Bruce Forster
School of Surveying
Centre for Remote Sensing
University of New South Wales
Kensington, N.S.W. 2033, Australia

Some Urban Measurements from Landsat Data

Landsat data over Sydney are used to predict urban reflectance, surface cover, housing density, average house value, and a residential quality index.

Abstract: *Landsat data acquired over the Sydney, Australia, metropolitan area is used with supporting ground data and multiple linear regression analysis to develop predictive equations for surface reflectance and a number of urban measures including surface cover proportions, housing density, relative average house values, and a residential quality index.*

Three distinct surface reflectance classes are indicated in the urban area with subclasses being differentiated by brightness. These classes could be considered as vegetation, urban residential, and urban non-residential. Percentage of total vegetative cover was related to Landsat derived reflectance data with a correlation of 0.82, which represented the highest cover prediction correlation at the pixel level. A residential quality index, using house size and vegetative content as a positive indicator of quality and roads and non-residential buildings as a negative indicator, was also related to Landsat data at the pixel level with a correlation of 0.87. Application to extended (5 by 8) pixel blocks and with the inclusion of textural data, substantially increased the correlation between ground and satellite data and allowed the prediction of the cover related variables—housing density and average house size. Because house value is strongly related to house size, it is demonstrated that average Sydney house values can be substantially predicted from Landsat data over extended areas. It is suggested that these results could be applicable in other similar cities. The study concludes that the potential of multi-spectral satellite data in urban analysis is considerable, particularly when used in association with other data and more so when the new generation of higher resolution satellites are operational.

Introduction and Background

Early Urban Studies Using Black-and-White Photography

The use of remote sensing in urban areas dates back to 1858 when Tournachon (later known as "Nadar") used a camera carried aloft in a balloon to study parts of the city of Paris. In his photographs of the village of Petit Bicetre the houses could be clearly seen (Am. Soc. of Photo., 1975, p. 27). Increasingly since then the imaged morphology, or form, of the urban space has been used directly or as a surrogate for functional identification and classification. Until the second world war, remote sensing techniques had remained essentially the same since the acquisition of the first aerial photographs. The war, however, brought about a dramatic increase in the awareness of the potential of remote sensing in urban areas. A textbook by Branch published in 1948 was the first attempt to examine the full potential of aerial photography in urban analysis. This book has since been revised (Branch, 1971).

Various papers and articles followed which at-

0099-1112/83/4912-1693$02.25/0

tempted to develop, or explore in greater depth, the applications and methods originally suggested by Branch. Witenstein (1954, 1955, 1956) and Wray (1960) dealt with the planning use of aerial photography. Wray developed methodology for implementing part of the analytical process outlined by Witenstein. This work laid the foundations for later contributions to the USGS Census Cities Project (Wray, 1970). Other studies involving dwelling unit estimation include Hadfield (1963) and Binsell (1967).

The use of conventional black-and-white photography in socio-economic and demographic studies, as suggested by Branch, was further extended by Green (1957) and Green and Monier (1959). The goal of these studies was to predict socio-economic variables from photointerpreted data. Extensive literature was cited as evidence for social values attached to housing and residential communities and, by extension, that *observable physical data have meaningful sociological correlates*. The generality of Green's approach, his aggregate treatment of data, and the choice of data items have been criticized by Witenstein (1957, p. 97) and Wellar (1968a). Nevertheless it is still significant that Green's scale of residential desirability accounted for 78% of the variation in his socio-economic status scale.

Mumbower and Donoghue (1967) substantially revised Green's approach. Photointerpreted surrogates for poverty included residential location, structure type, density, adjacent land use and transportation routes, presence of litter, absence of landscaping, and off-street parking. A further study involving the mapping of urban poverty areas was that by Metivier and McCoy (1971). Similar variables to those used by Mumbower and Donoghue (1967) were identified. Housing density was considered the most effective variable for identifying substandard housing areas. A high negative correlation was found between housing density and both median income and average house values, while density and percent non-white population were positively correlated. Westerlund (1972, p. 39) suggests that this one variable approach, using housing density, has value for initial analysis in areas where these correlations have been verified.

