Accuracy of Population Estimation from Medium-Scale Aerial Photography*

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ABSTRACT: The population of Athens, Georgia, was estimated using the dwelling unit count method from 1:12,000-scale black-and-white aerial photographs with the aid of an Old Delft Scanning Stereoscope. Before this was done, land-use and land-cover mapping was carried out by photointerpretation and field checks in order to identify residential structures and to establish a photointerpretation key of dwelling types. It was found that three dwelling types, namely, single-family dwellings, multiple-family dwellings, and group homes, could be distinguished. The number of dwelling units in each type was estimated from the aerial photographs. The study area was divided into 93 traffic zones by the Athens Clarke County Planning Commission, of which 74 could be aggregated into ten complete census tracts. Housing block data from the 1980 census were obtained for comparison with the photo count. In addition, population census data projected to the date of photography were employed as a standard for comparison. It was found that the dwelling unit count errors fluctuated widely from zone to zone, but the aggregated total for the entire study area gave relative error of only −9.2 percent. For the population estimation, family size factors of 2, 3, and 4 were employed for multi-unit dwellings, small single-family dwellings, and large single-family dwellings, respectively. This gave rise to an overall relative error of −1.7 percent. This relative error was +0.92 percent when the ten larger census tracts were used. Further investigations on the effects of population densities, percentages of multi-unit dwellings, and areal sizes of traffic zones were conducted. It was found that the accuracy of dwelling unit count was slightly affected by population density, traffic zone area, and the percentage of multi-unit structures. However, the relative errors of the dwelling unit count and the population estimation were not correlated. Other factors, notably the nature of the photographic data, the skill of the photointerpreter, and the family size factors, have an important impact on the accuracy of the estimates. It was concluded that the approach presented a realistic appraisal of the population estimation methodology as applied to a complete city.

INTRODUCTION

THE USE OF AERIAL PHOTOGRAPHY for population estimation has been applied to specific regions in both developing and developed countries for a variety of purposes. In the developing countries, population census data are not regularly available and aerial photography may provide the most speedy and economical means to obtain up-to-date population statistics of a specific region, as demonstrated by the works of Allan and Alemayehu (1975) for Ethiopia and Olorunfemi (1984) for Nigeria. Therefore, despite the uncertain accuracy of the resultant data, these are usually accepted for lack of an alternative source. For the developed countries were decennial census and sample surveys are regularly carried out, the use of aerial photography for population estimation has been largely exploratory and has tended to focus on the speed, accuracy, and completeness of the approach *vis-a-vis* the more conventional census method, as exemplified by the works of Collins and El-Beik (1971) for the city of Leeds in England; Green (1957) for the city of Birmingham, Alabama; Hsu (1971) for the city of Atlanta; Clayton and Estes (1980) for the Goleta Valley of the Santa Barbara Standard Metropolitan Statistical Area; and Watkins and Morrow-Jones (1985) for the city of Boulder, Colorado. The population data so obtained have been normally regarded as valuable supplements to or independent checks on the decennial census data, and the technique has been deemed appropriate, especially when used in conjunction with conventional census data for purposes such as data updating in a small region.

In all of the applications mentioned above, the dwelling count method has been used. This method, which requires counting the number of dwelling units from the aerial photographs followed by an estimation of the number of persons occupying each dwelling unit, provides an excellent basis on which population can be estimated. Thus, the following

*Based on a paper presented at the 1986 ACSM-ASPRS Annual Convention, Washington, D.C.

PHOTOGRAMMETRIC ENGINEERING AND REMOTE SENSING,
Vol. 52, No. 12, December 1986, pp. 1859–1869.

0099-1112/86/5212-1859$02.25/0

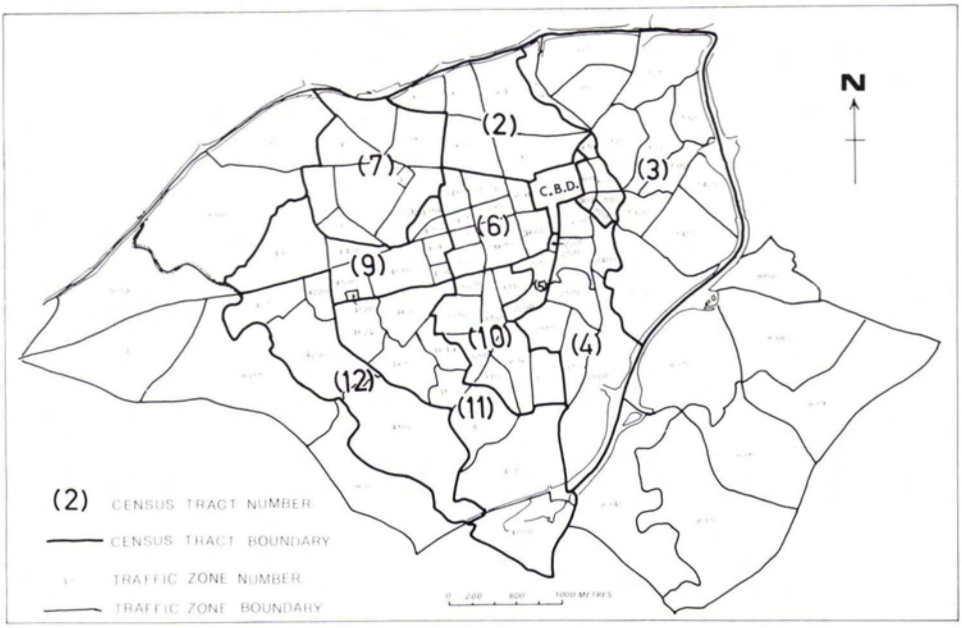

FIG. 1. Census tract and traffic zone map of Athens, Georgia.

