.0\%$  is acceptable. However, any bias in estimation should be considered as unacceptable. First of all, relief displacement is hypothesized to approach zero percent acreage error in the long run. Secondly, tilt always has a positive bias when the tract is centered under the camera. Thus, leveling the camera is important, and rejecting photographs with tilt of six degrees or more is recommended to limit the positive bias. Thirdly, lens distortion can also induce bias. By calibrating the lens, one can take advantage of low distortion sections of the lens. Additionally, the nominal focal length and flying height should not be used to compute photo scale. Therefore, the 35-mm format can easily produce photographic images usable for computing ground acreages within five percent. Furthermore, with control of tilt and calibrated lenses, 35-mm camera systems can produce images within  $\pm 1\%$  of the true tract area. This  $\pm 1\%$  error, however, may not be realized. In this study, the precise photo coordinates were known because they were calculated from the ground coordinates. In the application of the photographs to the area estimation problem, the photo coordinates must be measured in some way. Dot grids, planimeters, and tablet digitizers are commonly used devices, all of which have their own respective errors in addition to the photographic errors. It is the conclusion of this thesis that these other errors of application will contribute an equal or greater amount of error than the errors derived from the photograph of limited tilt and centered tracts.

## **BIBLIOGRAPHY**

- American Society of Photogrammetry. 1980. "Manual of Photogrammetry," (2nd ed). Slama, C. C. editor. American Society of Photogrammetry.
- Brinker, R. C. and P. R. Wolf. 1977. "Elementary Surveying ", (6th ed). Harper & Row, Publishers, Inc. New York. 568p.
- Carson, W. W. 1985. What Is a Near-Vertical Photograph? *Photo Eng Rem Sens.* 51(5): 533-536.
- Clegg, R. H. and J. P. Scherz. 1975. A Comparison of 9-inch, 70-mm, and 35-mm Cameras. *Photo Eng Rem Sens.* 41(12): 1487-1500.
- Clements, H. B., D. E. Ward, and C. W. Adkins. 1983. Measuring Fire Behavior with Photography. *Photo Eng Rem Sens.* 49(2): 213-217.
- Dalman, D. W. 1978. Supplementary Aerial Photography in the Planning and Management of National Parks. 5th Canadian Symposium on Remote Sensing. p 120-124.
- Duncan, N., M. Meyer, and N. Moody. 1984. Remote Sensing Applications in Agriculture and Forestry. University of Minn. IAFHE RSL Research Report 84-4. St. Paul, Minn. 13p.
- Goodrich, D. C. 1982. A Simple 35-mm SLR Photogrammetric System for Glacier Measurements. *Photo Eng Rem Sens.* 48(9): 1477-1485.
- Grumstrup, P. D., M. P. Meyer, R. J. Gustafson, and E. R. Hendrickson. 1980. Aerial Photographic Assessment of Transmission Line Structure Impact on Agriculture Crop Production. University of Minn. IAFHE RSL Research Report 80-3. St. Paul, Minn. 18p.
- Klein, W. H. 1970. Mini-Aerial Photography. *Journal of Forestry.* 68(8): 475-478.
- Mead, R. A. and D. A. Rasberry. 1980. Current Use of Remote Sensing By Foresters in the South. *Southern Journal of Applied Forestry.* 4(3): 143-147.
- Mead, R. A. and P. T. Gammon. 1981. Mapping Wetlands Using Orthophotoquads and 53-mm Aerial Photographs. *Photo Eng Rem Sens.* 47(5): 649-652.

- Meyer, M. P. 1982. Place of Small-Format Aerial Photography In Resource Surveys. *Journal of Forestry*. 80(1): 15-17.
- Meyer, M. P., and P. D. Grumstrup. 1978. Operating Manual for the Montana 35-mm Aerial Photography System. 2nd revision. University of Minn. IAFHE RSL Research Report. 78-1. St.Paul, Minn. 62p.
- Miller, N. L. and M. P. Meyer. 1981. Application of 35mm Color Aerial Photography to Forest Land Change Detection. Proc., Eighth Biennial Workshop on Color Aerial Photography in the Plant Sciences and Related Fields. American Society of Photogrammetry. p 67-72.
- Montgomery, S. B. and P. R. Wolf. 1986. Mensuration System for Small Format, Non-Metric Analytical Photogrammetric Applications. ACSM-ASPRS Annual Convention. Washington D.C. Vol.4 p 127-133.
- Needham, T. D. 1983. *The Accuracy of 35mm Aerial Photography for the Measurement of Plantation Grown Loblolly Pine*. Master of Science Thesis, Dept. of Forestry, Virginia Polytechnic Institute and State University, Blacksburg, Va. 126p.
- Needham, T. D. and J. L. Smith. 1984. Consequences of Enlarging 35-mm Aerial Photography. *Photo Eng Rem Sens*. 50(8): 1143-1144.
- Olson, C. E. Jr. 1983. Detection of Forest Stress With 35mm Color Photographs. Proc., Ninth Biennial Workshop on Color Aerial Photography in the Plant Sciences. American Society of Photogrammetry. p 45-50.
- Roberts, A. and L. Griswold. 1986. Practical Photogrammetry from 35-mm Aerial Photography. *Photo Eng Rem Sens*. 52(4): 501-508.
- Shafer, R. V. and S. A. Degler. 1986. 35-mm Photography: An Inexpensive Remote Sensing Tool. *Photo Eng Rem Sens*. 52(6): 833-837.
- Society of American Foresters. 1984. *Forestry Handbook*, (2nd ed). Wenger, K. F. editor. John Wiley & Sons. New York. 1335p.
- Spencer, R. D. 1978. Map Intensification from Small Format Camera Photography. *Photo Eng Rem Sens*. 44(6):697-707.
- Spurr, S. H. 1960. *Photogrammetry and Photo- interpretation* , (2nd ed). The Ronald Press Company, New York. 472p.
- Weih, R., G. Nord, and M. Meyer. 1984. Application of 35mm Aerial Photography to Evaluate Post-Harvest Aspen Regeneration. University of Minn. IAFHE RSL Research Report 84-2. 26p.
- Wolf, P. R. 1983. *Elements of Photogrammetry, with Air Photo Interpretation and Remote Sensing* . (2nd ed). McGraw-Hill, Inc. New York. 628p.
- Wood, E. S. Jr. 1949. Photogrammetry for the Non-Photogrammetrist. *Photo Eng*. 15(2): 249-275.
- Wood, E. S. Jr. 1950. The Use of High Altitude Photography for Mapping and Reconnaissance. *Photo Eng*. 16(4): 613-618.
- Zsilinsky, V. G. 1969. Supplementary Aerial Photography with Miniature Cameras. *Photogrammetria*. 25(1): 27-38.

