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16. **Summary/Notes** *LANDSAT (MSS) imagery, aerial photography and the IMAGE-100 system were used in this study for demographic estimations and for monitoring of urban growth. Two sets of urban test sites, one with 35 cities and one with 70 cities were selected in the State of São Paulo. A high degree of colinearity (0.96) was found between urban areal measurements taken from aerial photographs and LANDSAT (MSS) imagery. High coefficients were observed when census data was regressed against aerial information (0.95) and LANDSAT data (0.92). The validity of population estimations was tested by regressing three urban variables, against three classes of cities. The results supported the effectiveness of LANDSAT to estimate large city populations with diminishing effectiveness as urban areas decrease in size. The IMAGE-100 system computed urban growth between October, 1972 and June, 1976. Residential and industrial sectors in São José dos Campos showed growth along the São Paulo to Rio de Janeiro urban "corridor". Further research will refine the LANDSAT system's precision to analyse and predict urban growth in the State of São Paulo, although the methodology should be of use to any other region, with adequate adaptation.*

17. **Remarks** *This paper will be presented at the "Simpósio Internacional de Percepcion Remota aplicada a Demografia y Uso actual de la Tierra", in Lapaz, Bolivia, (28-30 November).*

1 - INTRODUCTION

The utilization of LANDSAT data for demographic research and for the monitoring of urban growth is one of the most challenging aspects of applications in Remote Sensing.

The Brazilian government conducts a demographic census every 10 years to monitor population growth. However, inter-census estimations are considered to be inaccurate owing to the rapid growth of urban areas.

The purpose of this study is to develop a viable methodology using LANDSAT data as a primary source for population estimation and assessment of urban growth in the intercensal period.

This research in the use of low resolution imagery is an attempt to verify existing relationships between spectral reflectance characteristics and variations in urban population.

The specific objectives of this study are to: 1) identify and quantify the size of individual urban areas using information obtained from LANDSAT and conventional imagery, and the IMAGE-100 system; 2) make comparisons between the results obtained from LANDSAT data (scale = 1:500,000) and those obtained from conventional aerial photographs (scale = 1:25,000); 3) evaluate LANDSAT data as a monitor of the expansion of urban growth, and 4) analyze the relationship between population data, based on the "Demographic Census" of 1970, and urban area measurements obtained from LANDSAT positive imagery in spectral channel 5.

The potential of LANDSAT data for population estimates has been examined in previous papers of Foresti and Mendonça (1974). Other working papers on the subject include: Ellefsen et al (1974), Hsu (1973), Durland (1974) and Durland (1975), Reining (1974), Reining and Egbert (1975), Christenson et al (1975) and others.

1.1 - DEMOGRAPHIC FEATURES OF THE STUDY AREA

The State of São Paulo was selected for this research for reasons of high urban growth and its geographic situation as a vital region of development and organization in Brazil (Figure 1).

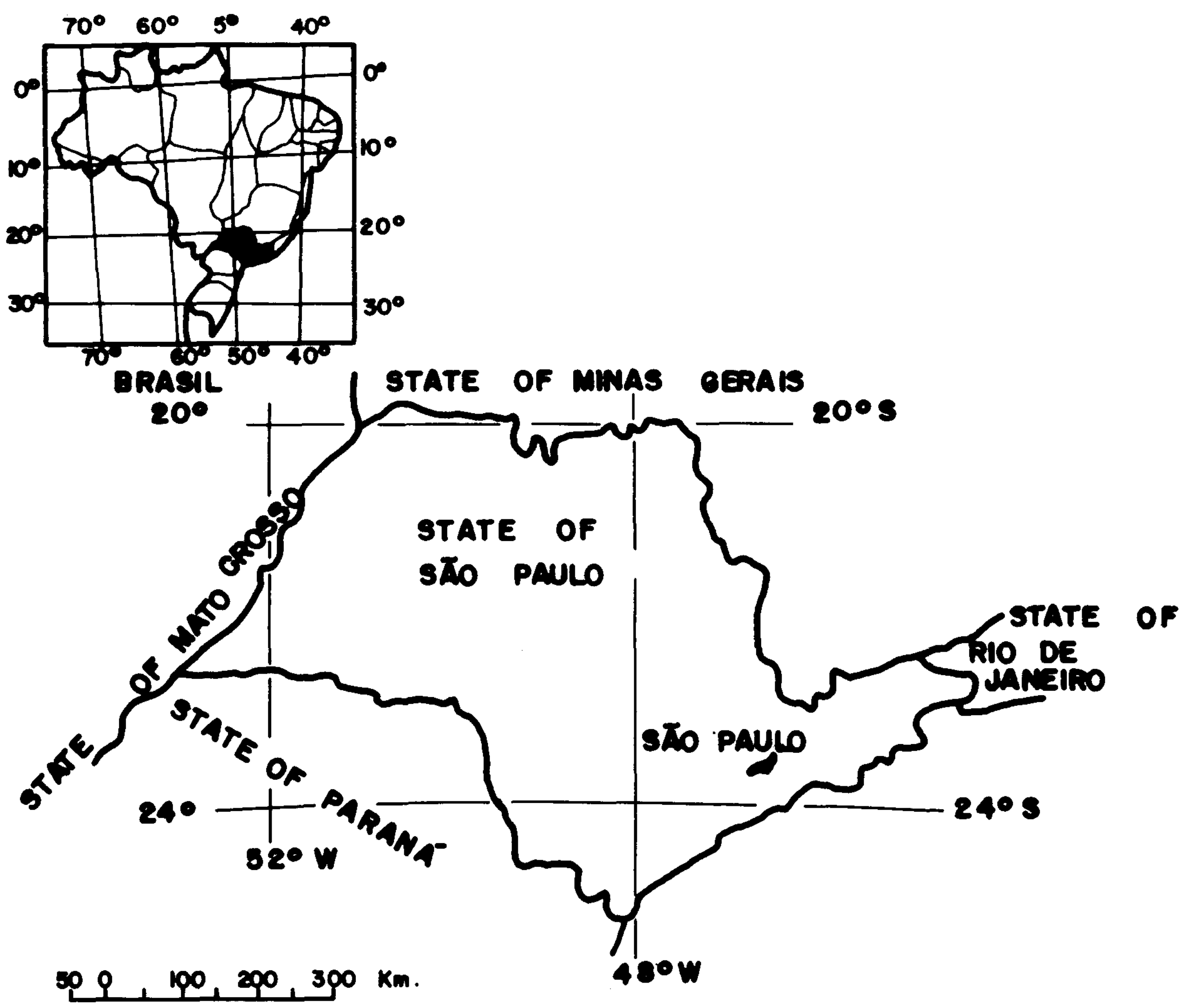


Fig. 1 - State of São Paulo: Study Area

The population of the State of São Paulo encompasses about 19.0% of the total Brazilian population according to the national "Demographic Census" of 1970. This figure is impressive considering that the state's area (247,898 km^2) represents only 2.9% of the country's total area (8,511,965 km^2). The demographic growth of the State of São Paulo is more a result of incoming migrants than of natural population growth. Moreover, the industrial development of the São Paulo metropolitan area and of other regional urban centers are important factors in the urban development of the whole State.

Porcaro and Oliveira (1976) report that urbanization is a function of population concentration in urban centers. Table 1 shows urban and total population growth from 1940 - 1950 and from 1960 - 1970 for the State of São Paulo and for Brazil.