formula can be developed:

$$\text{population size} = (\text{number of dwelling units}) \times (\text{number of persons per dwelling unit}) \quad (1)$$

Aerial photography, ranging in scales from 1:5,000 to 1:20,000, has been employed in various applications for the dwelling unit count. Although both true color and color infrared aerial photographs have been used (Binsell, 1967; Lindgren, 1971; Clayton and Estes, 1980), many applications made use of black-and-white panchromatic photography (Hsu, 1971; Watkins and Morrow-Jones, 1985), probably because of its more general availability.

A major problem in this method of population estimation is the high degree of variability in the accuracy of the dwelling unit count. The relative errors resulting from the dwelling unit count have been highly variable across studies: −15.7 percent with Binsell (1967), −7 percent with Green (1957), −3.1 percent with Lindgren (1971), and −0.79 percent with Watkins (1984). On the other hand, one can also view this as evidence of improvement resulting from the refinement of the method of dwelling unit count, notably in the enumeration of multi-unit structures from aerial photographs, which appeared to cause most errors in these studies.

It is noteworthy that the population size determined on the basis of a dwelling unit count does not necessarily exhibit the same magnitude of error because another variable, the number of persons per dwelling unit, is also involved. In the study by Collins and El-Beik (1971), the overall population estimate for the city of Leeds, England from aerial photographs was found to be in error by only 2 percent despite a dwelling type identification error of about 10 percent.

Finally, this method of population estimation has been found to be tedious and time-consuming, especially when applied over a large area. Most studies have, therefore, confined their focus to smaller areas within cities.

In this paper, an application of the dwelling count method of population estimation to Athens, Georgia—a university town with a 1980 population of 42,529 in the city area—was attempted. The study area covers the ten census tracts of the complete city and two outlying suburban areas to its southeast and southwest (Figure 1). The objectives are

- to evaluate the various factors which effect the accuracy of the final population estimation, and
- to demonstrate a simplified yet accurate approach in implementing the dwelling unit count method of population estimation over a large area.

METHODOLOGY

Black-and-white aerial photography obtained at a nominal scale of 1:12,000 on 6 January 1983 for the city of Athens was employed in this investigation (Figures 2 and 3). This photography is of excellent quality, and the scale permitted detailed identification of building features when examined under the 4.5 times magnification of an Old Delft Scanning Stereoscope. The latter is an ideal instrument for population estimation because of its scanning and differential x- and y-parallax eliminating capabilities. A lower 1.5 times magnification viewing is also