## Appendix A. MAPPER

```
100 REM THIS PROGRAM READS OUTPUT FROM THE DIGITIZING
110 REM TABLE AND WRITES THE OUTPUT INTO ASCII FILES TO
120 REM BE ANALYZED IN FURTHER MANIPULATIONS.
130 REM PROGRAM WRITTEN AUGUST 11, 1987 BY STEVEN WILES
140 REM WITH ASSISTANCE FROM BRENT KEEFER.
150 DECLARE REAL *8 X,Y,Z
160 DECLARE INTEGER I,N,ANS
170 DIM ST1$*1,ST2$*1,ST$*2,ED$*1,FMT$*50
180 LET ST1$=CHR$(27)
190 LET ST2$=CHR$(37)
200 LET ST$=ST1$&ST2$
210 LET ED$=CHR$(13)
215 LET NAME$=" "
220 FOR I=1 TO 15
230 PRINT
240 NEXT I
250 PRINT TAB(25);"MAPPER IS RUNNING"
260 PRINT TAB(20);"PROGRAM TO SET UP COMMUNICATION"
270 PRINT TAB(20);"BETWEEN TABLE AND PROGRAM"
280 PRINT
290 PRINT
300 PRINT
310 PRINT "HAS TABLE BEEN INITIALIZED"
320 GOSUB 8000
330 IF ANS=0 THEN GOSUB 5000
340 PRINT
350 PRINT
360 PRINT
370 PRINT "PLACE MAP ON TABLE AND COMPLETE ANY TABLE ROTATION AND";
380 PRINT " SCALING."
390 LINPUT PROMPT "PRESS ANY KEY AND RETURN WHEN READY TO DIGITIZE ": TS
400 FOR I=1 TO 15
410 PRINT
420 NEXT I
430 REM
440 INPUT PROMPT "NAME FILE OUTPUT --> ": NAME$
450 OPEN FILE(1,1),NAME$
460 FOR I=1 TO 15
470 PRINT
480 NEXT I
490 PRINT "INSTUCTIONS FOR DIGITIZATION"
```

```

500 PRINT "POINT TO BE DIGITIZED IS WRITTEN ON DISPLAY."
510 PRINT "FIRST ENTER THE Z VALUE (ELEVATION)"
520 PRINT "SECOND PLACE CURSOR OVER POINT AND PRESS ANY KEY."
530 PRINT
540 PRINT "*** TO SET Z VALUE USE EITHER"
550 PRINT "    -CURSOR, FFFD___E"
560 PRINT "    -MENU, Z DATA FACTOR___CR"
570 PRINT "    IT IS NOT NECESSARY TO BUFFER WITH ZEROS."
580 PRINT
590 PRINT "*** TO FINISH ENTERING DATA USE Z VALUE OF 9999."
600 PRINT
610 PRINT
615 ENABLE HANDLER CLOSE,RESUME AT 800
620 OPEN FILE(2,0),"@TABLE"
630 PRINT FILE(2),ST$;"M";ED$
640 PRINT "POINT          COORDINATES"
650 PRINT "NUMBER      X      Y      Z"
660 LET N=0
670 PRINT FILE(2),ST$;"M DEFINE Z, THEN DIGITIZE #";N;ED$
680 INPUT FILE(2),X,Y,Z
685 IF Z=9999 THEN GOTO 740
690 LET FMT$="%%%%%%%% #,###,### #,###,### #,###"
695 LET N=N+1
700 PRINT USING FMT$:N,X,Y,Z
710 PRINT FILE(1),X;" ";Y;" ";Z
720 GOTO 670
740 CLOSE
750 PRINT
760 PRINT
770 PRINT "PROGRAM ENDED NORMALLY"
780 PRINT "OUTPUT WRITTEN TO FILE --> ";NAME$
790 REM
800 DISABLE HANDLER
850 PRINT
860 PRINT
870 PRINT "DO YOU WANT TO DIGITIZE ANOTHER MAP?"
880 GOSUB 8000
890 IF ANS=1 THEN GOTO 340
900 STOP
901 REM
902 REM
5000 REM THIS SUBROUTINE SETS UP COMMUNICATIONS BETWEEN
5010 REM TABLE DIGITIZER, DATA GENERAL, AND OUTPUT FILE
5020 REM PROGRAM WRITTEN AUGUST 11, 1987 BY STEVE WILES
5030 REM WITH ASSISTANCE FROM BRENT KEEFER.
5040 FOR I=1 TO 15
5050 PRINT
5060 NEXT I
5070 PRINT "    TABLE FORMATTOR AND COMMUNICATIONS SET-UP"
5080 PRINT
5090 PRINT "FORMAT IS SET TO F8.0 FOR X AND Y COORDINATES";
5100 PRINT ", AND F5.0 FOR Z."
5110 PRINT
5120 PRINT "*** LOCATE LOWER LEFT CORNER OF LARGE MENU !!!"
5130 OPEN FILE(2,0),"@TABLE"
5135 PRINT FILE(2),ST$;"D1";ED$

```

```

5140 PRINT FILE(2),ST$;"F XF8.0,N2C,YF8.0,N2C,ZF5.0,N0D";ED$
5150 PRINT FILE(2),ST$;"VL";ED$
5160 CLOSE FILE(2)
5170 FOR I=1 TO 8
5180 PRINT
5190 NEXT I
5200 RETURN
5210 REM
8000 REM SUBROUTINE TO RETURN A YES OR NO ANSWER
8010 REM
8015 LET ANS=3
8020 INPUT PROMPT "ANSWER EITHER Y OR N --> ": ANS$
8030 IF ANS$="Y" THEN LET ANS=1
8035 IF ANS$="y" THEN LET ANS=1
8040 IF ANS$="N" THEN LET ANS=0
8045 IF ANS$="n" THEN LET ANS=0
8050 IF ANS=3 THEN GOTO 8020
8060 RETURN
8070 REM
8500 HANDLER CLOSE
8510 REM CLOSSES ALL FILES INCASE OF ABORT ENDING
8520 PRINT "ABNORMAL ENDING, CHECK DATA TYPE."
8530 PRINT "OUTPUT FILE -->";NAME$;" MAY HAVE DATA."
8540 CLOSE
8550 PRINT "ERROR ON LINE";EXLINE
8560 PRINT "ERROR CODE";EXTYPE
8570 RESUME
8580 REM
9000 END

```

## Appendix B. ACREAGE

```
/* acreage.c */
#include <stdio.h>
#include <stdlib.h>
#include <math.h>

/* Defines clear screen, press key to continue, degree to */
/* radian conversion and cursor position. */
#define CLEAR printf("\x1B[2J")
#define PRESS printf("\x1B[25;10fPRESS ANY KEY");getch()
#define DTOR(deg) ((deg)/57.29578)
#define GO(r,c) printf("\x1B[%d;%df",r,c)

/* External variable; ground and photo coordinates are in */
/* arrays of structures, flite[] are the orientation and */
/* position parameters, and num is the number of coords. */
struct ground {double x; double y; double z;};

struct ground g[300];

int num=0;

/*****/
/* Main Program: */
/* Clears screen, and draw title screen the inputs data */
/* and controls flow of program. */
main()
{
    CLEAR;
    scrn();
    PRESS;
    in();
    while(1)
    {
        CLEAR;
        puts("\n\n\t\tInput coordinates (I)");
        puts("\n\n\t\tCalculate Acreage (C)");
        puts("\n\n\t\tExit program (X)");
        printf("\n\n\t\tSelect one of the options:");
        switch( getch() )
        {
            case 'I': case 'i': in(); break;

```

```

        case 'C': case 'c': area(); break;
        case 'X': case 'x': CLEAR; exit(0);
        default: puts("\nEnter only selections listed"); break;
    }
}
}

/*-----*/
/* in() */
/* Inputs ground coordinates. */
/* Checks for pre-existing data, calls function to load */
/* data and allows verification of input data. */
in()
{
    char ch;
    CLEAR;
    if(num)
    {
        printf("\x1B[10;25\x1B[5m\x1B[7mYOU HAVE DATA ALREADY,");
        printf("\x1B[12;20fLOADING NEW DATA WILL DELETE OLD: \x1B[0m");
        printf("\x1B[25;10fDO YOU WANT TO CONTINUE ?");
        if (!tru()) return;
    }
    if ( loadg() )
    {
        printf("\x1B[25;10fPRESS 'R' TO REVIEW COORDINATES: ");
        ch = getch();
        if( ch == 'r' || ch == 'R')
            pg();
        return;
    }
    else
    {
        printf("\x1B[20;10fNO DATA WAS READ,");
        printf("\x1B[25;10fPRESS <Y> FOR ANOTHER CHANCE <N> TO EXIT PROGRAM");
        if (tru()) in();
        else exit(0);
    }
}

/*-----*/
/* loadg() */
/* Reads ground coordinates from file specified by user */
/* and calculates tract center (center of bounding rect- */
/* angle) and average elevation (simple average of all */
/* elevation). Tract center is stored as point [num] */
loadg()
{
    FILE *fptr;
    char tx[10], ty[10], tz[10];
    char file[40];
    CLEAR;
    num = 0;
    printf("\nInput the name of the ground coordinates file: ");
    gets(file);
}