TABLE 1

URBAN AND TOTAL POPULATION GROWTH

	URBAN POPULATION (%)			TOTAL POPULATION (%)		
	1940-1950	1950-1960	1960-1970	1940-1950	1950-1960	1960-1970
State of São Paulo	51.6	69.5	80.3	27.2	42.0	37.0
	45.8	70.3	62.9	26.0	36.7	31.3

Porcaro and Oliveira (1976) concluded that the ratio between urban population and total population for a region is a primary indicator of the degree of urbanization. Table 2 shows urbanization rates for the State of São Paulo and for Brazil from 1940 to 1970, based on "Demographic Census" data.

TABLE 2

URBANIZATION RATES

	1940	1950	1960	1970
State of São Paulo	44.1%	52.8%	62.8%	80.3%
Brazil	31.2%	36.1%	45.8%	55.9%

2 - MATERIALS AND METHODS

2.1 - MATERIALS

This study was carried out using LANDSAT system products. The description and specification of these products can be found in the NASA Data User Handbook (1972).

A visual interpretation of urban areas was conducted using black and white LANDSAT positives at scales of 1:1,000,000 and 1:500,000.

The tonal response of channel 5 (0.6 μm - 0.7 μm) was found to be the most suitable for visual analysis of urban areas. The tonal contrast between urban and surrounding areas, observed in this channel, provided an excellent base for the delineation of urban boundaries. CCT were employed for automatic interpretation using the IMAGE-100 multispectral analyzer (GE, 1975). Black and white, conventional aerial photographs (scale = 1:25,000) were used to obtain areal information for comparison with LANDSAT data. Topographic charts

(1:1,000,000), transportation maps (1:1,000,000) and a packaged computer program were used as supplementary materials.

2.2 - METHODS

Two sets of urban study areas were identified on LANDSAT imagery in accordance with Carter's and Stone's methodology (1974). Anderson's et al (1972) criteria were applied to delineate urban areas on aerial photographs and LANDSAT imagery. Included within the urban limits are industrial, commercial, institutional, and recreational land--use types, service areas and transportation networks. Surface transport links among cities were collected from the imagery and existing maps, and, tested according to Ogrosky's methodology (1975).

Urban population data, for the years 1973, 1975 and 1976 were based upon "Demographic Census" for 1970 using the mathematical formula of geometrical growth:

$$P(t) = P(0)(1+i)^n$$

where:

$P(0)$ = lasted census data existing for the number of inhabitants;

$P(t)$ = population at year t (t = year of the projection);

i = annual growth rate;

n = number of years between $P(t)$ and $P(0)$.

Simple and multiple Linear Regressions were applied to the data for: 1) data obtained from 70 cities, and, 2) data separated into three classes based upon population size. Class limits were based upon Sigueira's methodology (1976) and adapted for the State of São Paulo. These are: a small city class composed of 35 cities with populations less than 30,000 inhabitants; a medium city class with 25 cities and less than 100,000 inhabitants, and, a large city class with 10 cities and populations greater than 100,000 inhabitants.

LANDSAT data processed from the IMAGE-100, by: 1) spectral signature study of the urban areas, 2) single cell classification, and 3) monitoring of urban growth in two different periods.

3 - RESULTS AND DISCUSSION

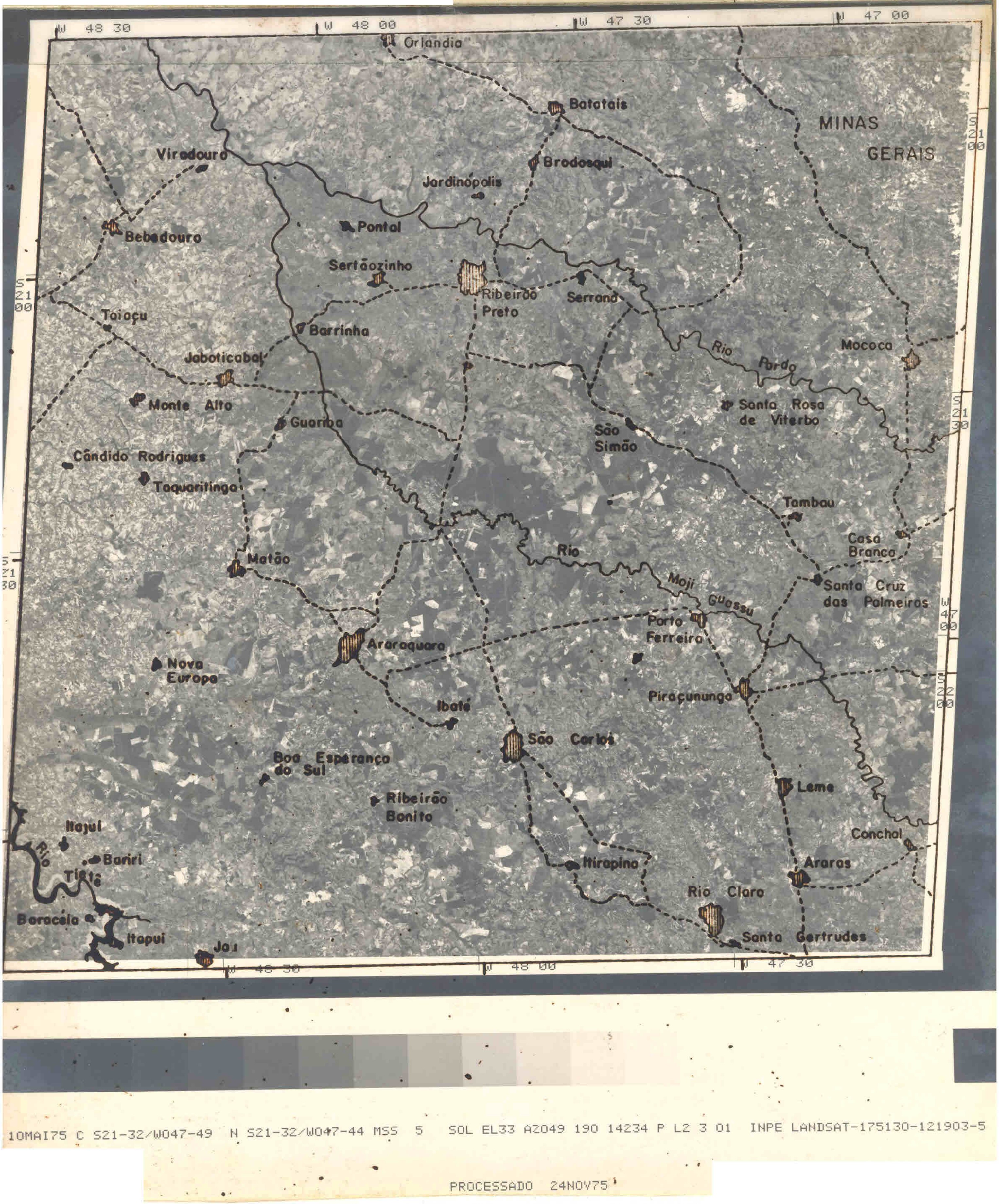
Table 3 shows urban population data and urban area measurements obtained from aerial photographs and LANDSAT imagery for 35 cities. Areal data from LANDSAT are usually overestimated when compared with data obtained from conventional photographs. The correlation coefficient of (0.96) obtained between aerial and LANDSAT imagery shows the compatibility of these data sources. The correlation coefficient between census data and aereal data from conventional photographs is (0.95). This value, which is slightly greater than the coefficient of (0.92) obtained for the correlation between census data and urban LANDSAT imagery, supports the suitability of satellite data as a source for estimating populations.