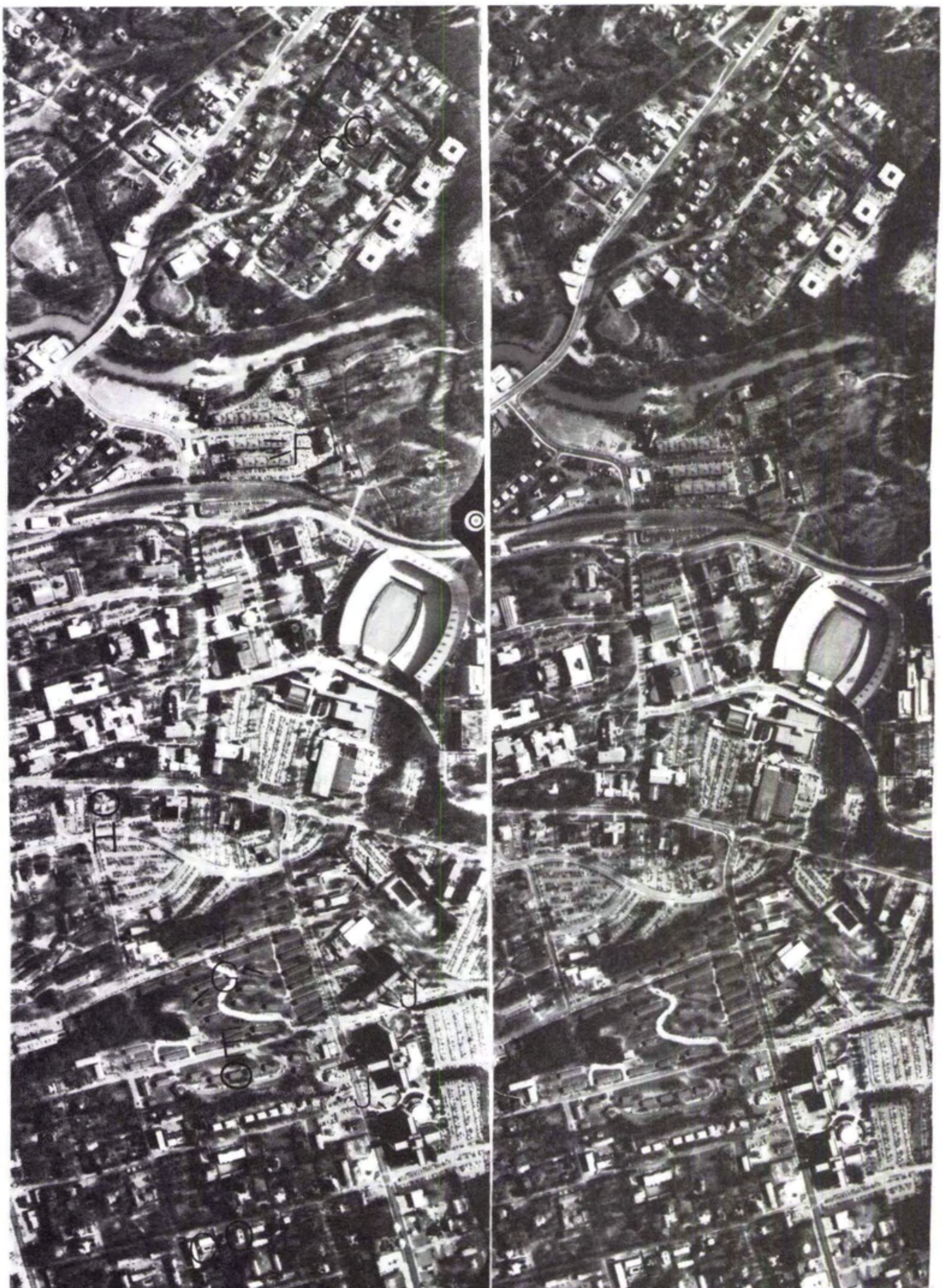

FIG. 2. Stereogram of the Central Region of the University of Georgia campus area. Sanford Stadium is clearly visible. University dormitories, public housing, and private apartments are found around the campus. This stereogram covers traffic zones 1300, 1500, 0800, 2210, 2220, 2300, 2400, 2510, 3600, and 3610 (see Figure 1).

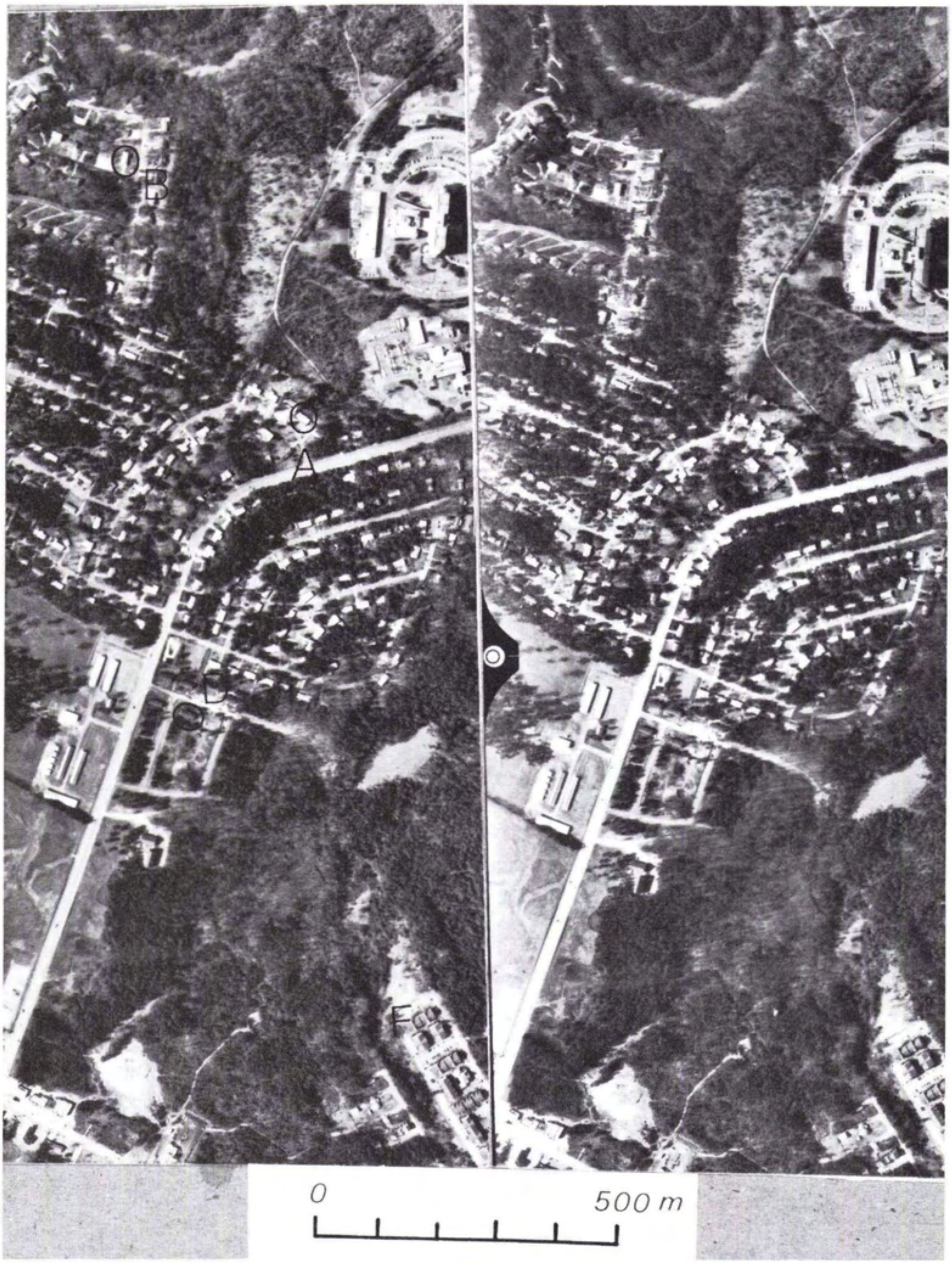

FIG. 3. Stereogram of a private housing district in East Athens, Georgia. It covers traffic zones 8350 and 8360 (see Figure 1).

provided, thus permitting larger portions of the whole study zone to be examined. Altogether, 46 photographs covered the study area.

