FRONTISPIECE. Unmagnified high-altitude image of Bremerton, Washington (scale 1:135,000). Original image recorded on false-color-infrared reversal film.

CHARLES E. OGROSKY
University of Washington
Seattle, WA 98195

Population Estimates from Satellite Imagery

A high degree of association between urban area population and four variables representing urban size and relative dominance, as measured on high-altitude satellite imagery, indicated that such imagery may be useful for estimating urban population.

(Abstract on next page)

INTRODUCTION

NUMEROUS examples of the use of conventional aerial photographs in analyzing urban problems have been reported. The purpose of this study was to investigate the suitability of high-altitude satellite imagery for estimation of regional urban population.

CENSUS METHODS

Both field and mail questionnaire enumeration methods are frequently employed to completely survey the population of the United States and its characteristics. Such methods of data collection have been criticized as being overly costly and time consuming, given the accuracy of the resultant data. Use of aerial imagery for collecting certain types of census information has been suggested as a procedure which can successfully supplement existing techniques.[1] Although much of the data presently collected by traditional methods would not be directly obtainable from remotely sensed images,

ABSTRACT: *The suitability of medium ground resolution, high altitude satellite imagery as a data source for intercensal population estimates was evaluated. Four variables representing urban size and relative dominance were measured directly from unmagnified high-altitude, color-infrared transparencies for each of 18 urban test sites in the Puget Sound region. Linear relationships between each variable and the population of the test sites were established, the strongest association being between the logarithm of the area of the site* **(Y), r^2 = 0.964.** *Use of all four independent variables in a multiple linear regression equation resulted in a slight increase in the* **r^2** *value, to* **0.973.** *The high degree of association indicated that relatively low ground resolution images may be useful for certain intercensal estimating purposes. Further research is needed to define additional variables which may be useful for predictive purposes.*

some information is immediately obvious or may be inferred from known relationships to patterns of physical phenomena. One of the best-established uses of aerial photographs in urban area management is for collection of information about population dispersal. Advantages of such uses are—

- *Intercensal Estimates.* Changes in urban population patterns which occur within the existing census cycle can be detected.
- *Wide application.* Although expensive, uniform aerial coverage of large regions has potential applications in numerous disciplines.
- *Permanent Record.* Remote sensing provides a relatively nonselective, permanent recording of physical phenomena and, by inference, of the interrelationships between those phenomena and their total environment.
- *Ease of Access.* Aerial survey is well suited to coverage of remote areas and for data collection where political, social or economic conditions make field enumeration impractical.

EXISTING RESEARCH

Most investigations of aerial imagery as a data source for studies of urban phenomena have used large-scale, conventional black-and-white or color photographs. Hsu,[2] for example, employed images with an average scale of about 1:5000 for derivation of intercensal population estimates of urban areas near Atlanta, Georgia. Holtz *et al*,[3] using aerial photographs, attempted to develop a model for predicting existing and future populations for urban places of 2500 or more persons in the Tennessee River Valley. Five variables were recorded for each test site. The dependent variable, urban population (P_i) of each test site i, was recorded from census records. The four independent variables were recorded from a variety of sources:

L_i - number of surface transport links from test site i to other urban plaes was obtained directly from the large-scale imagery.

P_j - population of the nearest larger urban area j was recorded from census records.

D_{ij} - highway distance from test site i to nearest larger urban area j measured on highway maps.

A_i - urbanized area of test site i obtained from imagery.

The variables were combined using a stepwise linear regression procedure to yield a regression equation of the form:

$$P_i = k \pm b_1L_i \pm b_2P_j \pm b_3D_{ij} \pm b_4A_i$$

where k is a constant and $b_{1..4}$ are the coefficients of each independent variable. Coefficients of determination (r_2) of 0.90 and 0.77 were obtained for each year studied (1953 and 1963). Analysis showed that A_i correlated particularly well with P_i for smaller urban places but that other variables were needed to more accurately estimate populations of larger urban areas.

The results obtained by Holtz *et al.*,[3] Hsu,[2] Lindgren and others[4] indicate that data collection from conventional aerial images may be a viable alternative to ground-based techniques for some estimating purposes. As Wobber[5] suggests, the increasing availability of high-altitude and satellite imagery for non-military purposes makes evaluation of such images as potential data sources appropriate. Use of small-scale satellite imagery, such as from the Earth Resources Technology Satellite *(ERTS)* or from *SKYLAB,* may be desirable for two reasons: it provides a synoptic view of regional patterns and trends and repetitive coverage which has proven useful in analysis of dynamic natural and man-made processes.