Population estimates were based on an enlarged sample of 70 cities provided by recent LANDSAT imagery (1975/1976). Figures 2, 3, and 4 show urban areas identified on three LANDSAT images located in the central east and southeast region of the State of São Paulo. Only well defined urban areas could be used as test sites. Figure 5 shows the location of the test sites. The numeration for each city is included in Appendix A which presents urban population (P), urban area (A) and surface transport (L) data. Table 4 shows the results for the simple linear regression and Figures 6, 7, 8, and 9 illustrate dispersion diagrams for the four regression runs presented in Table 4. The results show that the best fit was obtained for the "total sample" with a r^2 coefficient of 0.9418. The division of the sample into three classes did not improve the accuracy of the population estimation model. A test of the correlation coefficients was applied to the values among the three classes of cities. The results show no significant differences among the coefficient values at a $p = 0.01$ level. A multiple linear regression was run, where the surface transportation linkage index was introduced

TABLE 3

POPULATION AND URBAN AREA DATA (1973) FOR 35 TEST SITES

Nº	CITIES	POPULATION	URBAN AREA AERIAL PHOTOGRAPH (km^2)	URBAN AREA LANDSAT (km^2)
1	ITIRAPINA	4,556	0.76	1.72
2	AVANHANDAVA	3,997	0.81	1.48
3	VINHEDO	7,944	1.32	2.16
4	BURITAMA	6,550	1.53	1.60
5	ITATIBA	22,474	1.90	4.16
6	SUMARÉ	13,751	2.30	3.24
7	MIRANDÓPOLIS	11,677	2.45	2.52
8	SANTO ANASTÁCIO	14,144	2.70	3.40
9	SÃO ROQUE	17,178	2.85	2.90
10	SALTO	20,264	2.90	3.00
11	ITAPIRA	26,959	3.15	3.48
12	PEREIRA BARRETO	20,364	3.37	5.00
13	MOCOCA	22,347	3.64	4.00
14	Sta BÁRBARA D'OESTE	24,127	3.92	3.44
15	VALINHOS	22,088	3.92	4.60
16	MOGI GUASSU	34,228	4.04	6.44
17	LEME	26,132	5.21	5.92
18	BRAGANÇA PAULISTA	40,472	5.26	4.72
19	ARARAS	44,478	5.29	7.96
20	BIRIGUI	28,698	5.37	7.64
21	PENÁPOLIS	26,661	5.65	7.00
22	PIRASSUNUNGA	27,046	5.67	5.92
23	JAU	42,678	5.98	4.56
24	ITU	48,959	6.40	12.60
25	ANDRADINA	48,675	7.06	9.92
26	BOTUCATU	55,835	9.50	12.60
27	RIO CLARO	72,819	13.81	14.80
28	PRESIDENTE PRUDENTE	98,696	14.80	14.84
29	PIRACICABA	134,217	15.09	17.40
30	MOGI DAS CRUZES	95,183	15.94	17.03
31	SÃO CARLOS	79,565	17.21	17.80
32	ARAÇATUBA	91,890	18.56	18.76
33	ARARAQUARA	87,045	19.45	19.88
34	SOROCABA	176,742	22.40	28.70
35	RIBEIRÃO PRETO	205,597	26.45	21.24