Before beginning the population estimation, a land-use and land-cover map was prepared by interpreting the aerial photographs and conducting field checks. The USGS land-use and land-cover classification system developed by Anderson *et al*. (1976) was adopted for mapping at Level II. This exercise permitted the photointerpreter to get acquainted with the different building types in the city. The land use or land cover was delineated directly on the aerial photographs with color grease pencils so that residential uses at the time of population estimation were revealed. The area was dominated by the University of Georgia campus and a small Central Business District immediately adjoining it to its north. Surrounding them is predominantly residential use, which has spread out most notably to the west and the east of the city.

From observations in the field, the residential structures in Athens were classified into three types: (1) single-family dwellings, (2) multiple-family dwellings, and (3) group homes. Single-family dwellings typically contained relatively large wooded lots and were mostly suburban. The style of the houses tended to vary. Brick ranches, split levels, Cape Cods, and contemporaries were the more common styles found. The structures also varied in size. Multiple-family dwellings referred to those structures with more than one family unit, and included private apartment blocks and public housing blocks. Group homes referred to student dormitories and sorority or fraternity houses. The dormitories are provided by the University of Georgia for the purpose of student residence and are mostly high-rise buildings of modern style. The sorority and fraternity houses are usually old-style houses of various sizes which tend to concentrate along a single avenue. Hotels and motels are excluded from the study because they are commercial in nature and the residents are transient. All these different types of residential building structures are distinct in style, and a photointerpretation key (Table 1) can be easily prepared to help in their identification.

In population estimation, these residential structures must not only be identified, but the number of dwelling units they contain must also be enumerated. The enumeration of housing units in multiple-family dwellings and group homes from aerial photographs is difficult, and a method was developed to help overcome this problem. For the modern high-rise dormitories, it was possible to measure the length of the structure with the aid of a measuring magnifier. This measurement was then correlated with the actual number of dwelling units of the structure counted in the field or collected from the University's housing department. The number of dwelling units per millimetre length of the structure was computed. The number of stories for each structure was obtained from stereoscopic observation of the aerial photographs, either by measuring with a parallax bar or by comparing to neighboring buildings of a known number of stories. The dwelling unit factor derived in this approach can be applied to other similarly styled high-rise structures. For high-rise structures of different styles, a new set of dwelling unit factors had to be developed. The greatest difficulty was experienced in estimating the number of dwelling units within irregularly styled fraternity and sorority houses. In such cases, both the lengths and widths of the structures had to be measured. However, a measurement of the sizes of these houses from aerial photographs often allowed a good estimate of the number of dwelling units to be made.

Apartment buildings and public housing could be easily identified by their regularly laid out blocks. Where a large complex of apartment buildings occurred, a swimming pool was usually found in its center. The estimation of the number of dwelling units in these blocks of apartment buildings and public housing was based on a measurement, made from stereoscopic observation of the aerial photographs, of the length of the block and the number of stories. In addition, the number of walkways or driveways, the number of air vents, and the style of roof were used to aid in the estimation. These types were the predominant multi-unit housing structures in Athens, but, because of the lack of uniformity in the size of a dwelling unit inside different types of apartment buildings, the correct number of dwelling units was difficult to obtain from aerial photographs.

The single-dwelling units were visually classified into a large or small category from the stereopair of aerial photographs. A rough guiding rule was to use 140 m^2 (1,500 ft^2) as the upper limit for the small dwellings. This classification facilitated the determination of the population factor per dwelling unit in the computation of the population estimates in a later stage.

The dwelling unit count was carried out by marking each identifiable dwelling unit under stereoscopic observation on a transparent Mylar sheet registered on top of the aerial photograph. The enumeration was conducted by traffic zones delineated by the Athens Clarke County Planning Commission. Each traffic zone consisted of a minimum of one to a maximum of 19 census housing blocks. The population size in each block varied considerably from zero to over 200. There were, in total, 93 traffic zones covering the study area (Figure 1), which varied in area from 3.59 ha (8.88 acres) to 275.98 ha (681.68 acres). Seventy-four of these 93 traffic zones could be aggregated into ten larger census tracts.

Housing unit data by Block Numbering Areas (BNA) were obtained from the 1980 Census of Population and Housing block statistics (Bureau of the Census, 1983a) and were aggregated to the traffic zone level for comparison with the result of the photographic dwelling unit count. Population data for each traffic zone were also obtained from the Athens Clarke County Planning Commission. These data projected the population of Athens from the year 1980 to the year 2000 in five-year intervals. It was, therefore, possible to estimate, based on these figures, the projected population of each traffic zone at the time of aerial photography, i.e., January 1983. This set of population data provided the most representative base for comparison with the population estimates from aerial photographic interpretation.