```

```

if( (fptr = fopen(file,"r")) == NULL)
{
    printf("\nFile %s cannot be opened!", file);
    return(0);
}
fscanf(fptr,"%s %s %s",tx,ty,tz);
g[num].x = atof(tx);
g[num].y = atof(ty);
num ++;
while( (fscanf(fptr,"%s %s %s",tx,ty,tz)) != EOF )
{
    g[num].x = atof(tx);
    g[num].y = atof(ty);
    num ++;
}
fclose(fptr);
return(1);
}

/*-----*/
/* pg() */
/* outputs data to screen one page at a time */

pg()
{
    int i, j, k;
    CLEAR;
    for(i=0; i < num/23; i ++ )
    {
        for(j=0; j < 24; j ++ )
        {
            k=j+(23*i);
            printf("\n%d : %10.1f %10.1f %10.1f",k,g[k]);
        }
        printf("\nPress key for next screen:");
        getch();
    }
    for(j=0; j < fmod(num,23); j ++ )
    {
        k=j+(i*23);
        printf("\n%d : %10.1f %10.1f %10.1f",k,g[k]);
    }
    printf("\nTC: %10.1f %10.1f %10.1f",g[num]);
    getch();
}

/*-----*/
/* area() */
/* Calculates area in photo units (mm square) and converts*/
/* them using the square of scale, where scale is the */
/* focal length divided by flying height above average */
/* terrain elevation. After printing screen function */
/* allows either storing the coordinates to file or */
/* listing to the screen. */

```

```

area()
{
    double sum, acres;
    int i;

    CLEAR;

    sum = g[0].x * (g[num-1].y - g[1].y);
    for(i = 1; i < num-1; i++)
        sum += g[i].x * (g[i-1].y - g[i+1].y);
    sum += g[num-1].x * (g[num-2].y - g[0].y);
    sum /= (sum < 0.0) ? -2 : 2;

    acres = sum/43560;

    GO(21,15);printf("ACRES:%9.3f",acres);
    GO(21,45);printf("POINTS: %-d",num);
    PRESS;
}

/*-----*/
/* tru() */
/* returns either a 0 or 1 */

tru()
{
    switch( getch() )
    {
        case 'y' : return(1);
        case 'Y' : return(1);
        case 'n' : return(0);
        case 'N' : return(0);
        default : return( tru() );
    }
}

/*-----*/
/* scrn() */
/* draws title screen */

scrn()
{
    T(6,5); R(6,10); U(6,15); A(6,20); C(6,25);
    GO(17,5);
    printf("Calculates true ground acreages.");
    GO(20,5);
    printf("Written By: Steven J. Wiles");
    GO(20,45);
    printf("Date: February, 1988");
}

/*-----*/
/* LETTERS() */
/* DRAWS 5x3 LETTERS AT ROW,COLUMN STARTING AT LOWER LEFT OF LETTER */

```

```

A(r,c)
int r,c;
{
    GO((r-4),c); printf("\xC9\xCD\xBB");
    GO((r-3),c); printf("\xBA\xFF\xBA");
    GO((r-2),c); printf("\xCC\xCD\xB9");
    GO((r-1),c); printf("\xBA\xFF\xBA");
    GO(r,c);    printf("\xD0\xFF\xD0");
}
C(r,c)
int r,c;
{
    GO((r-4),c); printf("\xC9\xCD\xB8");
    GO((r-3),c); printf("\xBA\xFF\xFF");
    GO((r-2),c); printf("\xBA\xFF\xFF");
    GO((r-1),c); printf("\xBA\xFF\xFF");
    GO(r,c);    printf("\xC8\xCD\xBE");
}
E(r,c)
int r,c;
{
    GO((r-4),c); printf("\xC9\xCD\xCD");
    GO((r-3),c); printf("\xBA\xFF\xFF");
    GO((r-2),c); printf("\xCC\xCD\xFF");
    GO((r-1),c); printf("\xBA\xFF\xFF");
    GO(r,c);    printf("\xC8\xCD\xCD");
}
G(r,c)
int r,c;
{
    GO((r-4),c); printf("\xC9\xCD\xB8");
    GO((r-3),c); printf("\xBA\xFF\xFF");
    GO((r-2),c); printf("\xBA\xC6\xBB");
    GO((r-1),c); printf("\xBA\xFF\xBA");
    GO(r,c);    printf("\xC8\xCD\xBC");
}
H(r,c)
int r,c;
{
    GO((r-4),c); printf("\xD2\xFF\xD2");
    GO((r-3),c); printf("\xBA\xFF\xBA");
    GO((r-2),c); printf("\xCC\xCD\xB9");
    GO((r-1),c); printf("\xBA\xFF\xBA");
    GO(r,c);    printf("\xD0\xFF\xD0");
}
I(r,c)
int r,c;
{
    GO((r-4),c); printf("\xFF\xD2\xFF");
    GO((r-3),c); printf("\xFF\xBA\xFF");
    GO((r-2),c); printf("\xFF\xBA\xFF");
    GO((r-1),c); printf("\xFF\xBA\xFF");
    GO(r,c);    printf("\xFF\xD0\xFF");
}
L(r,c)
int r,c;

```

```

    {
    GO((r-4),c); printf("\xD2\xFF\xFF");
    GO((r-3),c); printf("\xBA\xFF\xFF");
    GO((r-2),c); printf("\xBA\xFF\xFF");
    GO((r-1),c); printf("\xBA\xFF\xFF");
    GO(r,c);    printf("\xC8\xCD\xCD");
    }
M(r,c)
int r,c;
    {
    GO((r-4),c); printf("\xC9\xCB\xBB");
    GO((r-3),c); printf("\xBA\xBA\xBA");
    GO((r-2),c); printf("\xBA\xD0\xBA");
    GO((r-1),c); printf("\xBA\xFF\xBA");
    GO(r,c);    printf("\xD0\xFF\xD0");
    }
N(r,c)
int r,c;
    {
    GO((r-4),c); printf("\xD6\xBF\xD2");
    GO((r-3),c); printf("\xBA\xB3\xBA");
    GO((r-2),c); printf("\xBA\xB3\xBA");
    GO((r-1),c); printf("\xBA\xB3\xBA");
    GO(r,c);    printf("\xD0\xC0\xBD");
    }
O(r,c)
int r,c;
    {
    GO((r-4),c); printf("\xC9\xCD\xBB");
    GO((r-3),c); printf("\xBA\xFF\xBA");
    GO((r-2),c); printf("\xBA\xFF\xBA");
    GO((r-1),c); printf("\xBA\xFF\xBA");
    GO(r,c); printf("\xC8\xCD\xBC");
    }
P(r,c)
int r, c;
    {
    GO((r-4),c); printf("\xC9\xCD\xBB");
    GO((r-3),c); printf("\xBA\xFF\xBA");
    GO((r-2),c); printf("\xCC\xCD\xBC");
    GO((r-1),c); printf("\xBA");
    GO(r,c);    printf("\xD0");
    }
R(r,c)
int r, c;
    {
    GO((r-4),c); printf("\xC9\xCD\xBB");
    GO((r-3),c); printf("\xBA\xFF\xBA");
    GO((r-2),c); printf("\xCC\xCB\xBC");
    GO((r-1),c); printf("\xBA\xC8\xBB");
    GO(r,c);    printf("\xD0\xFF\xD0");
    }
S(r,c)
int r,c;
    {
    GO((r-4),c); printf("\xC9\xCD\xB8");