LEGEND

CITIES
RESERVOIRS
INTERSTATE BOUNDARIES
RIVERS
HIGHWAYS

Fig. 2 - Delimitation of Urban Areas of the Ribeirão Preto Region

LEGEND

CITIES

RESERVOIRS

INTERSTATE BOUNDARIES

RIVERS

HIGHWAYS

Fig. 3 - Delimitation of Urban Areas of the Campinas Region

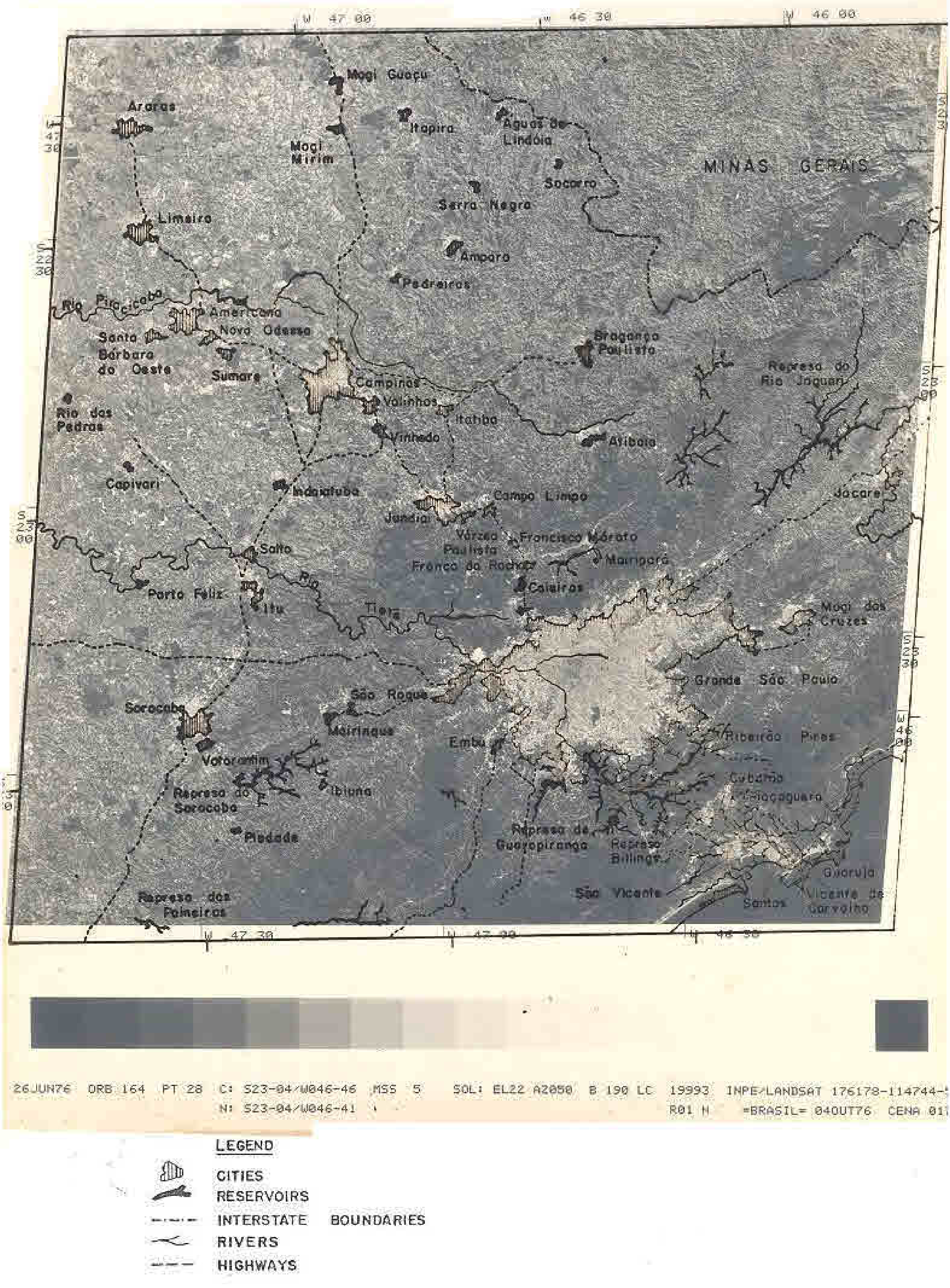


Fig. 4 - Delimitation of Urban Areas of the São José dos Campos Region

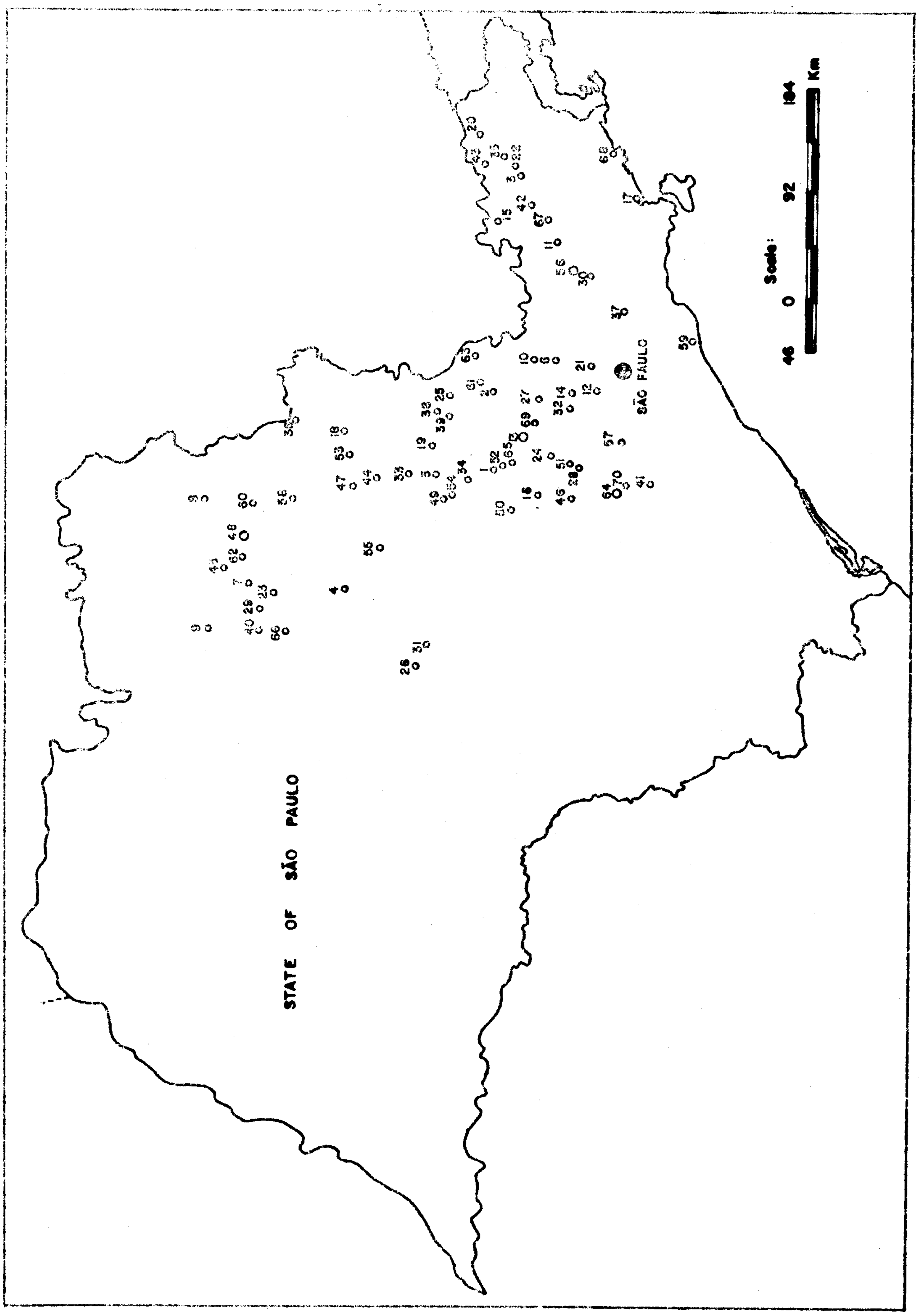


Fig. 5 - Location of Test Sites

TABLE 4

SIMPLE LINEAR REGRESSION

	n	r^2	$\hat{y} = a + bx$	$S_{y.x}$ (nº inhabitants)
Small Cieties (less than 30,000 inhabitants)	35	0.7289	Pi = 4,061 + 4,507 (Ai)	3,844
Medium Cities (30,000-100,000 inhabitants)	25	0.8147	Pi = 14,046 + 4,444 (Ai)	8,676
Large Cities (more than 100,000 inhabitants)	10	0.8529	Pi = 16,618 + 6,337 (Ai)	46,630
TOTAL SAMPLE	70	0.9418	Pi = 1,186 + 6,672 (Ai)	18,355

into the model. Holtz et al (1969), Ogrosky (1975) and Foresti (1976) found this variable to be a useful estimator of population after the "urban area" variable. Table 5 shows the results of the regression run where the addition of the transportation index increased the coefficients of determination (R^2): for small cities (0.0020), medium cities (0.0135), and large cities (0.0026). Ogrosky (1975) reported an increment of 0.0068 in the R^2 coefficient when the surface transportation index was included in the multiple algorithm. The standard error ($S_{y.x}$) showed an increment for all classes of population size except for the medium class.

Appendix B and C provide estimates of population and error estimates found for each of the 70 urban areas based upon simple Linear Regression and Multiple Linear Regression, respectively.

It must be pointed out that a small error factor of about 8.0% is inherent in our projections of population growth for 1976 based on the Demographic Census of 1960/1970.