Finally, in order to estimate the population from the number of dwellings counted for each traffic

TABLE 1. PHOTOINTERPRETATION KEY FOR IDENTIFICATION OF RESIDENTIAL BUILDING TYPES IN THE CITY OF ATHENS, GEORGIA.

Type	Roof Form	Geometric Characteristics	No. of Stories	Remarks
I. Single-family dwellings				
(a) Brick ranch	simple, ridged	rectangular, symmetrical	1	Example A (Fig. 2)
(b) Split-level	simple, ridged	symmetrical	half in 1 and half in 2	Example B (Fig. 2)
(c) Cape Code style	very steep, ridged with large dormer windows	asymmetrical, elaborate	2	Example C (Fig. 1)
(d) Georgian style	simple, ridged, dormer windows	square to rectangular, symmetrical, large	2	Example D (Fig. 2) I(a) to I(d) all have lawns and wooded lots
(3) mobile home	flat	long, narrow, rectangular symmetrical	1	Lawn commonly shared
II. Multiple-family dwellings				
(a) Duplex	simple, ridged	rectangular, symmetrical	1	two sets of air vents; two separate driveways may be visible Example E (Fig. 1)
(b) Apartment houses				
(i) Low-rise	simple, ridged	long, rectangular, symmetrical	1-4	occurs in group with well defined limits; swimming pool may be found; also occur as a single block Example F (Figs. 1 and 2)
(ii) High-rise	flat	square, symmetrical	8 or more	usually a single block
(c) Public housing	simple, ridged	long, rectangular, dark tone	1-2	air vents visible; walkways clear Example G (Fig. 1)
III. Group homes				
(a) Fraternity and sorority houses	elaborate, ridged	asymmetrical and symmetrical	2-4	usually old houses of distinct architectural style Example H (Fig. 1)
(b) Student dormitories				
(i) Low-rise	flat or ridged	long, symmetrical, rectangular	2-4	could be historical houses with Georgian style Example I (Fig. 1)
(ii) High-rise	flat	long, symmetrically balanced layout, central lift shaft visible	8-9	Example J (Fig. 1)

zone using Equation 1, the number of persons per dwelling unit was estimated from the occupancy, utilization, and financial characteristics of housing units collected in the 1980 housing census (Bureau of Census, 1983b). It was found that, for the city of Athens, the median number of persons in owner-occuped housing units was 2.23 and in renter-occupied housing units was 1.81. Outside the city, these became 2.86 and 2.12, respectively. It was further observed that occupied housing units with four or more persons comprised 17 percent of the total occupied housing units in the city and 28.4 percent outside. The following population factors were therefore adopted in the computation: 2 persons for each dwelling unit in apartment blocks and group homes, 3 persons for a small single-family dwelling unit, and 4 persons for a large single-family dwelling unit. This last household size variable was adopted on the assumption that people with a large family size would normally require a bigger house than those with a small family size in Athens.

THE NATURE OF ERRORS IN POPULATION ESTIMATION

In the course of estimating the population of Athens by traffic zones from aerial photographs, errors have occurred in the following processes:

- the photointerpretation of the land use and land cover, particularly in differentiating between residential and non-residential uses;
- the identification of different dwelling types based on a photographic key in areas of residential uses;
- the enumeration of the number of dwelling units for each dwelling type; and
- the computation of the population total using the appropriate population factors.

These factors of observation are usually grouped as *systematic* and *random* (Wolf, 1983; Topping, 1972). Systematic errors tend to follow some regular physical laws and are constant in magnitude. They are cumulative in nature. On the other hand, random errors are generally small and do not follow any physical laws. they tend to compensate each other. In photointerpretation, a feature misidentified with reference to a photographic key would be consistently misidentified, thus giving rise to a systematic error. In addition, the accuracy of photointerpretation relates closely to the interpreter's knowledge of the environment under study (the so-called level of reference). A *personal* error, which is largely systematic, would also occur.

As for the enumeration of the dwelling units and the computation of the population estimate for each traffic zone, the element of random error is very strong. The present study has revealed at least two major causes of random errors in these respects: the extent of tree cover and the occurrence of multi-unit housing structures in the traffic zone studied.

One should note that the evaluation of the accuracy of the dwelling unit count and the estimated population size has to depend on the accuracy of the corresponding census data. The housing unit data employed for comparison in the present study are not particularly ideal because of a time discrepancy between the housing census data (1980) and the aerial photographic data (1983). Also, the housing unit data from the 1980 census did not give the number of group quarters, which include college dormitories as well as sorority and fraternity houses commonly found in a university town. On the other hand, residents in group quarters were enumerated in the 1980 population census.

Finally, dwelling units identified and counted from the aerial photographs are not necessarily occupied. This makes the estimation of accurate population size based on the dwelling unit count method all the more difficult. Fortunately, in Athens the percentage of vacant housing units is small. It was only 0.09 percent or 26 units in 1980, and its impact is, therefore, negligible in this study.

RESULTS

In view of the occurrence of different types of errors mentioned in the previous section, the accuracy evaluation was conducted at three different levels: (1) the differentiation between residential and non-residential uses, (2) the dwelling unit count, and (3) the population estimates as determined by Equation 1.