The use of aerial photographs as auxiliary census data was studied by Eyre *et al.* (1970) and Shin-Yi Hsu (1970). Although a number of difficulties were encountered, the techniques devised were considered most useful for intercensal extrapolation of census data. Work in Britain by Collins and Bush (1969), Collins and El-Beik (1971), and Gibson (1976) has further extended the use of conventional aerial photographs in the acquisition of urban land-use information and for derelict land studies, by applying previously researched techniques to real world problems. De Bruijn (1976, pp. 185-186) suggests, however, that techniques developed elsewhere, especially for American cities, have not been particularly applicable to the more compact and varied urban areas of Europe.

THE APPLICATION OF MORE ADVANCED AIR AND SPACE PHOTOGRAPHY

The sixties and early seventies saw a gradual change in the conventional approach to remote sensing with the introduction of color, color infrared, multiband, small scale, and space photography. As a natural result of the trend towards smaller scales and greater coverage, research using these advanced techniques has emphasized regional rather than intra-city application, with the exception of housing quality studies (Westerlund, 1972, p. 57).

Application of multiband and color infrared photography to the evaluation of housing quality, neighborhood environment, and socio-economic criteria was pursued by Northwestern University and the University of California-Riverside in a joint research program during 1968 to 1970. Much of this work built directly upon the earlier studies of Green (1957) and Mumbower and Donoghue (1967). Wellar (1968a) used large scale aerial photography in nine spectral bands to evaluate the quality of housing and neighborhood environment. He found that 20 of the 24 items used by the American Public Health Association as criteria for housing environment appraisal could be consistently interpreted from the photography.

A study using estimated income, house value, and other socio-economic criteria, based on correlated surrogates observed on color infrared imagery, was described by Moore (1969a) and Thrower *et al.* (1968). Various significant correlations were found; for example, the results indicated a satisfactory ability to differentiate between income levels using interpreted surrogates. In a related study, Moore (1969b, 1970) used existing documentary data on housing characteristics for the same three residential areas and developed a set of seven environmental variables. They argued that based on the work of Wellar (1968a) these environmental variables could be interpreted from large scale multiband aerial photography. Horton and Marble (1969), using infrared photography, tested Moore's seven environmental variables and concluded that for quick look surveys of blight and decay an acceptable error level was achieved. Bowden (1970) further reviewed and analyzed the results of these residential studies.

In a study by Tuyahov *et al.* (1973) various levels of housing and environmental quality were assessed and mapped using conventional black-and-white photography at a scale of 1:23 000 and sub-orbital color infrared photography at a scale of 1:190 000. Eighteen indicators or image signatures of different socio-economic classes were identified. Those considered potentially observable from satellite imagery included housing density, geographic pattern and uniformity, surrounding amounts of vegetation, and percentage of roof cover. They concluded in part that the location, spatial arrangement, density, and character of the housing units have ecological meaning in that exterior characteristics are surrogate measures for interior conditions—a statement not unlike that used as a premise for the work of Green (1957) 16 years before.

Increasingly, research in the land-use area was being directed to sub-orbital and satellite imagery. Wray (1970) describes the objectives of the U.S. Geological Survey Census Cities Program which in part was to determine the capability of high altitude and satellite imagery. Wellar (1968b, 1969) discusses the applied aspects of hyperaltitude photography in urban and transportation research based on detailed analysis of Gemini photographs over various urban centers at scales of 1:283 000 to 1:1 000 000. Typical of several efforts at regional land-use analysis from manned spacecraft photography, was a study by MacPhail and Campbell (1970). They analyzed 17 frames of Gemini 5, Apollo 6, and Apollo 9 photography of the El Paso region of Texas—New Mexico. A similar regional project was undertaken at the University of California, Los Angeles by Thrower *et al.* (1970) using photography from four Gemini and Apollo missions over the southwestern area of the United States. The problem of extracting land-use data from space imagery was well stated by the authors ". . . .at orbital altitudes a single photographic resolution cell represents the integration of a variety of spectral responses associated with a number of phenomena and their condition . . . consequently, generalizing a variety of such cells into land-use categories requires sophisticated interpretation and inference." This was one of the first statements of this important problem.