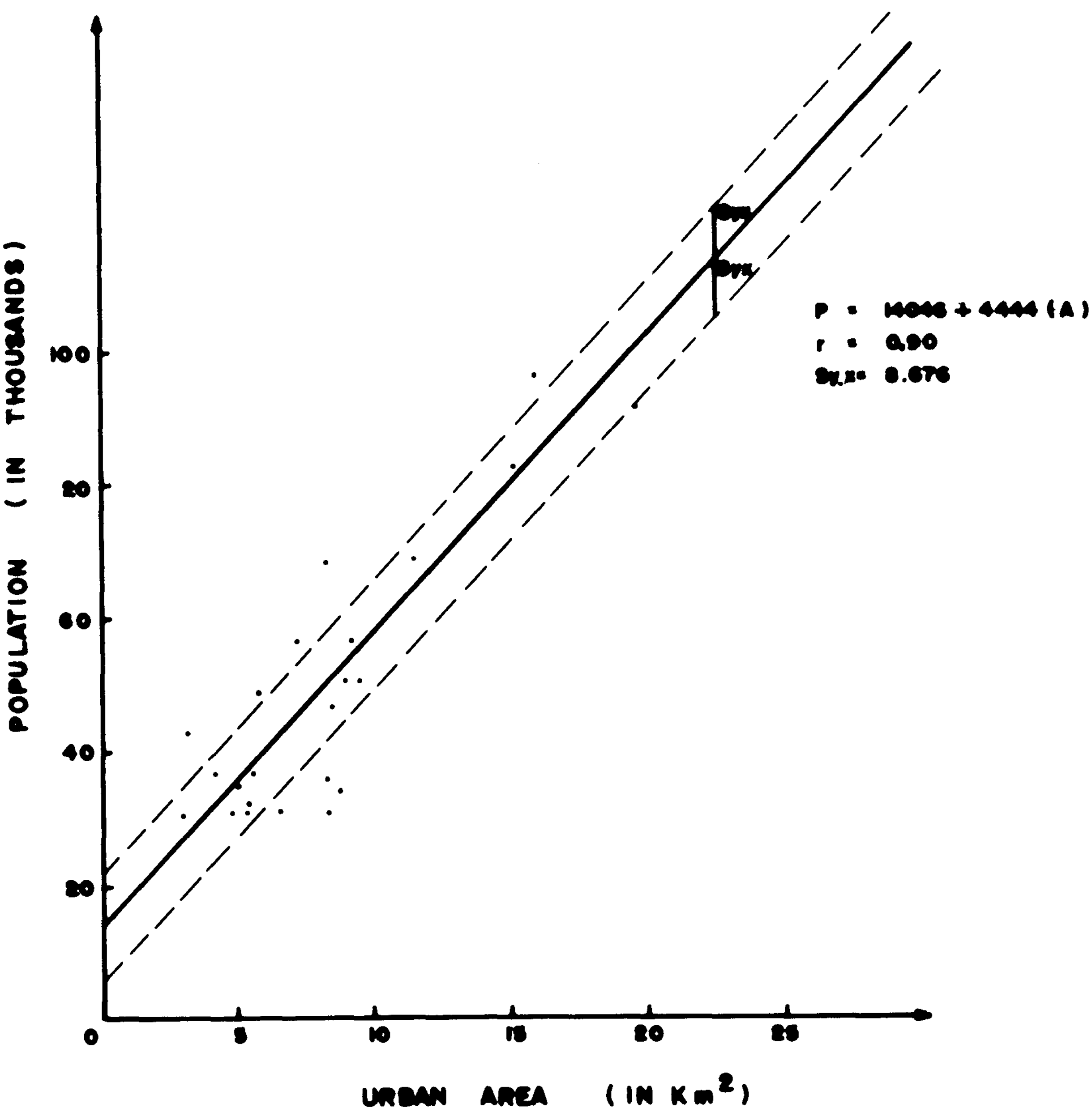


Fig. 7 - Relationship Between Population and Urban Area for Medium Cities

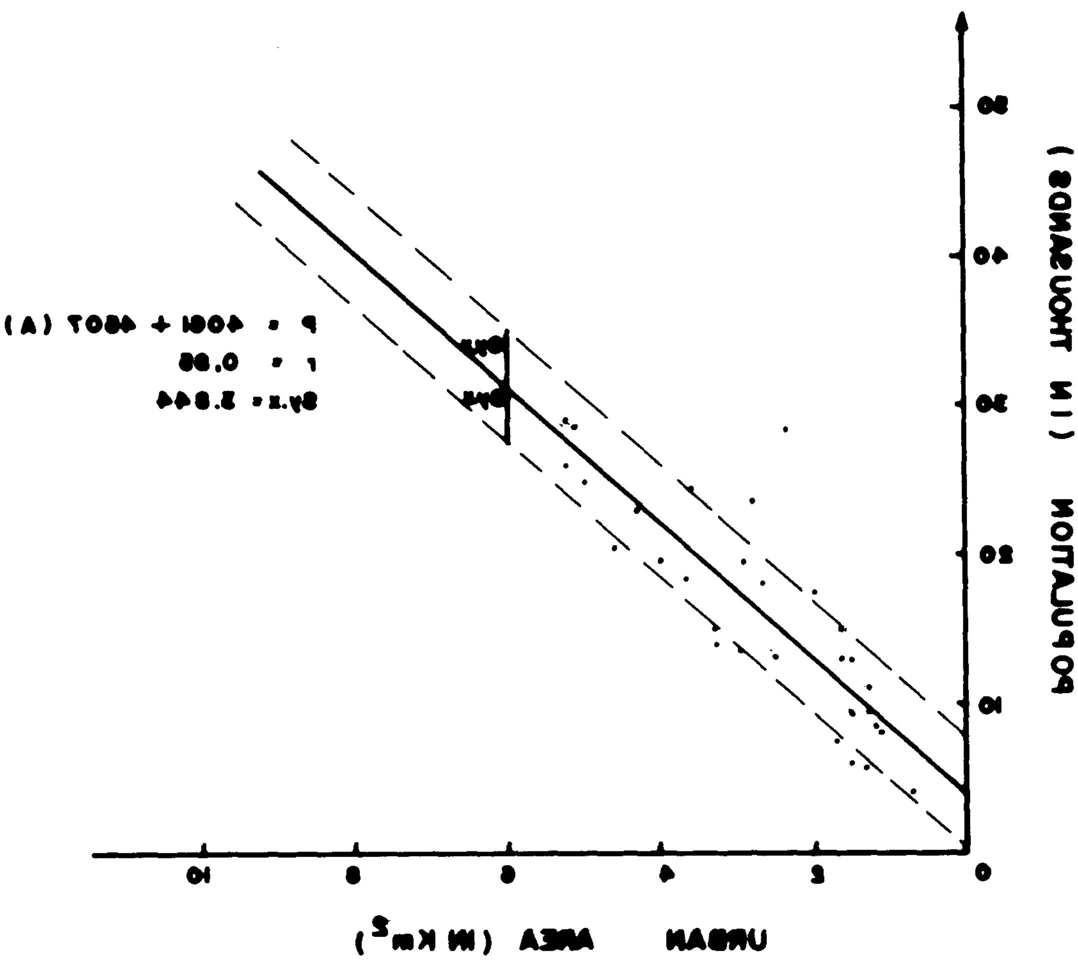


Fig. 6 - Relationship Between Population and Urban Area for Small Cities

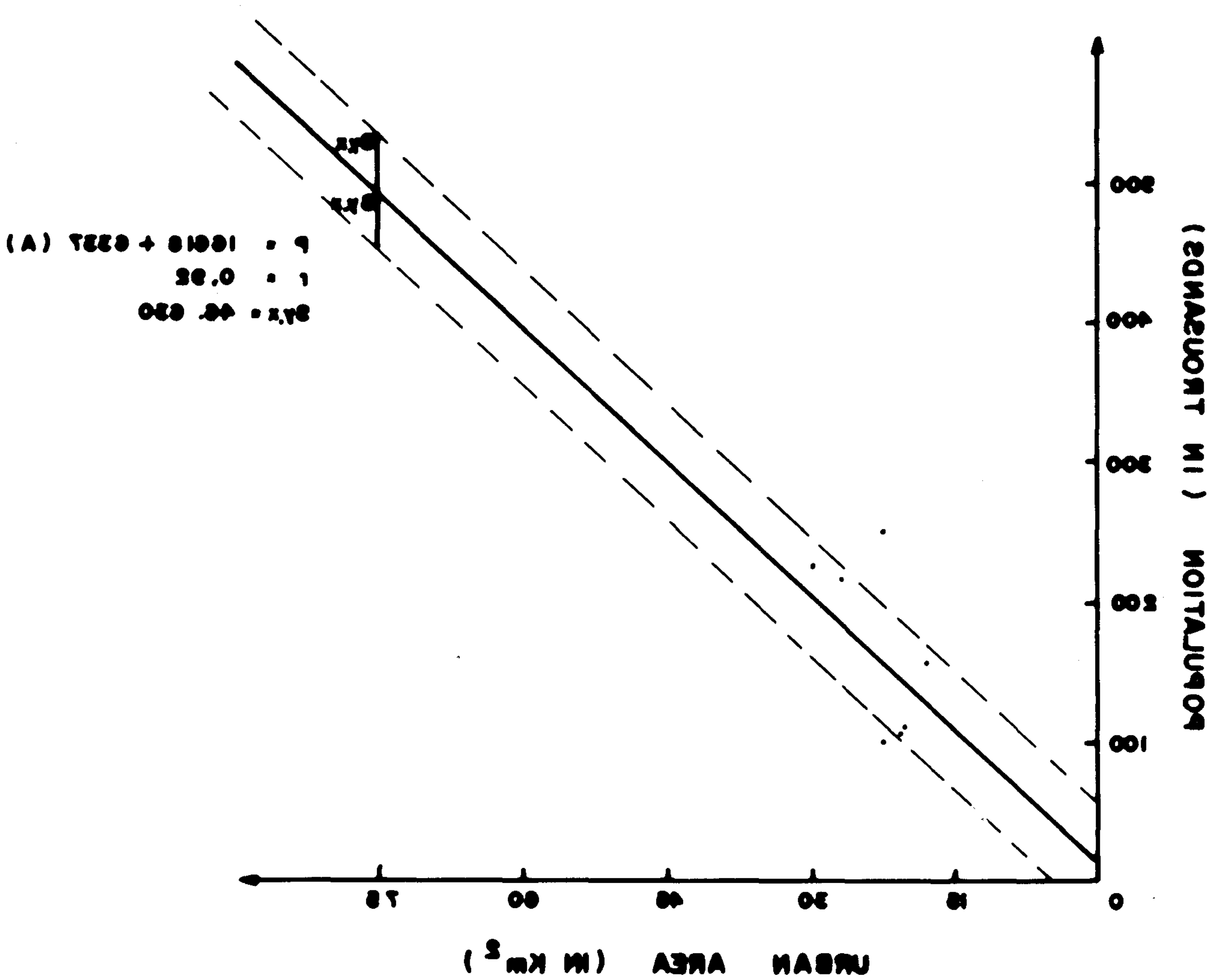


Fig. 8 - Relationship Between Population and Urban Area for Large Cities

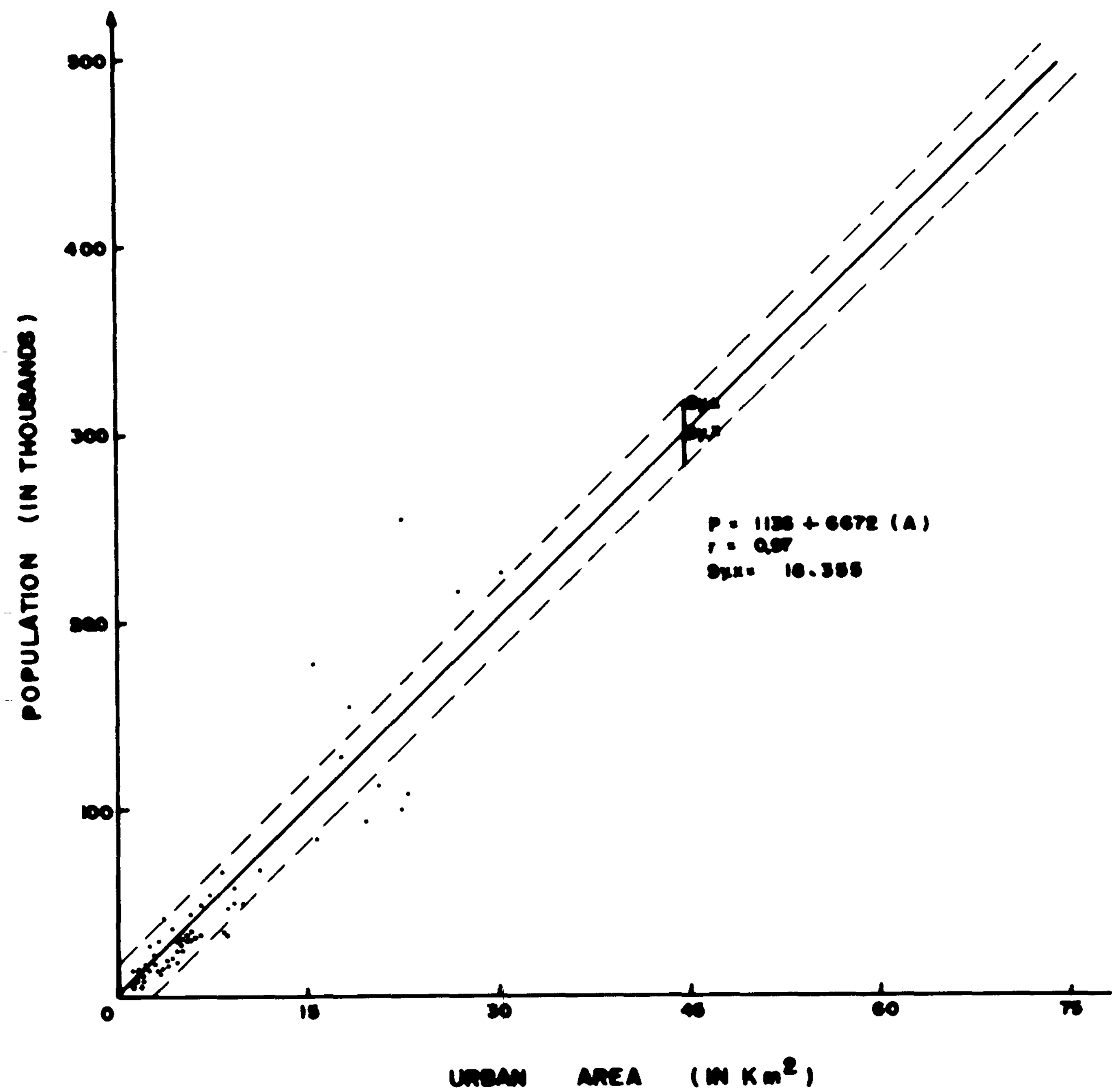


Fig. 9 - Relationship Between Population and Urban Area for Total Sample
(70 Cities)

TABLE 5

MULTIPLE LINEAR REGRESSION

	N	R^2	$\hat{y} = a + b_1 x_1 + b_2 x_2$	Sy.x
	35	0.7309	Pi = 3,224 + 4,462(Ai) + 63(Li)	3,889
Medium Cities (30,000 - 100,000 inhabitants)	25	0.8282	Pi = 25,481 + 4,806(Ai) - 625(Li)	8,542
Large Cities	10	0.8555	Pi = 10,495 + 5,952(Ai) + 1,217(Li	4,907
	70	0.9418	Pi = -2,231 + 6,638(Ai) + 66(Li)	18,488

Urban area data collected from LANDSAT imagery also presented problems. Among the difficulties encountered were such factors as shape (linear or star shaped areas). Also difficult to analyze are areas located in regions of rough topography where shadow effects are created. Cities surrounded by crop belts tend to obscure tonal features unless coverage is provided for the wet season, Murray (1975). In addition, cities located on or near the coast often exhibit overlapping reflectance between city and beach.