```

```

GO((r-3),c); printf("\xBA\xFF\xFF");
GO((r-2),c); printf("\xC8\xCD\xBB");
GO((r-1),c); printf("\xFF\xFF\xBA");
GO(r,c);    printf("\xC6\xCD\xBC");
}
T(r,c)
int r,c;
{
GO((r-4),c); printf("\xCD\xCB\xCD");
GO((r-3),c); printf("\xFF\xBA\xFF");
GO((r-2),c); printf("\xFF\xBA\xFF");
GO((r-1),c); printf("\xFF\xBA\xFF");
GO(r,c); printf("\xFF\xD0\xFF");
}
U(r,c)
int r,c;
{
GO((r-4),c); printf("\xD2\xFF\xD2");
GO((r-3),c); printf("\xBA\xFF\xBA");
GO((r-2),c); printf("\xBA\xFF\xBA");
GO((r-1),c); printf("\xBA\xFF\xBA");
GO(r,c);    printf("\xC8\xCD\xBC");
}

```

## Appendix C. PHOTOSIM

```

/* photosim.c */
/*****/
/*          PHOTOGRAPH SIMULATION          */
/* Program written to calculate photo coordinates from */
/* ground coordinates and to calculate the resultant tract*/
/* acreage from the photographs. Program was developed */
/* January 1988 by Steven J. Wiles for Master of Science */
/* Thesis project to analyze the effects of camera tilt, */
/* lens distortion and topographic displacement. Camera */
/* position and orientation are completely adjustable in */
/* the program. The program runs following the steps */
/* outlined below. */
/*****/
/*          PROGRAM STEPS          */
/* 1. Read in ground coordinates x,y,z into an array of */
/* structures g{x,y,z}. */
/* 2. Read in camera orientation parameters from file */
/* "param.def". This function also allows changes */
/* and calculates position of camera to center the */
/* tract given the desired tilt. Default position */
/* is directly over the center of the tract. */
/* 3. From the ground coordinates and the defined */
/* parameters, photo coordinates are calculated using */
/* collinearity equation. */
/* 
$$x = -f \frac{[M11(Xg - XI) + M12(Yg - YI) + M13(Zg - ZI)]}{[M31(Xg - XI) + M32(Yg - YI) + M33(Zg - ZI)]}$$
 */
/* 
$$y = -f \frac{[M21(Xg - XI) + M22(Yg - YI) + M23(Zg - ZI)]}{[M31(Xg - XI) + M32(Yg - YI) + M33(Zg - ZI)]}$$
 */
/* */
/* 4. From these photo coordinates, tract area is */
/* calculated using standard surveying technics. */
/* Tract acreage is then calculated by converting */
/* photo area mm2 to acres by scale2 where the */
/* scale is the focal length / flying height above */
/* average elevation. */
/* 5. Lens distortion adjustments are radially applied */
/* to the photo coordinates and the acreage is */
/* recalculated. */
/* */
/*****/

```

```

/* Libraries for input/output and higher level math */
#include <stdio.h>
#include <stdlib.h>
#include <math.h>

/* Defines clear screen, press key to continue, degree to */
/* radian conversion and cursor position. */
#define CLEAR printf("\x1B[2J")
#define PRESS printf("\x1B[25;10fPRESS ANY KEY");getch()
#define DTOR(deg) ((deg)/57.29578)
#define GO(r,c) printf("\x1B[%d;%df",r,c)

/* External variable; ground and photo coordinates are in */
/* arrays of structures, flite[] are the orientation and */
/* position parameters, and num is the number of coords. */
struct ground {double x; double y; double z;};
struct photo {double x; double y;};

struct ground g[300];
struct photo p[300];

double flite[8];
int num=0;

/*****/
/* Main Program: */
/* Clears screen, and draw title screen the inputs data */
/* and controls flow of program. */
main()
{
    CLEAR;
    scrn();
    PRESS;
    in();
    while(1)
    {
        CLEAR;
        puts("\n\n\t\tInput coordinates (I)");
        puts("\n\t\t\tRun Simulation (S)");
        puts("\n\t\t\tExit program (X)");
        printf("\n\n\t\tSelect one of the options:");
        switch( getch() )
        {
            case 'I': case 'i': in(); break;
            case 'S': case 's': run(); break;
            case 'X': case 'x': CLEAR; exit(0);
            default: puts("\nEnter only selections listed"); break;
        }
    }
}

/*-----*/
/* in() */
/* Inputs ground coordinates. */
/* Checks for pre-existing data, calls function to load */

```

```

/* data and allows verification of input data.          */
in()
{
char ch;
CLEAR;
if(num)
{
printf("\x1B[10;25f\x1B[5m\x1B[7mYOU HAVE DATA ALREADY,");
printf("\x1B[12;20fLOADING NEW DATA WILL DELETE OLD:\x1B[0m");
printf("\x1B[25;10fDO YOU WANT TO CONTINUE ?");
if (!tru()) return;
}
if ( loadg() )
{
printf("\x1B[25;10fPRESS 'R' TO REVIEW COORDINATES:");
ch=getch();
if( ch == 'r' || ch == 'R')
pg();
return;
}
else
{
printf("\x1B[20;10fNO DATA WAS READ,");
printf("\x1B[25;10fPRESS <Y> FOR ANOTHER CHANCE <N> TO EXIT PROGRAM");
if (tru()) in();
else exit(0);
}
}
}

/*-----*/
/* run() */
/* Calls functions to define parameters, run simulation */
/* and output results to screen and data to file or screen*/

run()
{
int i=0;
if(num < 1)
{
puts("No data entered");
PRESS;
return;
}

define();
sim();
area("No\0");

while(1)
{
CLEAR;
puts("\n\n\t\tChange Parameters (P)");
puts("\n\n\t\tLens Distortion (L)");
puts("\n\n\t\tMain Menu (M)");
printf("\n\n\t\tSelect one of the options:");
switch( getch() )

```

```

    {
    case 'P': case 'p':
        i=0;
        define();
        sim();
        area("No\0");
        break;
    case 'L': case 'l':
        if(i)
        {
            CLEAR;
            printf("\x1B[10;15f\x1B[5m\x1B[7m");
            printf("YOU HAVE ALREADY ADJUSTED FOR LENS DISTORTION\x1B[0m");
            printf("\x1B[25;10fDO YOU WANT TO CONTINUE ?");
            if (!tru()) break;
        }
        lens();
        i + +;
        if (i < 2) area("Yes\0");
        else area("Db\0");
        break;
    case 'M': case 'm': return;
    default : puts("Enter option listed"); PRESS;
    }
}
}

/*-----*/
/* define */
/* Reads camera orientation from file and position form */
/* load() tract center calculation. All parameters are */
/* adjustable and by typing 'c' the tract is centered to */
/* acount for tilt of the camera. */

define()
{
    char temp[10], temp1;
    int change, i;
    double offset;
    FILE *param;

    if( (param = fopen("param.def","rb")) != NULL)
    {
        for(i=0;i < 8;i + +) fread(&flite[i],sizeof(flite[i]),1,param);
        fclose(param);
    }

    flite[5]=g[num].x;
    flite[6]=g[num].y;

    do {
        CLEAR;
        GO(2,15);printf("1. Focal Length : %-6.2f",flite[0]);
        GO(4,15);printf("2. Tilt : %-6.2f",flite[1]);
        GO(6,15);printf("3. Swing : %-6.2f",flite[2]);
        GO(8,15);printf("4. Azimuth : %-6.2f",flite[3]);
    }
}