NON-PHOTOGRAPHIC ORBITAL IMAGERY

The development of non-photographic remote sensing systems—primarily thermal infrared, multispectral scanners, and radar—and research into their application has generally paralleled that of advanced photographic techniques. However, the amount of research into urban applications using these new sensors had, until the early 1970's, been comparatively small. The greatest advance in non-photographic Earth orbital imagery was undoubtedly the launch of the first Earth Resources Technology Satellite, ERTS 1 (renamed Landsat 1) on 23 July 1972. The repetitive, synoptic, regional overview of Landsat stimulated much research into urban and regional applications. Many studies, particularly in the United States, were commenced with great expectation, broad land-use classes were mapped, and urban boundary change detection was attempted. In general the pattern recognition techniques used were essentially those developed for agricultural studies where the spectral and spatial responses were considered sufficiently simple and consistent to encourage their development (Westerlund, 1972, 137).

Early research using Landsat data in urban areas was reported by Erb (1974). Both unsupervised and supervised clustering techniques were used to derive a number of land-use cover classes. Considerable effort was expended in an attempt to develop distinct spectral signatures for residential areas in four general categories. He indicates that separating these categories spectrally with a reasonable degree of accuracy proved almost impossible because of confusion with other uses. It was concluded that the best accuracies for classifying residential areas would be achieved using only two categories, single family residential and mixed urban. Zobrist *et al.* (1976) reported a more detailed breakdown having large buildings, strip cluster development, single family residential, and multiple family trailer courts as separate classes. Erb (1974) suggests that the residential land-use category is one of the most complex and least consistent categories to be delineated by spectral classification, because of the spectrally heterogeneous inter-mixing of small vegetated and non-vegetated surfaces. He concludes that *urban classification is difficult because of the integrated response from pixels of mixed surface cover proportions and more particularly where vegetation is a major component of the urban scene.*

Improved techniques were adopted by Todd *et al.* (1973) and Todd and Baumgardner (1973) in an attempt to overcome some of the urban classification problems. In the latter study over Marion County, Indiana, a number of new approaches were considered. The most innovative technique introduced was the inclusion of numerical spectral characteristics, other than single spectral class, into the clustering process. Parameters such as mean, range, standard deviation, and correlation coefficients (between spectral bands) were considered. The most useful of these parameters for land-use separation were found to be the means and standard deviations in the infrared bands. An alternative approach was reported by Ellefsen *et al.* (1974). In this study pattern recognition techniques were applied to a combined multispectral and multitemporal data set. The authors reported that unintentionally this procedure also resulted in the uncovering of a number of subclasses, for example, older and newer residential areas, a level of discreteness beyond some earlier studies. They suggested that Landsat data held promise for such distinctions as the quality of housing and the nature of open space.

In a recent extensive study of the Sydney metropolitan area, Bailey (1979) makes a clear distinction between land use and land cover or landscape. She suggests that it is the ratio between the elements of the urban landscape which causes groupings chiefly the ratio of the size of the buildings and/or other man-made surfaces, and a ratio of vegetation to building and other man-made surfaces.

Another study of the Sydney Metropolitan area by Forster (1980b) also attempted to disaggregate urban residential cover classes and include the effects of atmosphere and sensor point spread function. This latter effect causes localized scene degradation and has been theoretically examined by Dye (1975). While being of little consequence in agricultural areas, single pixel classification in heterogeneous areas can be markedly affected. While Carter (1977) attempted to reduce atmospheric effects by normalizing, very few studies to date have attempted to quantify these effects and apply them in an urban situation, a necessary requirement for signature extension. A number of researchers have, however, examined the theoretical problems, notably Turner *et al.* (1971), Turner *et al.* (1972), and Turner (1975). One example of the application of atmospheric corrections to an urban scene is given by Kawata *et al.* (1978); however, only a qualitative expression of the improvement in pattern recognition and image interpretation was reported.

Since the launching of the first Landsat satellite, virtually all research in urban areas has been directed towards urban land-use or land-cover classification, which is in marked contrast to the studies of housing density, housing quality, poverty areas, demography, and other socio-economic factors, which were so apparent with larger scale aerial photographs. A number of researchers have, however, pointed to the potential of Landsat for image surrogate application. Erb (1974) suggests that a measure of vegetative cover can be used to determine density and age. Todd *et al.* (1973) discuss associations between the classified imagery and published socio-economic data. One association suggested was that between medium family income and various land-use classes. Inner city classification compared well with the distribution of low income areas, while wooded suburb classification was essentially correlated with high income areas.