Research Objectives

Imagery obtained from very high-flying aircraft such as the *U-2* and from satellite sensor platforms incorporates, in effect, a spatial filter due to sensor system resolution limits. The effect of such filtering is to eliminate spatially high frequency (small) phenomena while passing lower frequency (large) objects. Although larger-scale, high-ground-resolution images may be available, use of spatially 'filtered' records may be beneficial. Such use requires concentration on synoptic, or neighborhood-regional, elements and may enhance gross urban structure which might otherwise be masked by a wealth of high-frequency detail. Thus, on most available small-scale civilian imagery, individual structures are not readily discernible and conventional approaches to urban population estimation, such as individual house counts or structural density evaluation, are inappropriate. However, residential, industrial and commercial areas are visible in gross form. This study is an effort to determine whether the physical phenomena recorded in relatively low ground-resolution images can be successfully related to variations in urban population.

Data Acquisition

Recent census data[6] was reviewed and 18 incorporated urban places in the Puget Sound Basin (Figure 1) were selected for analysis. The test sites represent the most intensely populated portions of the region, including suburban communities on the urban-rural fringe. High-altitude color-infrared transparencies (9 by 9 inches) at a scale of 1:135,000 (Frontispiece) were the primary data source.[7] To simulate use of medium-ground resolution satellite imagery, such as from the *SKYLAB* missions, test sites were limited to urban places of 10,000 or more persons and no magnification of the high-altitude images was used during data collection.

The four independent variables measured by Holtz *et al.*[3] were retained for this study, but were modified to make them more consistent with the theories of urban settlement dispersal and to make it possible to obtain all data directly from the imagery rather than from a variety of sources. The data, derived from the transparencies, are listed in Table 1.

- *Urban Area.* (A_i) Gross urban form was recorded for each test site by tracing the boundaries of residential, commercial and industrial areas on an overlay. Allowance was made for major parks, water bodies and undeveloped military reservations in urban areas. The outlined area was measured with a polar planimeter and the data converted to square miles.
- *Surface Links.* (L_i) Rather than simply recording the total number of highway and rail links leading from each urban test site, differentiation by link significance was incorporated by assigning arbitrary values of 4 to multiple lane highways, 2 to secondary roads and 1 to railroads. The information was obtained directly from the images.
- *Urban Area of Nearest Larger Neighborhood (NLN).* (A_j) To restrict data collection to aerial images, the population of the nearest larger neighborhood variable (P_j) used by Holtz *et al.*[3] was changed to area. The area in square miles was recorded as for 'Urban Area' above. However, high altitude imagery for Vancouver, British Columbia and for San Francisco, nearest larger neighboring urban areas for Bellingham and Seattle, was not available and other documents were used to obtain the area of these cities.
- *Highway Distance to Nearest Larger Neighbor.* (D_{ij}) The distance, in miles, from each test site to its nearest larger urban neighbor was measured directly from the imagery. Ferry routes were used when appropriate.

Data Analysis

The four independent variables (X) were first plotted singly against the dependent

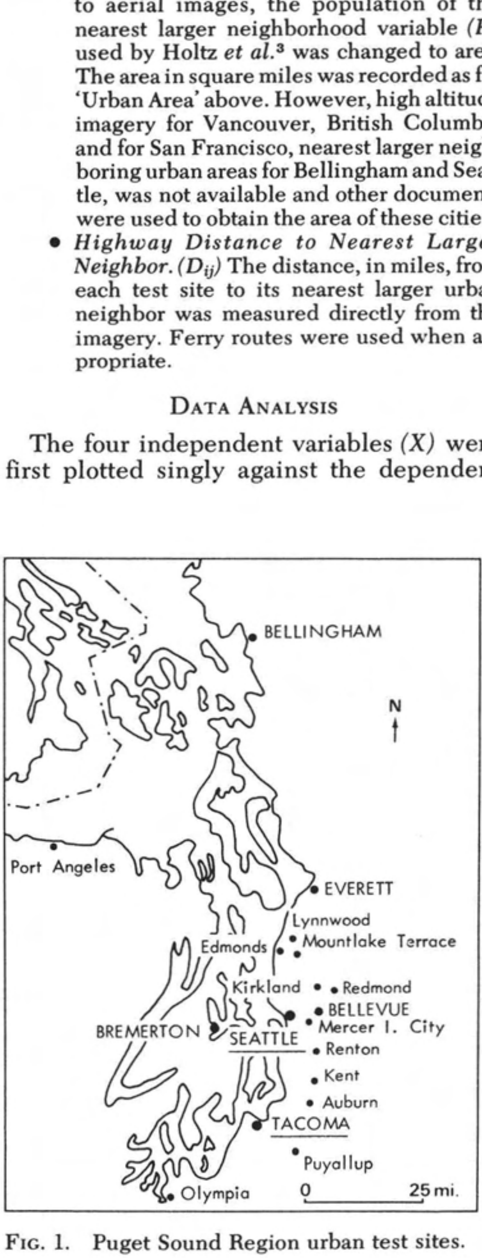

Fig. 1. Puget Sound Region urban test sites.