ACCURACY OF PHOTOGRAPHIC INTERPRETATION

The aerial photographic interpretation was found to be effective in differentiating between residential and non-residential uses. There were seven traffic zones (namely, 0610, 0900, 1320, 2300, 4220, 4520, and 6300) which had no residential structures and, therefore, recorded no population. All seven of these were identified from the aerial photographs but, in addition, two other traffic zones (0500 and 0600) that were located adjacent to the Central Business District were misidentified as having no residential population although one in fact had one dwelling unit and the other had 47 dwelling units. The difficulty arose because the dwelling units were intermixed with the commercial office buildings in zone 0500 and industrial building structures in zone 0600. The Central Business District proper was excluded from this study because it was not a significantly residential district; non-residential structures, notably those for commerce and services, were distinguished by their larger size, ample parking space, and a concentration along major thoroughfares. The land-use interpretation was supplemented by field checks, and a comparison with the 1983 land-use map prepared by the Athens Clarke County Planning Commission was also made. It was, therefore, concluded that an accuracy of 90 percent for the residential land-use identification has been achieved with the aerial photographic interpretation.

ACCURACY OF DWELLING UNIT COUNT

In evaluating the accuracy of the dwelling unit count, the 1980 housing census by blocks had to be used. Great care was exercised to ensure that only the dwelling units as defined by the 1980 housing census were counted. This usually meant an exclusion of group quarters. As expected, the relative errors fluctuated from one traffic zone to another. Those traffic zones dominated by college dormitories and sorority and fraternity houses (namely, 2110, 2210, 2220, 2500, and 2510) were least accurately enumerated with −100 percent error. In these zones, the number of housing units recorded by the 1980 census were small: 18, 15, 3, 1, and 5, respectively, and a slight miscount therefore resulted in the extreme errors. All of these structures could not be recognized from the aerial photographs. Because of a difference between the time of the census and the time of photography, these housing units might have been demolished or converted to residential use. On the whole, dwelling units tended to be underestimated.

Examination of individual traffic zones with poor enumeration results revealed the following factors:

(1) While the photointerpretation key presented in Table 1 effectively identified single-family dwelling

units, omissions invariably occurred in densely wooded areas where the tree cover either completely hid some dwelling units, or where the tone of the foliage was so close to that of the roofs of the dwelling units as to make their identification difficult. Furthermore, the photography, which was taken in winter, indicated the predominance of evergreen coniferous trees (pines) which were rather tall. The shadows cast by the pine foliage consequently introduced problems in counting those housing structures that were affected.

(2) As a university town, Athens has many apartment building or condominium complexes in different size categories aimed specifically at accommodating the needs of students, professors, and retired persons. Although these buildings could be easily distinguished from the aerial photographs, the number of dwelling units inside each of these buildings was difficult to estimate. The method using length and width measurement made directly on the aerial photographs gave only a conservative estimate. It is noteworthy that the photographic measurement was affected by the location of the building in relation to the principal point of the aerial photograph. Relief displacement, which varies radially from the nadir of the photograph, would produce exaggerated building length and width measurements at the edge of the photograph. In addition, building height differences also cause errors in length-width measurements, irrespective of the locations of the buildings in the photograph. Field checks on the number of dwelling units of six apartment blocks and two public housing blocks revealed an average relative error of about −3.5 percent. However, the relative error varied between −18.6 percent and +6.9 percent. This is the multi-unit structure error long recognized by the workers in the field ever since the pioneering work of Green in 1957. Some research has recently been done to improve the technique of enumerating dwelling units within such structures (Watkins, 1984).

(3) The housing unit data obtained from the 1980 census did not, in fact, provide an infallible standard for comparison with the 1983 photo-count data. In a number of cases, the Block Numbering Areas (BNA) were split up into different parts surrounding other BNAs. Some BNAs straddled two or more traffic zones. Clayton and Estes (1980), working on census tract 30.03 in the Santa Barbara, California, Standard Metropolitan Statistical Area, reported an average census error of an overcount of 1.47 units per block, while that of the aerial photography was an undercount of 0.39 units per block. This overcount mostly occurred at the boundary between two blocks.

Excluding the seven traffic zones which had no dwelling units, the mean relative error of the dwelling unit count was −17.4 percent with a standard deviation of ±29.8 percent. The precision of the count was, therefore, not very good. However, the aggregate total of dwelling units for the entire study area exhibited a relative error of −9.2 percent. This was much improved over the mean error recorded for all the traffic zones.

Accuracy of Population Estimation

The accuracy of the population estimation depended on the correct application of the household size factor employed for different types of dwelling units. The classification of single-family dwelling units into large and small was easily carried out by visual observation once the size difference between them was compared. However, care had to be exercised to allow for the elevation differences in topography from one part of the aerial photograph to another because houses on the top of a hill appeared larger than those found in the valley.

The evaluation of the accuracy of the population estimates by traffic zone was better accomplished with the estimated 1983 population data derived from Athens Clarke County Planning Commission Projections than was the case of the dwelling unit count. The relative errors of the population estimates fluctuated less widely than those of the dwelling unit count, and their magnitudes were much smaller. The mean relative error for all 93 traffic zones was +2.3 percent with a standard deviation of ±28.9 percent. While the mean error was lowered considerably compared with that of the dwelling unit count, the precision was similar. The aggregate total population of the entire study area revealed a relative error of −1.74 percent, which is much better than the accuracy of the dwelling unit count.