A more extensive study of relationship between Landsat data and socio-economic data was carried out by Landini and McLeod (1979). The Landsat data items were used as independent variables in a multiple regression analysis to predict a number of socio-economic variables. Single family land use and open vacant use were shown to be the most significant Landsat data items in predicting total population. The authors conclude, in part, that one of the major difficulties to be overcome in the use of Landsat data for socio-economic studies is the development of techniques to increase the number of land-use categories. They suggest that it would be more useful to focus on one particular land-use type, and further "that the discrimination of more categories of residential land use would hold the greatest benefit, particularly if this could be expanded to encompass an environmental quality and housing quality index" (Landini *et al.*, 1979, p. 104).

SUMMARY AND OVERVIEW

Associated with the greater use of Landsat data has been the increasing application of computerized methods compared with the virtually exclusive use of visual interpretation methods with large scale photographic sensors. In developing urban classes from Landsat data, researchers have relied on the assumption that the area of study is comprised of a number of unique internally homogeneous classes and that cluster or some other form of grouped analysis can be used to identify these unique classes by means of ground truth areas. A number of researchers have begun to question this approach, which essentially was developed for the recognition of homogeneous agricultural land-use classes. Researchers have pointed out the problem of classifying responses which have derived from a varying mixture of urban surfaces. While a number of attempts have been made to overcome this problem, in general, a marked improvement in classification accuracy has not been forthcoming.

Unlike earlier work with large- to medium-scale photographic sensors, very little progress has been made using Landsat data in image surrogate applications to socio-economic differentiation of urban areas. A number of researchers have inferred or shown for selected areas that a relationship between Landsat data and socio-economic variables does exist, a relationship proved conclusively, in pre-Landsat research, for aerial photographs.

Using data derived from larger scale imagery, there was little need to account for the effects of the atmosphere through which the reflected energy passed. However, for data derived from orbital sensors, atmospheric effects are significant, yet there is very little evidence to suggest that these effects have been considered important in urban area studies. A related problem that also causes a degradation of image quality is the effect of the sensor point spread function. The effects of low registration accuracy between ground truth areas and Landsat data, an insignificant problem with larger scale photographic sensors or homogeneous agricultural areas, would also appear to be a source of classification error.

This review of the use of remotely sensed data in urban areas has indicated a number of scene and sensor related limitations to the current methods being used for the analysis of Landsat data. These have lead to a restriction in its potential to distinguish sub-classes of the residential class and its application to socio-economic studies. These limitations are considered to be due to a number of interrelated causes:

- the heterogeneous nature of urban areas produces a mixed pixel response;
- the point spread function of the sensor integrates the response from the observed and surrounding pixels—in urban areas this can significantly affect

the signature from a single cover class if the surrounding cover is dissimilar;

- within broad general urban land-use classes, particularly residential, a continuum of cover classes exist which cannot be easily broken into discrete nominal classes: this may substantially reduce the effectiveness of cluster or similar analysis for feature determination;
- in urban areas the degradation of the recorded response due to atmospheric effects is dependent on background reflectance and will, therefore, be spatially variable and increase the difficulty of accurate classification; and
- the distance of the sensor from the scene reduces the contextual clues of site and association so that only cover classes and not use classes can be inferred.

AIMS OF THE STUDY

Based on the preceding comments, it was considered that a more detailed analysis of the effects of mixed cover response in residential areas and the relationship of cover variables to socio-economic data was a significant area of research. The results given in this paper, therefore, derive from a major examination of the application of Landsat multispectral data to the analysis of urban residential quality in the Sydney, Australia, metropolitan area (Forster, 1981a). While accounting for these limitations the aims of this research were threefold: first, to determine the reflectance of various urban residential cover surfaces using Landsat data; second, to develop equations to predict the percentage area of surfaces contributing to the total reflectance of a pixel; and third, to determine the relationship between cover percentages, as predicted from Landsat data, and average residential house value as an input to a measure of urban residential quality. It was not the intention of the research to develop general models for urban analysis using Landsat data. However, the results determined and the techniques used may point the way to similar applications in other cities.