The decrease of the error associated with the urban population can be lowered using imagery taken at the same period of the demographic census.

Greater precision, for collecting urban area data, can be obtained using higher resolution images and by employing correction factors through magnification or enhancement techniques.

An urban expansion study of São José dos Campos, using the IMAGE-100 system was conducted by the following procedure:

1) Examination of LANDSAT (MSS) black and white positives (scale = = 1:500,000);

2) Visual monitoring of black and white CRT images in each of four channels (4, 5, 6, 7) at a scale of 1:60,000;

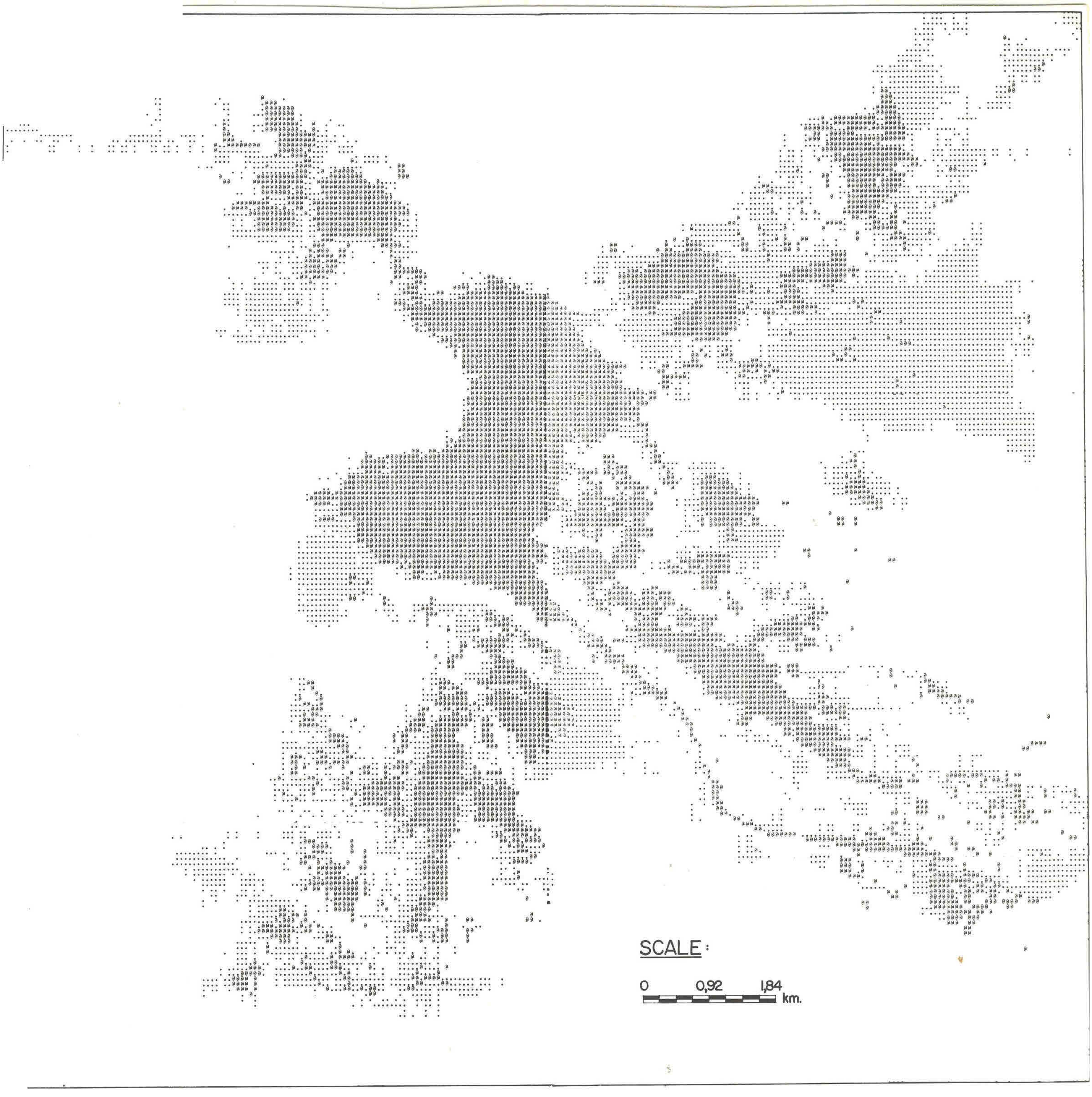
3) Selection of "training sites" and development of an urban land use classification system;

4) Examination of spectral signatures for class I land-use types (Anderson et al, 1972);

5) Analysis of alphanumeric computer printouts and redefinitions of "training sites";

6) Utilization of an auxiliary program algorithm to compare urban growth between the periods of October 1972 and June 1976.

The study of urban structure is among the most complex in Remote Sensing and requires the combination of several basically different ground cover classes into a single land use classification system (Odenyo and Pettry, 1977). Because city componentes are not uniformly distributed within any one area, they are spectrally multi-modal. Such is the case for São José dos Campos where the difference in spectral signatures, for each CRT image, are probably caused by seasonal differences in data acquisition. For example, June 1976 (dry season) data, presented higher reflectance in all channels compared to the signatures of other images examined. Residential and industrial areas presented mixed spectral responses which can be confused with the response from crop areas, characterized by bare soil and vegetation. This fact makes spectral discrimination between urban and rural areas difficult when automatic analysis is performed. Figure 10 shows the output from the interactive digital system in alphanumeric printout characters. The printout represents a data element or pixel which corresponds to the cell resolution of the satellite. Figure 10 represents the São José dos Campos



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● SÃO JOSÉ DOS CAMPOS urban area in 1972

. URBAN GROWTH UP TO 1976

Fig. 10 - IMAGE-100 Generated Alphanumeric Printout for São José dos Campos Urban Area in 1972 and for Urban Growth up to 1976

urban area in 1972 and urban growth up to 1976. Single-family residential dwellings are in the urban sector with the greatest amount of growth. The expansion of this urban class has taken place along the highway that links São José dos Campos with Rio de Janeiro, to the northeast, and São Paulo to the southwest. Major industries were observed to have developed along these "corridors" leading out of São José dos Campos in the past year alone.

As additional evidence for urban expansion, São José dos Campos experienced an increase in urban area from 30.0 km^2 to approximately 54.0 km^2 in 1976, an 80.0% physical growth rate in three and one half years.

The foregoing results must be considered as a preliminary stage of interpretation, until further research refines the ability to analyze and predict urban growth using the LANDSAT system.

4 - CONCLUSIONS

The high degree of colinearity between the size of urban areas and population, demonstrated the viability of using LANDSAT data to estimate population numbers. Preliminary results also point to the system's usefulness to determine urban expansion.

The compatibility between the data provided by conventional aerial photographs and LANDSAT (MSS) imagery points to an increasing dependence on the LANDSAT system, based on a lower cost/ benefit ratio, high degree of precision and usefulness of automatic data processing.