```

```

GO(10,15);printf("5. Flying Height : %-9.2f",flite[4]);
GO(12,15);printf("6. Exposure X   : %-9.2f",flite[5]);
GO(14,15);printf("7. Exposure Y   : %-9.2f",flite[6]);
GO(16,15);printf("8. Relief Factor : %4.2f",flite[7]);

GO(20,10);
printf("Type parameter to be changed <1-8> or <return> ");
GO(21,10);printf("Type c for tilt auto centering\n\n");
temp1=getch();

if(temp1 > '0' && temp1 < '9')
{
    change = atoi(&temp1);
    GO((change*2),45);
    printf("New => ");
    gets(temp); flite[change-1]=atof(temp);
}
if(temp1 == 'c')
{
    offset = flite[4]*tan( DTOR(flite[1]) );
    flite[5] = g[num].x + offset*sin( DTOR(flite[3] + 180) );
    flite[6] = g[num].y + offset*cos( DTOR(flite[3] + 180) );
}
}
while(temp1 != '\r');

param = fopen("param.def", "wb");
fwrite(flite, sizeof(flite[0]), 8, param);
fclose(param);
}

/*-----*/
/* sim() */
/* Calculates photo coordinates from ground data and */
/* camera orientation and position parameters. */
/* Collinearity equations are from Wolf, P. R. 1983 */
/* Elements of Photogrammetry. */

sim()
{
    int i, out=0;
    double ct, cs, ca, st, ss, sa;
    double m11, m12, m13, m21, m22, m23, m31, m32, m33;
    double ht, xnum, ynum, deno;
    double a, b, c, elev[300];

    CLEAR;
    P(16,25); H(16,30); O(16,35); T(16,40); O(16,45);

    ct=cos( DTOR(flite[1]) );
    cs=cos( DTOR(flite[2]) );
    ca=cos( DTOR(flite[3]) );
    st=sin( DTOR(flite[1]) );
    ss=sin( DTOR(flite[2]) );
    sa=sin( DTOR(flite[3]) );
    m11=-ca*cs-sa*ct*ss;

```

```

m12=sa*cs-ca*ct*ss;
m13=-st*ss;
m21=ca*ss-sa*ct*cs;
m22=-sa*ss-ca*ct*cs;
m23=-st*cs;
m31=-sa*st;
m32=-ca*st;
m33=ct;

for(i=0;i <= num;i++)
    elev[i]=g[i].z*flite[7];
ht=flite[4]+elev[num];

for(i=0;i <= num;i++)
{
    a=g[i].x-flite[5];
    b=g[i].y-flite[6];
    c=elev[i]-ht;
    xnum=m11*a+m12*b+m13*c;
    ynum=m21*a+m22*b+m23*c;
    deno=m31*a+m32*b+m33*c;
    p[i].x=-flite[0]*xnum/deno;
    p[i].y=-flite[0]*ynum/deno;
    if( (p[i].x*p[i].x)+(p[i].y*p[i].y) > 468 ) out++;
}
if(out)
{
    GO(6,23);printf("Results may be incorrect!");
    GO(9,20);printf("%d points were off photograph",out);
    PRESS;
}
}

/*-----*/
/* loadg() */
/* Reads ground coordinates from file specified by user */
/* and calculates tract center (center of bounding rect- */
/* angle) and average elevation (simple average of all */
/* elevation). Tract center is stored as point [num] */

loadg()
{
    FILE *fptr;
    char tx[10], ty[10], tz[10];
    char file[40];
    double maxx, minx, maxy, miny, sumz;
    CLEAR;
    num=0;
    printf("\nInput the name of the ground coordinates file: ");
    gets(file);

    if( (fptr = fopen(file,"r")) == NULL)
    {
        printf("\nFile %s cannot be opened!", file);
        return(0);
    }
}

```

```

fscanf(fp, "%s %s %s", tx, ty, tz);
maxx = minx = g[num].x = atof(tx);
maxy = miny = g[num].y = atof(ty);
sumz = g[num].z = atof(tz);
num ++;
while( (fscanf(fp, "%s %s %s", tx, ty, tz)) != EOF )
{
    g[num].x = atof(tx);
    g[num].y = atof(ty);
    sumz + g[num].z = atof(tz);
    if(g[num].x > maxx) maxx = g[num].x;
    if(g[num].x < minx) minx = g[num].x;
    if(g[num].y > maxy) maxy = g[num].y;
    if(g[num].y < miny) miny = g[num].y;
    num ++;
}
fclose(fp);
g[num].x = (minx + maxx)/2;
g[num].y = (miny + maxy)/2;
g[num].z = sumz/num;
return(1);
}

/*-----*/
/* pg() */
/* outputs data to screen one page at a time */

pg()
{
    int i, j, k;
    CLEAR;
    for(i=0; i < num/23; i++)
    {
        for(j=0; j < 24; j++)
        {
            k = j + (23*i);
            printf("\n%d : %10.1f %10.1f %10.1f", k, g[k]);
        }
        printf("\nPress key for next screen:");
        getch();
    }
    for(j=0; j < fmod(num,23); j++)
    {
        k = j + (i*23);
        printf("\n%d : %10.1f %10.1f %10.1f", k, g[k]);
    }
    printf("\nTC: %10.1f %10.1f %10.1f", g[num]);
    getch();
}

/*-----*/
/* pp() */
/* outputs data to screen one page at a time */

pp()
{

```

```

int i, j, k;
CLEAR;
for(i=0; i < num/23; i++)
{
    for(j=0; j < 24; j++)
    {
        k=j+(23*i);
        printf("\n%d : %10.4f %10.4f",k,p[k]);
    }
    printf("\nPress key for next screen:");
    getch();
}
for(j=0; j < fmod(num,23); j++)
{
    k=j+(i*23);
    printf("\n%d : %10.4f %10.4f",k,p[k]);
}
printf("\nTC: %10.4f %10.4f",p[num]);
getch();
}

/*-----*/
/* odata() */
/* outputs photo coordinates in ASCII format to file */
/* entered at output screen in function area(). */
/* The last point is the tract center and ave elev. */

odata(file)
char file[40];
{
    FILE *out;
    int i;
    CLEAR;
    if(!num)
    {
        puts("\x1B[10;25fNo data to write to file.");
        return;
    }
    if( (out = fopen(file,"w")) == NULL )
    {
        printf("\x1B[10;25fFile %s cannot be opened.",file);
        return;
    }
    for(i=0;i <= num;i++) fprintf(out,"%f %f\n",p[i]);
    fclose(out);
}

/*-----*/
/* area() */
/* Calculates area in photo units (mm square) and converts*/
/* them using the square of scale, where scale is the */
/* focal length divided by flying height above average */
/* terrain elevation. After printing screen function */
/* allows either storing the coordinates to file or */
/* listing to the screen. */