The aims necessitated the sampling of ground cover and satellite response from a number of ground truth sites distributed over an urban area. The city of Sydney was chosen for this purpose and a Landsat scene of December 1972, which covered the whole of the Sydney Metropolitan area, was chosen as the Landsat data source. At the time of the commencement of the research program, 1975, this was the most suitable cloud-free image available to the author. Figure 1 illustrates the study area.

Data Collection and Preprocessing

For this study it was considered that a correlation (r) between two variables of less than 0.3 was of limited value and that its significance should be such as to reject the null hypothesis as the one percent level. A minimum of 60 sampled data pairs is required to achieve this significance. It was found that 70 ground truth sampling areas, at approximately four kilometre intervals, adequately covered the Sydney area. Sample areas were considered as those relatively homogeneous single family residential areas at or nearest the four-kilometre grid intervals. A systematic spatial distribution of these areas was decided upon so as to obtain an adequate representation of the sampled population. A cluster of 40 Landsat pixels, eight along-scan and five across-scan, was selected at each sampling site so that the effects of the sensor point spread function could be contained within the sampling area. This effect essentially extends over a three by three array centered upon a target pixel. Each residential area to be used as a ground truth site was, therefore, approximately half a kilometre on a side, which was also considered adequate for analysis of residential neighborhood phenomena.

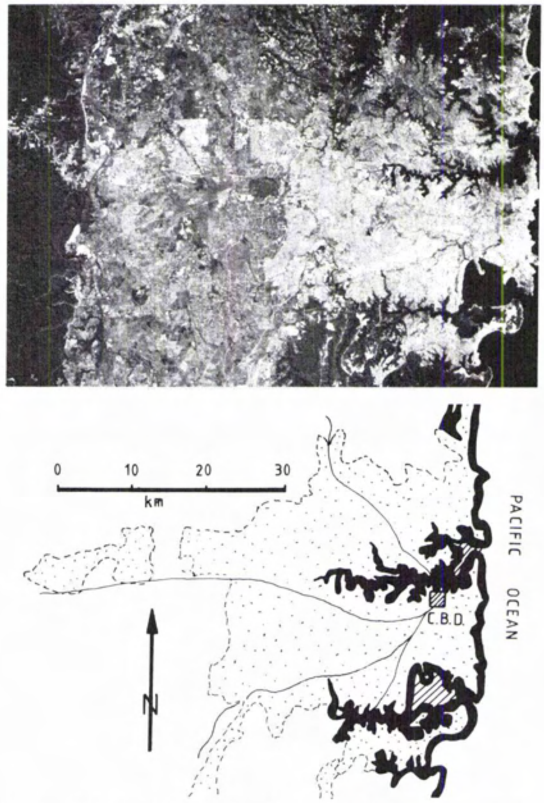

Fig. 1. Landsat image and map of the Sydney metropolitan area. On the map the urban area is shown stippled. On the image, light grey areas are essentially urban, agricultural areas are medium grey, forest areas are dark grey, and water is imaged as black.

Ground control points were selected around each ground truth area, and their coordinates in both the Landsat and ground system were determined. Transformation parameters were calculated which allowed the registration of the selected ground truth area with the Landsat response data on a pixel-by-pixel basis. Ground and Landsat coordinates were related using a fifth order polynominal, resulting in standard errors of the order of 30 metres (Forster, 1980a).

The percentages of various urban cover surfaces, contained in each ground equivalent pixel area, were sampled from large scale (1:15 000) black-and-white panchromatic photographs, taken in late 1971 and enlarged to 1:2 000 to act as a sampling base. Large scale color or color infrared photographs taken at the time of satellite overflight would have been preferred; these, however, were not available. It was considered that a maximum standard error of the estimate of the percentage cover of approximately ten percent would be adequate when an individual cover comprised 50 percent of the pixel. This figure can be approximately obtained when 20 sample points are used per pixel. A stratified unaligned systematic sample with the pixel divided into 20 grid cells was adopted because this method should reduce the systematic effects of a regular urban pattern. An overall cover of sample points is achieved with each point's position in the cell being essentially random. For further details of the sampling procedure see Forster (1980b), and see Figure 2 for a schematic diagram of the overall sampling procedure.