TABLE 1. Y DATA FROM BUREAU OF CENSUS REPORTS. X DATA COLLECTED FROM HIGH-ALTITUDE AERIAL IMAGERY

Test Site	Population (1000's)	Area (mi^2)	Links	N.L.N. Area (mi^2)	Distance to N.L.N. (mi^2)
Seattle	531	95.11	44	109.27	827
Tacoma	155	26.92	24	95.11	31
Bellevue	61	13.71	19	95.11	11
Everett	54	11.71	14	95.11	29
Bellingham	39	10.12	16	79.05	53
Bremerton	35	6.40	11	95.11	15
Renton	25	5.76	15	95.11	13
Edmonds	24	4.13	10	95.11	14
Olympia	23	5.17	15	26.92	28
Auburn	22	5.03	12	26.92	10
Kent	21	4.13	13	5.93	6
Mercer I. City	19	3.99	6	13.71	7
Lynnwood	17	3.63	5	4.13	4
Mountlake Terrace	17	3.54	8	4.13	5
Port Angeles	16	3.13	7	6.40	76
Kirkland	15	1.95	6	13.71	4
Puyallup	15	2.36	8	36.92	9
Redmond	11	2.04	7	1.95	4

population data *(Y)*; the results are portrayed graphically in Figures 2 through 5. Linear relationships of varying strengths between all independent variables and urban population (P_i) are shown by regression lines and the coefficients of correlation *(r)* are indicated. Three of the variables (P_i, A_i and D_{ij}) showed the best linear relationships when logarithmic transformations were employed. The correlation matrix (Table 2) shows the high degree of association between several of the variables on the basis of simple linear regression. Although $log\ A_i$ and L_i each correlated highly with $log\ P_i$ (r^2 of 0.964 and 0.897), there were high degrees of association between independent variables as well. For example, $log\ A_i$ and L_i showed an r^2 value of 0.874.

The dependent variable, $log\ P_i$, and all four independent variables were analyzed using the Biomedical Computer Programs *(BIOMED)* series multiple linear regression program *02R*. The stepwise procedure adds independent variables to the regression equation until all data classes with an *F* value of more than 0.01 have been used. In this study, all four variables were added, yielding the regression equation:

$$log\ P_i = 0.6896 log\ A_i + 0.0106 L_i + 0.0004 A_j + 0.0143 log\ D_{ij} + 0.7724$$

where 0.7724 is a constant analagous to '*a*' (*Y* intercept) in the two-dimensional linear-regression equation $Y = a + bX$.

A positive association exists between all of the independent data categories and $log\ P_i$. Although the coefficient of determination (0.973) is slightly higher than that obtained by Holtz *et al.*[3] for either year of their study (0.902 and 0.774), the same general relations prevailed. By far the best single estimator of urban population which was visible on high altitude imagery was $log\ A_i$. Because of their non-orthogonality, addition of the other in-

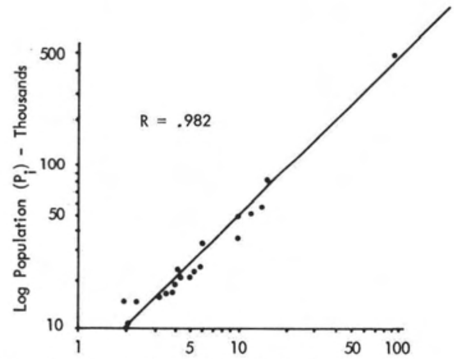

FIG. 2. Area (Log A_i) plotted against population (Log P_i).

TABLE 2. CORRELATION MATRIX

Variable	Log P_i	Log A_i	L_i	A_j	Log D_{ij}
Log P_i	1.000				
log A_i	0.982	1.000			
L_i	0.948	0.935	1.000		
A_j	0.739	0.742	0.651	1.000	
log D_{ij}	0.729	0.713	0.743	0.540	1.000

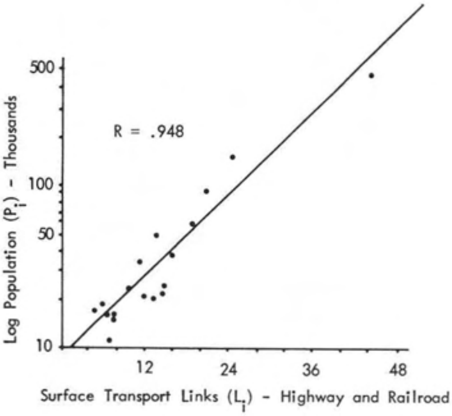

FIG. 3. Surface transport links (L_i) plotted against population (Log P_i).