```

```

area(lensd)
char lensd[4];
{
double sum, scale, psr2, acres;
int i;
char ch, name[40];

CLEAR;

sum = p[0].x * (p[num-1].y - p[1].y);
for(i = 1; i < num-1; i++)
    sum += p[i].x * (p[i-1].y - p[i+1].y);
sum += p[num-1].x * (p[num-2].y - p[0].y);
sum /= (sum < 0.0) ? -2 : 2;

scale = flite[0]/flite[4];
psr2 = 1/(scale*scale);
acres = (sum*psr2)/43560;

GO(10,15);printf("TILT:  %6.2f deg",flite[1]);
GO(9,45);printf("HEIGHT: %5.0f ft",flite[4]);
GO(12,15);printf("SWING:  %6.2f deg",flite[2]);
GO(11,45);printf("LENS:   %6.2f mm",flite[0]);
GO(14,15);printf("AZIMUTH:%6.2f deg",flite[3]);
GO(13,45);printf("DIST:   %s",lensd);
GO(15,45);printf("RELIEF: %4.2f",flite[7]);
GO(19,15);printf("MM²:   %7.3f",sum);
GO(19,45);printf("SCALE 1:%-.0f", (304.8/scale));
GO(21,15);printf("ACRES:%9.3f",acres);
GO(21,45);printf("POINTS: %-d",num);
GO(05,15);printf("FILE NAME:");

gets(name);
GO(25,10);printf("PRESS 'F' TO FILE COORDINATES: ");
ch = getch();
if (ch == 'f' || ch == 'F')
    odata(name);
GO(25,10);printf("PRESS 'S' FOR SCREEN LISTING: ");
ch = getch();
if (ch == 's' || ch == 'S')
    pp();
}

/*-----*/
/* tru() */
/* returns either a 0 or 1 */

tru()
{
switch( getch() )
{
case 'y' : return(1);
case 'Y' : return(1);
case 'n' : return(0);
case 'N' : return(0);
default  : return( tru() );
}
}

```

```

    }
}

/*-----*/
/* lens() */
/* calculates and adjusts for lens distortions */

lens()
{
    double r, r3, r5, r7, d;
    int i;

    CLEAR;
    L(16,25); E(16,30); N(16,35); S(16,40);

    for(i=0;i < num;i++)
    {
        r=sqrt( pow(p[i].x,2) + pow(p[i].y,2) );
        r3=pow(r,3);
        r5=pow(r,5);
        r7=pow(r,7);
        d=(r*-5.967984) + (r3*0.0280528) + (r5*0.000194025) + (r7*-7.09349E-07);
        d /= 1000.0;

        p[i].x *= (1 + d/r);
        p[i].y *= (1 + d/r);
    }
}

/*-----*/
/* scrn() */
/* draws title screen */

scrn()
{
    P(6,5); H(6,10); O(6,15); T(6,20); O(6,25);
    G(6,30); R(6,35); A(6,40); P(6,45); H(6,50);
    S(13,5); l(13,10); M(13,15); U(13,20); L(13,25);
    A(13,30); T(13,35); O(13,40); R(13,45);
    camera(11,55);
    GO(17,5);
    printf("Calculates photo coordinates from ground coordinates.");
    GO(18,5);
    printf("Camera position and orientation are adjustable.");
    GO(20,5);
    printf("Written By: Steven J. Wiles");
    GO(20,45);
    printf("Date: January, 1988");
}

/*-----*/
/* LETTERS() */
/* DRAWS 5x3 LETTERS AT ROW,COLUMN STARTING AT LOWER LEFT OF LETTER */

A(r,c)
int r,c;

```

```

    {
    GO((r-4),c); printf("\xC9\xCD\xBB");
    GO((r-3),c); printf("\xBA\xFF\xBA");
    GO((r-2),c); printf("\xCC\xCD\xB9");
    GO((r-1),c); printf("\xBA\xFF\xBA");
    GO(r,c);    printf("\xD0\xFF\xD0");
    }
E(r,c)
int r,c;
    {
    GO((r-4),c); printf("\xC9\xCD\xCD");
    GO((r-3),c); printf("\xBA\xFF\xFF");
    GO((r-2),c); printf("\xCC\xCD\xFF");
    GO((r-1),c); printf("\xBA\xFF\xFF");
    GO(r,c);    printf("\xC8\xCD\xCD");
    }
G(r,c)
int r,c;
    {
    GO((r-4),c); printf("\xC9\xCD\xB8");
    GO((r-3),c); printf("\xBA\xFF\xFF");
    GO((r-2),c); printf("\xBA\xC6\xBB");
    GO((r-1),c); printf("\xBA\xFF\xBA");
    GO(r,c);    printf("\xC8\xCD\xBC");
    }
H(r,c)
int r,c;
    {
    GO((r-4),c); printf("\xD2\xFF\xD2");
    GO((r-3),c); printf("\xBA\xFF\xBA");
    GO((r-2),c); printf("\xCC\xCD\xB9");
    GO((r-1),c); printf("\xBA\xFF\xBA");
    GO(r,c);    printf("\xD0\xFF\xD0");
    }
I(r,c)
int r,c;
    {
    GO((r-4),c); printf("\xFF\xD2\xFF");
    GO((r-3),c); printf("\xFF\xBA\xFF");
    GO((r-2),c); printf("\xFF\xBA\xFF");
    GO((r-1),c); printf("\xFF\xBA\xFF");
    GO(r,c);    printf("\xFF\xD0\xFF");
    }
L(r,c)
int r,c;
    {
    GO((r-4),c); printf("\xD2\xFF\xFF");
    GO((r-3),c); printf("\xBA\xFF\xFF");
    GO((r-2),c); printf("\xBA\xFF\xFF");
    GO((r-1),c); printf("\xBA\xFF\xFF");
    GO(r,c);    printf("\xC8\xCD\xCD");
    }
M(r,c)
int r,c;
    {
    GO((r-4),c); printf("\xC9\xCB\xBB");

```

```

    GO((r-3),c); printf("\xBA\xBA\xBA");
    GO((r-2),c); printf("\xBA\xD0\xBA");
    GO((r-1),c); printf("\xBA\xFF\xBA");
    GO(r,c);    printf("\xD0\xFF\xD0");
}
N(r,c)
int r,c;
{
    GO((r-4),c); printf("\xD6\xBF\xD2");
    GO((r-3),c); printf("\xBA\xB3\xBA");
    GO((r-2),c); printf("\xBA\xB3\xBA");
    GO((r-1),c); printf("\xBA\xB3\xBA");
    GO(r,c);    printf("\xD0\xC0\xBD");
}
O(r,c)
int r,c;
{
    GO((r-4),c); printf("\xC9\xCD\xBB");
    GO((r-3),c); printf("\xBA\xFF\xBA");
    GO((r-2),c); printf("\xBA\xFF\xBA");
    GO((r-1),c); printf("\xBA\xFF\xBA");
    GO(r,c); printf("\xC8\xCD\xBC");
}
P(r,c)
int r, c;
{
    GO((r-4),c); printf("\xC9\xCD\xBB");
    GO((r-3),c); printf("\xBA\xFF\xBA");
    GO((r-2),c); printf("\xCC\xCD\xBC");
    GO((r-1),c); printf("\xBA");
    GO(r,c);    printf("\xD0");
}
R(r,c)
int r, c;
{
    GO((r-4),c); printf("\xC9\xCD\xBB");
    GO((r-3),c); printf("\xBA\xFF\xBA");
    GO((r-2),c); printf("\xCC\xCB\xBC");
    GO((r-1),c); printf("\xBA\xC8\xBB");
    GO(r,c);    printf("\xD0\xFF\xD0");
}
S(r,c)
int r,c;
{
    GO((r-4),c); printf("\xC9\xCD\xB8");
    GO((r-3),c); printf("\xBA\xFF\xFF");
    GO((r-2),c); printf("\xC8\xCD\xBB");
    GO((r-1),c); printf("\xFF\xFF\xBA");
    GO(r,c);    printf("\xC6\xCD\xBC");
}
T(r,c)
int r,c;
{
    GO((r-4),c); printf("\xCD\xCB\xCD");
    GO((r-3),c); printf("\xFF\xBA\xFF");
    GO((r-2),c); printf("\xFF\xBA\xFF");
}