The accuracy of the total population estimation is also affected by the number of areal units employed. Because the population estimation is largely random in nature, the overestimations in some areal units are compensated by the underestimations in others when a large number of areal units is used, even though the individual errors may be fairly extreme. The final result for the entire study area is, therefore, quite accurate. The present study illustrated the validity of this argument using 93 traffic zones with an average area of 162.97 acres (66 ha).

In order to investigate the effect of spatial aggregation on accuracy, the traffic zones were aggregated into census tracts which were made up of three to 13 traffic zones. The relative errors were then recomputed based on the census tracts (Table 2). Only ten census tracts could be formed from the traffic zones which covered 56 percent of the study area. The range of relative errors varied more narrowly between −10.5 percent and +15.9 percent. When the population of each census tract was added up, it was found that the aerial photographic estimation gave a relative error of only +0.92 percent (Table 2)—a significant improvement over the individual census tract population estimates. It was interesting to note that the mean relative error was +0.90 percent, which is very close to the aggregated population relative error. The standard deviation was ±8.9 percent, thus indicating much higher precision

TABLE 2. ACCURACY OF POPULATION ESTIMATION AT CENSUS TRACT LEVEL

Census Tract (1)	Projected Census Population (2)	Estimated Population (3)	Difference Col(3)-Col(4) (4)	Relative Error (%) $\frac{Col(4)}{Col(2)} \times 100$ (5)
2	2,516	2,640	+124	+4.9
3	5,603	5,380	−223	−4.0
4	3,294	3,367	+73	+2.2
5	4,825	5,246	+421	+8.7
6	3,364	3,701	+337	+10.0
7	3,937	4,561	+624	+15.9
9	4,069	3,640	−429	−10.5
10	3,436	3,346	−90	−2.6
11	4,259	3,968	−291	−6.8
12	2,264	2,064	−200	−8.8
Overall	37,567	37,913	+346	+0.92
Mean				+0.90
Standard Deviation				±8.9

of the estimation at the census tract level than that at the traffic zone level. It appeared, therefore, that with the use of the population estimation technique the census tract was more suitable for use in reporting the population figures than the traffic zone. It should be noted that the mean relative error and its standard deviation would vary according to the scheme of aggregating areal units of the study area.

THE EFFECTS OF AREAL UNITS SIZES, POPULATION DENSITIES, AND MULTI-UNIT DWELLINGS ON ACCURACY

In order to discover the causes of the errors in the dwelling unit count and in the population estimation, the relative errors by traffic zones were correlated with the government census data on areas, population densities, and percentage of multi-unit dwellings of the corresponding traffic zones after merging a number of traffic zones to conform to the census blocks that had been split. All the non-residential traffic zones were dropped. In all, there were data for 79 zones. The Pearson product-moment correlation coefficients were computed (Table 3). The relative errors of the dwelling unit count were found to be correlated inversely with both the population density and with the percentage of multi-unit dwellings but directly with the area of the traffic zones at the 5 percent level of significance (i.e., the lowest acceptable level of significance for correlation coefficients using a t-test). These findings suggested that the relative error of the dwelling unit count was somewhat affected by the area, the population density, and the percentage of multi-unit dwellings of the traffic zone. Because relative errors were employed in the correlation analysis, the negative and positive signs of the correlation coefficients indicated the tendency to undercount and overcount as the values of the independent variables increased. Thus, an increase in the population density and the percentage of multi-unit structures would cause an undercount of dwelling units, whereas an increase in traffic zone area tended to give rise to an overcount of dwelling units.

The population estimation error was not strongly correlated with the population density, the percentage of multi-unit dwellings, and the area of the traffic zone. The strongest correlation (at 9.4 percent of significance) was with the area of the traffic zone, which exhibited a negative relationship. This could be interpreted as a tendency to underestimate the population as the traffic zone area increased. This was obvious from Figure 4, which seemed to suggest a wide fluctuation of relative errors as the size of the traffic zone became smaller. Population densities and percentages of multi-unit dwellings of the traffic zones had no significant effect on the relative error of population estimation. Thus, it is clear that the choice of the family size factor has probably compensated for the errors of the dwelling unit count.

The fact that it has not been possible to establish a stronger relationship between population density and the percentage of multi-unit dwellings on the accuracy of the dwelling unit count seemed to indicate that other factors, notably the nature of the photographic data and the skill of the photointerpreter, must have also played a part.

Finally, the relationship between the relative error of the dwelling unit count and that of the population estimation was also investigated. No significant correlation between them was noted (Table 3).