The following data were sampled over each pixel:

- House percentage cover (H)
- Other building percentage cover (O)
- Road percentage cover (R)
- Concrete percentage cover (C)
- Tree percentage cover (T)
- Grass percentage cover (G)
- Number of Houses (N).

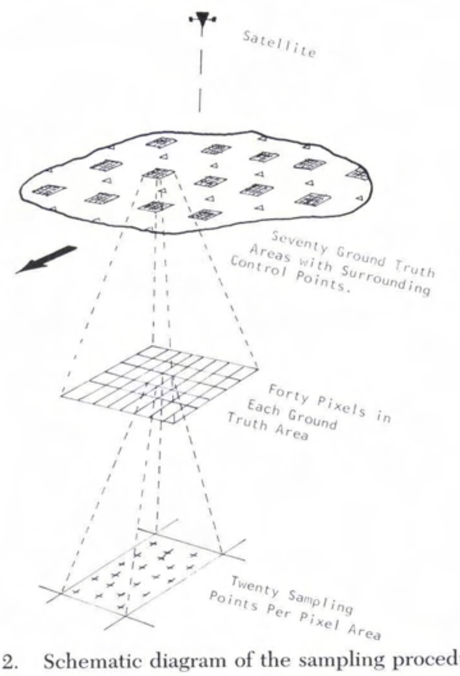

FIG. 2. Schematic diagram of the sampling procedure.

In Sydney, single family residential areas predominantly contain detached one-level housing, although some inner areas contain attached terrace housing. Percentage of roof cover is thus a good measure of house percentage cover. Some roof areas can be effected by overhanging trees, but based on sampling experience this was considered a relatively small effect and liable to cause far less error than that introduced by the sampling procedure. Roofs are mainly red/brown tile and should have similar reflectance characteristics. Other buildings consisted of small buildings separate from the main dwelling and a small percentage of commercial, industrial, and multi-family units that encroached on the predominantly single family dwelling areas. Roads were of asphalt construction, and concrete included footpaths, drives, parking areas, etc. Tree and grass percentages are self explanatory; however, grass at the time of overflight (southern summer) was relatively dry and trees are predominantly native with relatively few deciduous trees. The percentage of other surfaces such as soil and water were sufficiently small to be considered insignificant. The number of houses, N, in each pixel were estimated to the nearest unit. Where the pixel boundaries intersected houses, on the photographs being sampled, these components were added to the whole of house numbers counted. Figures 3 and 4 show enlarged photographs of a low- and a high-density residential area. The photographs illustrate two of the 70 ground truth areas. The total area covered by each image is 40 Landsat MSS pixels, being eight pixels along scan by five lines across. The scan direction of Landsat is from left to right on the photograph.

The equivalent Landsat response in each band for each individual pixel was obtained from the computer compatible tapes (Scene No. 1141-23140) by using the line and pixel coordinates of each to access

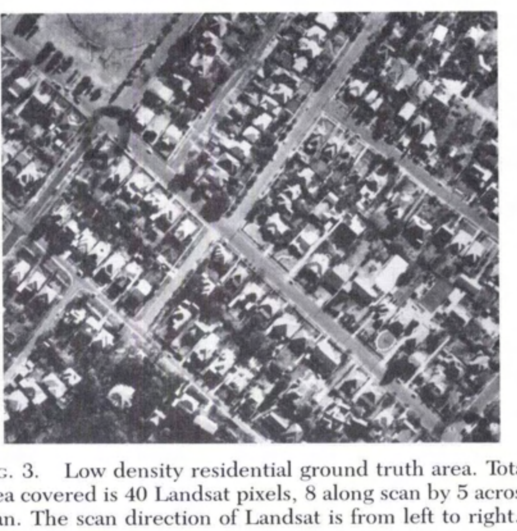

FIG. 3. Low density residential ground truth area. Total area covered is 40 Landsat pixels, 8 along scan by 5 across scan. The scan direction of Landsat is from left to right.