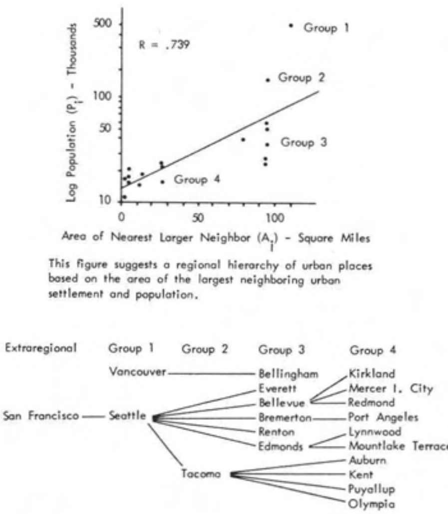

FIG. 4. Area of nearest larger neighbor (A_j) plotted against population (Log P_i).

dependent variables, which were based on more theoretical constructs about the hierarchical dispersion and connection of urban places, resulted in an increase of r^2 of less than 0.01 (Table 3).

CONCLUSIONS

The high degree of linear association between Puget Sound region population and four independent variables, most notably urban area, measured directly from unmagnified high-altitude imagery (scale 1:135,000) indicated that satellite imagery of approximately the ground resolution obtained on *SKYLAB* missions could be a useful indicator of regional urban structure. By objective definition and measurement of independent variables, investigators may be able to obtain reasonably accurate population estimates for politically, physically or economically inaccessible areas at reasonable cost. Assuming that wider availability of high-quality civilian satellite imagery is probable, further work should be done on defining other variables which may show even stronger associations with urban structure and from which other relationships may be inferred. In particular, relationships of the nature discovered in this and similar studies should be compared to define spatial (regional) differences. Temporal differences may be revealed by analysis of current and historical aerial coverage for a variety of test regions. In this manner, investigators may be able to develop enumeration techniques which may lead to increasingly powerful theoretical explanations about the arrangement and growth of urbanized areas.

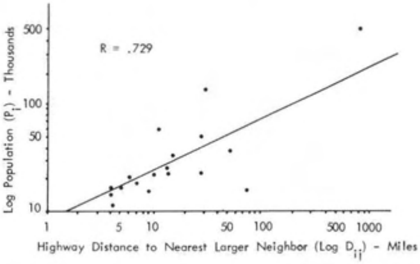

FIG. 5. Highway distance to nearest larger neighbor (Log d_{ij}) plotted against population (Log P_i).

TABLE 3. INCREASE IN COEFFICIENT OF DETERMINATION (R^2) WITH ADDITION OF INDEPENDENT VARIABLES

Step Number	X Variable Entered	R^2	Increase in R^2
1	$\log A_i$	0.9647	0.9647
2	L_i	0.9716	0.0068
3	A_j	0.9725	0.0010
4	$\log D_{ij}$	0.9727	0.0002

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REFERENCES

1. For example, B. S. Wellar, "Remote Sensing and Urban Information Systems,"

Photogrammetric Engineering, 39 (10), 1041-1050.
2. S. Y. Hsu, "Population Estimation," *Photogrammetric Engineering,* 37 (5), 449-454. 449-454.
3. R. K. Holtz, D. L. Huff and R. C. Mayfield, "Urban Spatial Structure Based on Remote Sensing Imagery," in R. K. Holtz, Ed., *The Surveillant Science,* (Boston: Houghton Mifflin, 1973), 375-380.
4. D. T. Lindgren, "Dwelling Unit Estimation with Color IR Photos," *Photogrammetric Engineering,* 37 (4), 373-377.
L. Mumbower and J. Donoghue, "Urban Poverty Study," *Photogrammetric Engineering,* 33 (6), 610-618.
D. M. Richter, "Sequential Urban Change," *Photogrammetric Engineering,* 35 (8), 764-770.
5. F. J. Wobber, "Orbital Photos Applied to the Environment," *Photogrammetric Engineering,* 36 (8), 852-864.
6. U. S. Bureau of the Census, *Census of Population,* 1970. Vol. 1, Characteristics of the Population, Part 49, Washington. (Washington, D.C.: G.P.O., 1973).

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