```

```

    GO((r-1),c); printf("\xFF\xBA\xFF");
    GO(r,c); printf("\xFF\xD0\xFF");
}
U(r,c)
int r,c;
{
    GO((r-4),c); printf("\xD2\xFF\xD2");
    GO((r-3),c); printf("\xBA\xFF\xBA");
    GO((r-2),c); printf("\xBA\xFF\xBA");
    GO((r-1),c); printf("\xBA\xFF\xBA");
    GO(r,c); printf("\xC8\xCD\xBC");
}
camera(r,c)
int r,c;
{
    GO((r-4),c);
    printf("\xFF\xFF\xFF\xFF\xD6\xC4\xC4\xC4\xC4\xC4\xB7\xFF\xFF\xFF\xFF");
    GO((r-3),c);
    printf("\xC9\xCD\xCD\xCD\xBC\xFF\xAE\x99\xAF\xFF\xC8\xCD\xCD\xCD\xBB");
    GO((r-2),c);
    printf("\xBA\xB0\xB0\xFF\xFF\xFF\xDE\xDB\xDD\xFF\xFF\xFF\xB0\xB0\xBA");
    GO((r-1),c);
    printf("\xBA\xB0\xB0\xFF\xFF\xFF\xFF\xFF\xFF\xFF\xFF\xFF\xB0\xB0\xBA");
    GO(r,c);
    printf("\xC8\xCD\xCD\xCD\xCD\xCD\xCD\xCD\xCD\xCD\xCD\xCD\xCD\xCD\xBC");
}
}

```

## Appendix D. SLIDE

```
/* slide.c */
/*****
/*
/*   Written by Steven J. Wiles for plotting   */
/*   results of the program PHOTOSIM.       */
/*   March 1988                               */
/* Plot files are created in three steps.    */
/* 1. Border is located and drawn to proper */
/* size to simulate slide.                  */
/* 2. Polygon coordinate file is loaded into */
/* the program. The coordinates are then    */
/* written to the plot file with the correct */
/* pen and line type and adjustment to     */
/* recenter the tract for comparison.      */
/* 3. Keys and Lines are then drawn to identify */
/* the tracts plotted. These can be anywhere */
/* on the paper, the coordinates are photo */
/* coordiantes but can extend beyond the   */
/* photo boundary.                          */
/*                                           */
*****/
#include <stdio.h>
#include <stdlib.h>
#include <math.h>

#define CLEAR printf("\x1B[2J")
#define PRESS printf("\x1B[25;10fPRESS ANY KEY");getch()
#define GO(r,c) printf("\x1B[%d;%df",r,c)

struct photo {double x; double y;};
struct photo p[300];
int num=0, e=3;
FILE *plot;

/*****
/* main() */
/* This is the controlling function of the program */
/* all this function does is call the appropriate */
/* subroutines to open new plot files, load photo */
/* coordinates, draw the tract boundary, and place */
/* labeling and lines on the plot.                */
*****/
```

```

main()
{
while(1)
{
menu();
switch( getch() )
{
case '\r': menu(); break;
case '1': new(); break;
case '2': load(); break;
case '3': draw(); break;
case '4': lable(); break;
case '5': line(); break;
case '9': end(); break;
default: menu(); break;
}
}
}

/*-----*/
/* new() */
/* This subroutine opens plot files, initializes */
/* the plotter, resets P1 & P2, and then draws border */
new()

{
int i;
char file[81];

fclose(plot);

GO(14,30); printf("\xC9");
for(i=0;i<35;i++) printf("\xCD"); printf("\xBB");
GO(15,30); printf("\xBA PLOT FILE:          \xBA");
GO(16,30); printf("\xC8");
for(i=0;i<35;i++) printf("\xCD"); printf("\xBC");
GO(15,42);
gets(file);

if( (plot = fopen(file,"w")) == NULL)
{
GO(15,30);
printf("File %s cannot be opened!", file);
PRESS;
return;
}
fputs("\IN;RO90;IP1301,1568,6605,9524;IW;\n",plot);
fputs("\SC-12,12,-18,18;\n",plot);
bored();
}

/*-----*/
/* end() */
/* closes last plot file and exits program */
end()

```

```

    {
    fclose(plot);
    CLEAR;
    exit(0);
    }

/*-----*/
/* menu() */
/* Displays main menu showing available choices */
menu()
{
    int i;
    CLEAR;
    S(10,5);L(10,12);l(10,19);D(10,26);E(10,33);
    GO(13,5); printf("\xC9");
        for(i=0;i<20;i++) printf("\xCD"); printf("\xBB");
    GO(14,5); printf("\xBA 1 => NEW PLOT FILE \xBA");
    GO(15,5); printf("\xBA 2 => LOAD POLY FILE\xBA");
    GO(16,5); printf("\xBA 3 => DRAW POLYGON \xBA");
    GO(17,5); printf("\xBA 4 => DRAW LABELS \xBA");
    GO(18,5); printf("\xBA 5 => DRAW LINES \xBA");
    GO(19,5); printf("\xBA 9 => EXIT PROGRAM \xBA");
    GO(20,5); printf("\xC8");
        for(i=0;i<20;i++) printf("\xCD"); printf("\xBC");

    GO(13,30); printf("\xC9");
        for(i=0;i<14;i++) printf("\xCD"); printf("\xBB");
    GO(14,30); printf("\xBA SELECT #: \xBA");
    GO(15,30); printf("\xC8");
        for(i=0;i<14;i++) printf("\xCD"); printf("\xBC");
    GO(14,41);
}

/*-----*/
/* load() */
/* loads in the specified photo coordinates */
load()
{
    FILE *in;
    int i;
    char tx[10], ty[10];
    char file[81];

    GO(14,30); printf("\xC9");
        for(i=0;i<30;i++) printf("\xCD"); printf("\xBB");
    GO(15,30); printf("\xBA FILE: \xBA");
    GO(16,30); printf("\xC8");
        for(i=0;i<30;i++) printf("\xCD"); printf("\xBC");
    GO(15,37);
    gets(file);

    num=0;
    if( (in = fopen(file,"r")) == NULL)
    {

```

```

GO(15,30);
printf("File %s cannot be opened!", file);
PRESS;
return;
}
while( (fscanf(in,"%s %s",tx,ty)) != EOF )
{
p[num].x = atof(tx);
p[num].y = atof(ty);
num ++;
}
num--;
fclose(in);
}

/*-----*/
/* draw() */
/* Subroutine to draw the simulated tract photograph */
/* the window is set at the photograph border so that */
/* points off of the photograph are not plotted. */
/* Pen number, line type, and center are available. */
/* The centering option adjusts the tract coordinates */
/* so that the tract center and the photo principal point */
/* coincide. */
draw()
{
double xadj, yadj;
int i;
char pen,lt;

GO(14,30); printf("\xC9");
for(i=0;i<10;i++) printf("\xCD"); printf("\xBB");
GO(15,30); printf("\xBA PEN #: \xBA");
GO(16,30); printf("\xC8");
for(i=0;i<10;i++) printf("\xCD"); printf("\xBC");
GO(15,38);
pen = getche();

GO(15,30); printf("\xC9");
for(i=0;i<10;i++) printf("\xCD"); printf("\xBB");
GO(16,30); printf("\xBA LINE#: \xBA");
GO(17,30); printf("\xC8");
for(i=0;i<10;i++) printf("\xCD"); printf("\xBC");
GO(16,38);
lt = getche();

GO(16,30); printf("\xC9");
for(i=0;i<14;i++) printf("\xCD"); printf("\xBB");
GO(17,30); printf("\xBA CENTERING? \xBA");
GO(18,30); printf("\xC8");
for(i=0;i<14;i++) printf("\xCD"); printf("\xBC");
GO(17,43);

if( tru() )
{
xadj = p[num].x;