FIG. 4. High density residential ground truth area. Total area covered is 40 Landsat pixels, 8 along scan by 5 across scan. The scan direction of Landsat is from left to right.

the data. The complex effects of atmospheric interaction—including atmospheric transmittance, path radiance, and background reflectance—were removed from the Landsat response data to give percentage reflectance at the pixel level (Forster, 1981a, pp. 26-49). A data file relating cover percentages to pixel reflectance was then created.

Two further data files were prepared which largely accounted for the effects of the sensor point spread function, which effectively integrates the response from the observed and surrounding pixels (Forster, 1981a, pp. 49-53). Reflectance values were deconvolved using the reflectance values of the eight surrounding pixels and the central pixel; i.e., the *true reflectance* value of the central pixel was theoretically restored by mathematically reversing the effect of the sensor point spread function. These deconvolved reflectance values were then listed with the *measured cover data* of the central pixel to form a second data file. A third data file was created by the alternate method of convolving the percentage cover data of each pixel with the percentage cover of its eight surrounding neighbors to give weighted cover percentages. Because of the point spread function, the recorded response is effected by the cover surfaces in the central and the surrounding pixels. Surface cover in the central pixel contributes approximately 50 percent to the observed reflectance, the balance being due to the cover types in the surrounding pixels. For example, the reflectance from a 100 percent grass covered central pixel, surrounded by concrete covered neighbors, would be effectively due to a surface comprised of 50 percent grass and 50 percent concrete. The *observed reflectance* from the central pixel was listed with its equivalent *weighted cover percentages* to form the third data file. For each ground truth area, the mean and standard deviation of the reflectance in each Landsat band were also calculated.

The records of the New South Wales (State) Valuer General were accessed to determine average neighborhood housing values for each ground truth area. For each area the recorded house sales were extracted for the period commencing January 1968 and ending December 1972. The minimum number of house sales in any area was found to be 20. In those areas where more than 20 sales had occurred, a random sample of twenty properties was selected. Sales prices for these properties were adjusted in each area and meaned to give an estimated average neighborhood value for December 1972. The average age of the properties, number of rooms, and housing allotment size and the percentage of houses of each different building material, building type (detached or attached), and number of stories were determined. Additional data were also derived from available maps and comprised distance to the central business district, distance to the nearest coast or waterway, distance to the nearest railway station, average height above sea level, and a measure of terrain variability. These latter variables were considered to reflect some of the environmental and locational attributes of each ground truth area.

RESIDENTIAL SURFACE REFLECTANCE

For Lambertian surfaces, it can be shown (Am. Soc. of Photo., 1975, p. 98) that the reflectance from a mixed cover surface is a function of the proportional amounts of individual cover reflectances contained in that mixture. Apart from highly reflective metal surfaces and water, Forster (1981a, p. 36) considered that *no evidence substantially precluded adopting the Lambertian assumption for all urban materials*. An equation of the form

$$R_i = K_{i1}H + K_{i2}O + K_{i3}R + K_{i4}C + K_{i5}T + K_{i6}G$$

is proposed where R_i is the reflectance measured in Band i and K_{i1} to K_{i6} are coefficients to convert cover percentages (H, O, R, etc.) to reflectance values. Linear equations of this form are suitable for analysis by multiple linear regression techniques. Here reflectance in each band are the dependent variables and percentage cover are the independent variables.

Three models were studied. The first related reflectance to percentage cover without accounting for the effects of the sensor point spread function. The latter two models first related deconvolved reflectance to cover data, and then reflectance to convolved cover data. A forced origin stepwise regression procedure was used, where the constant in the regression is forced to a value of zero and the best subset of variables is output at each stage.

The convolved percentage cover model gave the highest multiple correlation in all four bands, ranging from an r value of 0.72 for band 5 to 0.56

for band 6. The deconvolved reflectance model had lower r values when compared to the other two models. This lower correlation was considered to be due to the deconvolution procedure enhancing not only the reflectance but noise effects as well, leading to larger residuals and hence a reduced correlation.