CONCLUSION

This paper has attempted to investigate the accuracy of population estimation from medium-scale aerial photographs using a dwelling unit count method for Athens, Georgia subdivided by traffic zones. A number of interesting observations can be made:

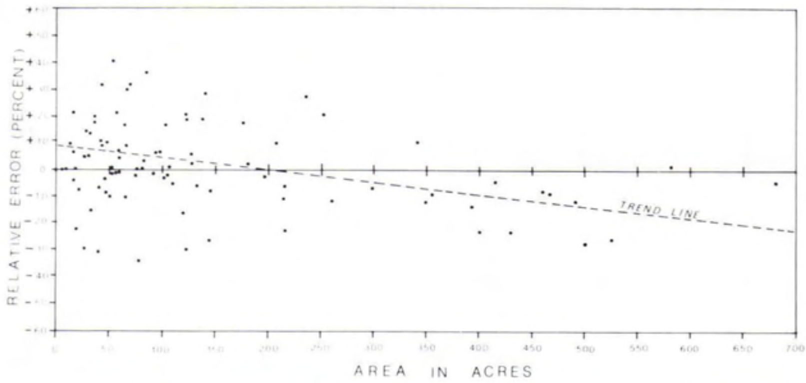

FIG. 4. Relationship between traffic zone area and relative errors of population estimation from aerial photographs.

TABLE 3. EFFECTS OF AREAL UNIT SIZES, POPULATION DENSITIES, AND MULTI-UNIT DWELLINGS ON RELATIVE ERRORS OF DWELLING UNIT COUNT AND POPULATION ESTIMATION

	Pearson Product Moment Correlation Coefficients				
	(1)	(2)	(3)	(4) Relative Error	
	Area	Population Density	Percent Multi-unit Dwellings	Dwelling Unit Count	Population Estimation
(A) Dwelling Unit Count Relative Error	0.3267* (0.3%)	−0.3573* (0.1%)	−0.3565* (0.1%)	- - -	−0.1309 (25.0%)
(B) Population Estimation Relative Error	−0.1896 (9.4%)	0.0114 (92.1%)	0.1190 (29.6%)	−0.1309 (25.0%)	- - -

Note: The percent figures in the brackets indicate the probability level of significance. The minimum probability level acceptance is 5 percent or smaller. Those correlation coefficients marked with an asterisk are statistically significant by this criterion.

- The accuracy of the dwelling unit count is weakly correlated with the building density, the percentage of multi-unit dwellings, and the size of the traffic zone used. Other factors which affect the photographic image, such as the density of tree cover, the tone of the foliage, and the shadow effect, have probably contributed more to the undercounting of dwelling units.
- Both the dwelling unit count and the subsequent population estimation have produced errors which have a random component. These errors can be compensated or reduced if the smaller areal units are aggregated into larger areal units. The present application to Athens resulted in relative errors for the city-wide totals of dwelling units and population of −9.2 percent and −1.7 percent, respectively.
- The accuracy of the dwelling unit count is not significantly correlated with that for the population estimation obtained by applying Equation 1. It is clear that the family size factor selected for each dwelling unit type is a more important influence on the accuracy of the population estimates. This point agrees with and lends statistical support to the findings of Watkins and Morrow-Jones (1985).
- In population estimation, the census tract was found to be an appropriate areal unit for aggregating population. Most of the study area was covered by ten census tracts which gave a resultant relative error of +0.92 percent, a mean relative error of +0.90 percent, and a standard deviation of ±8.9 percent.

From the above observations, it is recommended that the following approach to population estimation using aerial photography be adopted: The dwelling unit count should be carried out using relatively small areal units, and the counts should subsequently be used in the population estimation by applying the appropriate family size factors in Equation 1 for the different types of dwelling units. The estimated populations by the smaller areal units should be aggregated into larger areal units. In this way, the random errors caused by overestimating and underestimating of population because of the dwelling unit miscount can be compensated. The problem of vacant dwelling units may also be taken care of by this spatial aggregation if the number of vacant units within the city is relatively small.

This paper also attempts to demonstrate the validity of a simple approach to population estimation from aerial photographs. A major feature of the approach is the importance of field work, which can initially be achieved with a land-use and land-cover photointerpretation. This helps in the identification of residential districts. The second feature is the classification of the dwelling units into simple groups, and the preparation of a photo-key based on a correlation of photo-image characteristics and ground surveys. The present study revealed the difficulty in estimating the number of dwelling units in apartment buildings, condominiums, and multistoried buildings; therefore, the focus of establishing the appropriate interpretation key should be on enhancing the ability to identify these structures and enumerate the dwelling units within them. The third feature is the use of a unique family size factor, determined from the 1980 housing block statistics, for each category of dwelling units.

The results seemed to bear out the validity of the approach described above. The use of a mirror stereoscope, with scanning capability and two different magnification powers, has considerably facilitated the counting of dwelling units. The use of the Mylar sheet was invaluable for marking results in a permanent record of dwelling units counted, thus permitting the original data to be checked whenever doubts arose.

The present study differs from other similar studies in that the dwelling unit count method of population estimation using medium-scale aerial photography has been applied to a complete city. Thus, it has realistically appraised the operational problems of the method, and has enhanced the evaluation of its accuracy. Within the limitations of the government census and housing data, which had to be employed as "ground truth" data for the present evaluation, the photographic population estimation method has been found to be capable of generating accurate population data at the census tract level.

ACKNOWLEDGMENTS

The assistance provided by Mr. Marc Cunningham, graduate student, Department of Geography, University of Georgia in field survey and the preparation of the photointerpretation key is gratefully acknowledged. The author also wishes to thank the Athens Clark County Planning Commission for supplying the traffic zone maps and population data. The final version of this paper has benefitted greatly from the detailed and constructive criticisms of an anonymous reviewer to whom grateful thanks are also extended.

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(Received 23 August 1985; revised and accepted 12 June 1986)