Results produced by the IMAGE-100 system furnished more useful information about urban areas than conventional methods. The ability to superimpose contrasting spectral CRT images, acquired for the same place, in different periods, provides for multi-dimensional and multi-spatial classifications of urban data on a continuous basis.

The results of this study provide for a viable approach to the problem of population estimation and urban expansion and has future implications in the area of computer mapping and land use assessment.

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APPENDIX A

BASIC DATA FOR SELECTED TEST SITE

Nº	TEST SITE	POPULATION	AREA (km^2)	LINKS
1	AMERICANA	96,271	15.88	30
2	AMPARO	23,703	2.84	16
3	APARECIDA	30,153	3.20	18
4	ARARAQUARA	100,377	22.64	31
5	ARARAS	57,878	9.32	21
6	ATIBAIA	25,068	5.04	10
7	BARRINHA	9,841	1.52	14
8	BATATAIS	25,132	4.64	24
9	BEBEDOURO	37,069	5.72	31
10	BRAGANÇA PAULISTA	50,427	6.36	23
11	CAÇAPAVA	32,184	5.36	21
12	CAIEIRAS	17,623	2.08	14
13	CAMPINAS	485,409	74.60	46
14	CAMPO LIMPO	13,785	3.08	14
15	CAMPOS DO JORDÃO	19,777	4.00	13
16	CAPIVARI	14,314	2.20	22
17	CARAGUATATUBA	18,422	2.72	13
18	CASA BRANCA	13,410	2.56	31
19	CONCHAL	6,068	1.56	7
20	CRUZEIRO	57,130	7.40	25
21	FRANCO DA ROCHA	28,954	2.48	16
22	GUARATINGUETÁ	69,811	11.52	24
23	GUARIBA	13,211	1.52	8
24	INDAIATUBA	31,070	5.36	27
25	ITAPIRA	33,629	5.20	21
26	ITAPUI	4,188	0.72	6
27	ITATIBA	29,228	5.20	14
28	ITU	47,950	8.72	22

Nº	TEST SITE	POPULATION	AREA (km^2)	LINKS
29	JABOTICABAL	35,619	5.04	25
30	JACAREI	69,665	8.28	19
31	JAU	49,076	5.80	22
32	JUNDIAI	215,568	27.00	30
33	LEME	34,424	6.20	17
34	LIMEIRA	108,550	23.00	32
35	LORENA	51,750	9.08	20
36	MOCOCA	26,111	5.20	17
37	MOGI DAS CRUZES	112,856	20.64	24
38	MOGI GUAÇU	51,490	9.72	20
39	MOGI MIRIM	37,773	4.28	20
40	MONTE ALTO	18,585	3.76	14
41	PIEDADE	8,859	1.20	12
42	PINDAMONHANGABA	36,400	8.36	29
43	PIQUETE	14,250	3.36	15
44	PIRASSUNUNGA	31,976	5.96	24
45	PONTAL	8,132	1.16	13
46	PORTO FELIZ	15,409	1.76	13
47	PORTO FERREIRA	20,576	4.60	26
48	RIBEIRÃO PRETO	253,122	23.04	35
49	RIO CLARO	83,657	15.08	27
50	RIO DAS PEDRAS	13,220	1.68	20
51	SALTO	24,906	3.68	18
52	SANTA BÁRBARA	31,096	6.52	23
53	SANTA CRUZ DAS PALMEIRAS	11,322	1.32	17
54	SANTA GERTRUDES	5,548	1.32	10
55	SÃO CARLOS	92,784	19.60	29
56	SÃO JOSÉ DOS CAMPOS	225,463	30.40	32
57	SÃO ROQUE	19,686	2.96	16
58	SÃO SIMÃO	9,037	1.24	24

Nº	TEST SITE	POPULATION	AREA (km^2)	LINKS
59	SÃO VICENTE	156,384	18.60	20
60	SERRANA	10,779	1.52	10
61	SERRA NEGRA	7,573	1.72	10
62	SERTÃOZINHO	28,611	5.16	15
63	SOCORRO	9,506	1.36	16
64	SOROCABA	216,676	32.20	27
65	SUMARÉ	23,059	4.32	14
66	TAQUARITINGA	22,401	3.36	16
67	TAUBATÉ	129,163	17.80	35
68	UBATUBA	15,290	3.32	18
69	VALINHOS	31,387	4.92	18
70	VOTORANTIN	43,270	3.48	14

APPENDIX B

RELATIONSHIP BETWEEN ACTUAL AND ESTIMATED VALUES USING SIMPLE LINEAR REGRESSION

Nº	ACTUAL POPULATION	ESTIMATED POPULATION	DIFFERENCE
1	96,271	104,767	- 8,496
2	23,703	17,762	5,940
3	30,153	20,164	9,988
4	100,377	149,871	- 49,494
5	57,878	60,998	- 3,120
6	25,068	32,441	- 7,373
7	9,841	8,955	885
8	25,132	29,772	- 4,640
9	37,069	36,978	90
10	50,427	41,248	9,178
11	32,184	34,576	- 2,392
12	17,623	12,691	4,931
13	485,409	496,557	- 11,148
14	13,785	19,363	- 5,578
15	19,777	25,502	- 5,725
16	14,314	13,492	821
17	18,422	16,961	1,460
18	13,410	15,894	- 2,484
19	6,068	9,222	- 3,154
20	57,130	48,187	8,942
21	28,954	15,360	13,593
22	69,811	75,676	- 5,865
23	13,211	8,955	4,255
24	31,070	34,576	- 3,506
25	33,629	33,508	120
26	4,188	3,617	570
27	29,228	33,508	- 4,280

Nº	ACTUAL POPULATION	ESTIMATED POPULATION	DIFFERENCE
28	47,950	56,994	- 9,044
29	35,619	32,441	3,177
30	69,665	54,059	15,605
31	49,076	35,512	11,563
32	215,568	178,962	36,605
33	34,424	40,181	- 5,757
34	108,550	152,273	- 43,723
35	51,570	59,396	- 7,646
36	26,111	33,508	- 7,397
37	112,856	136,527	- 23,671
38	51,490	63,667	- 12,177
39	37,773	27,370	10,402
40	18,585	23,900	- 5,315
41	8,859	6,820	2,038
42	36,400	54,592	- 18,192
43	14,250	21,232	- 6,982
44	31,976	38,579	- 6,603
45	8,132	6,553	1,578
46	15,409	10,556	4,852
47	20,576	29,505	- 8,929
48	253,122	152,540	100,581
49	83,657	99,429	- 15,772
50	13,220	10,022	3,197
51	24,906	23,367	1,538
52	31,096	42,316	- 11,220
53	11,322	7,620	3,701
54	5,548	7,620	- 2,072
55	92,784	129,588	- 36,804
56	225,463	201,647	23,815
57	19,686	18,563	1,122
58	9,037	7,087	1,949

Nº	ACTUAL POPULATION	ESTIMATED POPULATION	DIFFERENCE
59	156,384	122,915	33,468
60	10,779	8,955	1,823
61	7,573	10,289	- 2,716
62	28,611	33,242	- 4,631
63	9,506	7,887	1,618
64	216,676	213,657	3,018
65	23,059	27,637	- 4,578
66	22,401	21,232	1,168
67	129,163	117,578	11,584
68	15,290	20,965	- 5,675
69	31,387	31,640	- 253
70	43,270	22,032	21,237