```

```

        yadj = p[num].y;
    }
else
{
    xadj = yadj = 0;
}

fputs("IW1301,1568,6605,9524;\n",plot);
fprintf(plot,"SP%c;LT%c;\n",pen,lt);
fprintf(plot,"PU%.3f,%.3f;\n",(p[0].x-xadj),(p[0].y-yadj));
for(i = 1;i < num;i++)
    fprintf(plot,"PD%.3f,%.3f;\n",(p[i].x-xadj),(p[i].y-yadj));
fprintf(plot,"PA%.3f,%.3f;\n",(p[0].x-xadj),(p[0].y-yadj));
fprintf(plot,"SMO;PU%.3f,%.3f;SM;\n",(p[num].x-xadj),(p[num].y-yadj));
fputs("IW;PU-12,-18;SP0;LT;\n",plot);
}

/*-----*/
/* lable() */
/* Pen number and character sizes are input to */
/* allow keying plots of several tract on the */
/* same page. */
lable()
{
    char pen, sh[10], sw[10], string[81], x[10], y[10];
    int i;

    GO(14,30); printf("\xC9");
    for(i=0;i < 20;i++) printf("\xCD"); printf("\xBB");
    GO(15,30); printf("\xBA          \xBA");
    GO(16,30); printf("\xBA          \xBA");
    GO(17,30); printf("\xBA          \xBA");
    GO(18,30); printf("\xBA          \xBA");
    GO(19,30); printf("\xBA          \xBA");
    GO(20,30); printf("\xBA          \xBA");
    GO(21,30); printf("\xBA          \xBA");
    GO(22,30); printf("\xC8");
    for(i=0;i < 20;i++) printf("\xCD"); printf("\xBC");

    GO(15,35);printf("Pen #:");
    pen = getche();
    GO(16,35);printf("Size:");
    GO(17,32); printf("H:"); gets(sh);
    GO(17,42); printf("W:"); gets(sw);
    GO(18,32);printf("Place:");
    GO(19,32); printf("X:"); gets(x);
    GO(19,42); printf("Y:"); gets(y);
    GO(20,35); printf("Label:");
    GO(21,32); gets(string);
    fprintf(plot,"SP%c;SI%s,%s;\n",pen,sw,sh);
    fprintf(plot,"PU%s,%s;LB%s%c;SI;\n",x,y,string,e);
    fputs("PU-12,-18;SP0;\n",plot);
}

/*-----*/
/* line() */

```

```

/* Pen number and line type are input to facilitate */
/* making a key */
line()
{
    char pen, lt, x1[10], y1[10], x2[10], y2[10];
    int i;

    GO(14,30); printf("\xC9");
    for(i=0;i < 20;i++) printf("\xCD"); printf("\xBB");
    GO(15,30); printf("\xBA \xBA");
    GO(16,30); printf("\xBA \xBA");
    GO(17,30); printf("\xBA \xBA");
    GO(18,30); printf("\xBA \xBA");
    GO(19,30); printf("\xBA \xBA");
    GO(20,30); printf("\xC8");
    for(i=0;i < 20;i++) printf("\xCD"); printf("\xBC");

    GO(15,32);printf("Pen #:");
    pen = getche();
    GO(15,41);printf("Line #:");
    lt = getche();
    GO(16,35);printf("From:");
    GO(17,32); printf("X:"); gets(x1);
    GO(17,42); printf("Y:"); gets(y1);
    GO(18,35);printf("To:");
    GO(19,32); printf("X:"); gets(x2);
    GO(19,42); printf("Y:"); gets(y2);
    fprintf(plot,"SP%c;LT%c;PU%s,%s;PD%s,%s;\n",pen,lt,x1,y1,x2,y2);
    fputs("LT;PU-12,-18;SP0;\n",plot);
}

/*-----*/
/* bored() */
/* Subroutine draws photograph border, and adds a 1 mm */
/* scale and identifies the X and O as the principal point */
/* and the tract center. */
bored()
{
    int i;
    char pen;

    GO(15,30); printf("\xC9");
    for(i=0;i < 17;i++) printf("\xCD"); printf("\xBB");
    GO(16,30); printf("\xBA BORDER PEN #: \xBA");
    GO(17,30); printf("\xC8");
    for(i=0;i < 17;i++) printf("\xCD"); printf("\xBC");
    GO(16,45);
    pen = getche();

    fprintf(plot,"SP%c;",pen);
    fputs("PA-12,-18;ER24,36;\n",plot);
    fputs("SMX;PA0,0;SM;SI0.15,0.3;\n",plot);
    fprintf(plot,"PU-11,-17.9;LB%s%c;\n","X-PRINCIPAL POINT",e);
    fprintf(plot,"PU-2,-17.9;LB%s%c;\n","O-TRACT CENTER",e);
    fprintf(plot,"PU8,-17.9;LB1 mm%c;\n",e);
    fputs("PU10,-17.5;PD10,-17.9,11,-17.9,11,-17.5;\n",plot);
}

```

```

    fputs("PU-12,-18;SI;SP0;\n",plot);
}

/*-----*/
/* tru() */
/* return 0 for false and 1 for true */
tru()
{
    switch( getche() )
    {
        case 'y': case 'Y': return(1);
        case 'n': case 'N': return(0);
        default : return( tru() );
    }
}

/*-----*/
/* LETTERS() */
/* DRAWS 5x5 LETTERS AT ROW,COLUMN STARTING AT LOWER LEFT OF LETTER */

D(r,c)
int r,c;
{
    GO((r-4),c); printf("\xD6\xC4\xC4\xC4\xBF");
    GO((r-3),c); printf("\xBA\xFF\xFF\xFF\xB3");
    GO((r-2),c); printf("\xBA\xFF\xFF\xFF\xB3");
    GO((r-1),c); printf("\xBA\xFF\xFF\xFF\xB3");
    GO(r,c);    printf("\xD3\xC4\xC4\xC4\xD9");
}

E(r,c)
int r,c;
{
    GO((r-4),c); printf("\xD6\xC4\xC4\xC4\xC4");
    GO((r-3),c); printf("\xBA");
    GO((r-2),c); printf("\xC7\xC4\xC4\xC4");
    GO((r-1),c); printf("\xBA");
    GO(r,c);    printf("\xD3\xC4\xC4\xC4\xC4");
}

I(r,c)
int r,c;
{
    GO((r-4),c); printf("\xFF\xFF\xD2");
    GO((r-3),c); printf("\xFF\xFF\xBA");
    GO((r-2),c); printf("\xFF\xFF\xBA");
    GO((r-1),c); printf("\xFF\xFF\xBA");
    GO(r,c);    printf("\xFF\xFF\xD0");
}

L(r,c)
int r,c;
{
    GO((r-4),c); printf("\xD2");
    GO((r-3),c); printf("\xBA");
    GO((r-2),c); printf("\xBA");
    GO((r-1),c); printf("\xBA");
    GO(r,c);    printf("\xD3\xC4\xC4\xC4\xC4");
}

```

```
S(r,c)
int r,c;
{
    GO((r-4),c); printf("\xD6\xC4\xC4\xC4");
    GO((r-3),c); printf("\xBA");
    GO((r-2),c); printf("\xD3\xC4\xC4\xC4\xB7");
    GO((r-1),c); printf("\xFF\xFF\xFF\xFF\xBA");
    GO(r,c);    printf("\xC4\xC4\xC4\xC4\xBD");
}
```

**The vita has been removed from  
the scanned document**