The calculated regression coefficients for each band and surface cover for the convolved percentage cover model are as shown in the following equations with their respective multiple correlation coefficient, r.

$$R_4 = 0.160H + 0.169O + 0.159R + 0.226C + 0.059T + 0.146G, \ r = 0.66$$

$$R_5 = 0.180H + 0.161O + 0.142R + 0.283C + 0.015T + 0.120G, \ r = 0.72$$

$$R_6 = 0.250H + 0.147O + 0.111R + 0.343C + 0.193T + 0.291G, \ r = 0.56$$

$$R_7 = 0.305H + 0.150O + 0.107R + 0.386C + 0.333T + 0.438G, \ r = 0.69$$

An F-ratio test indicated that all variables and equations were significant at the one percent level of confidence.

Using the regression coefficients of the convolved percentage cover model, estimates of the 100 percent reflectance for each variable in each band were calculated by substituting for the appropriate variable to give the results shown in Table 1 and Figure 5. Estimates of the reflectance for various mixtures can be calculated from the sum of the appropriate surface reflectances weighted by the proportion of area covered by each surface.

Most immediately obvious from Figure 5 is thai the discrimination of the individual covers is greatest in the infrared bands and also the typical vegetative signatures of grass and trees. On closer examination of the reflectance values, it can be seen that grass and trees, house and concrete, and other building and road reflectances closely parallel each other across the four bands; for example, the difference in reflectance between tree and grass is 8.7, 10.5, 9.8, and 10.5 percent for bands 4 to 7, respectively. This indicates three distinct surface classes, with subclasses being differentiated by brightness alone. These three classes might be considered as vegetation, urban residential, and urban non-residential.

PREDICTION OF SINGLE PIXEL COVER PERCENTAGES FROM REFLECTANCE DATA

Various ratios and transformations were examined to determine their value as cover predictors, including band-on-band ratios, band-difference-on-band-sum ratios, band-on-the-sum-of-all-band ratios (normalization), and band-difference/band-sum transformation. Each of these were considered as a set of independent variables for prediction of percentage cover of a particular surface as the dependent variable, necessitating the development of linear relationships between them so that multiple linear regression techniques could be applied. This was achieved by converting the reflectance in each band from rectangular coordinates to polar coordinates of *color ratios and brightness vectors* and second and third order polynomials thereof, which could be linearly related to the convolved cover variables (Forster, 1981a, pp. 72-88). Figure 6 shows the relationship between rectangular coordinates and polar coordinates for pixel reflectances R_4 and R_5 in bands 4 and 5.

Regression analysis of the cover variables with the derived ratios and vectors and with reflectance alone, showed that the band-on-band reflectance ratios in particular, and the normalized and difference-on-sum reflectance ratios generally, were more predictive of surface cover percentage than reflectance variables alone, although all regressions were highly significant. This is in contrast to results published by Richardson and Wiegand (1977), which showed untransformed response data as more predictive of crop and shadow cover percentages; however, these results were from extended fields.

It was found that one variable primarily contributed to the total multiple correlation of the regression, and these are as follows for each cover variable with multiple correction coefficient, r:

$$H\% \text{ (house)} = 43.2 + 44.2\left(\frac{R_5 - R_7}{R_5 + R_7}\right), \ r = 0.55$$

$$O\% \text{ (other)} = 0.5 + 23.3\left(\frac{R_5}{R_7}\right)^2, \ r = 0.53$$

$$R\% \text{ (road)} = 32.1 + 48.0\left(\frac{R_4 - R_7}{R_4 + R_7}\right), \ r = 0.63$$

$$C\% \text{ (concrete)} = -3.1 + 0.29\,(R_4 + R_5), \ r = 0.36$$

$$T\% \text{ (tree)} = -11.9 + 10.3\left(\frac{R_7}{R_5}\right), \ r = 0.68$$

$$G\% \text{ (grass)} = -14.0 + 1.56\,(R_7), \ r = 0.55$$

where R_i = pixel reflectance in bands i = 4 to 7.

TABLE 1. ESTIMATED PERCENTAGE REFLECTANCE FOR VARIOUS TYPES OF URBAN SURFACE COVER

BAND	HOUSE*	OTHER*	ROAD*	CONCRETE*	TREE*	GRASS*
4	16.0	16.9	15.9	22.6	5.9	14.6
5	18.0	16.1	14.2	28.3	1.5	12.0
6	25.0	14.7	11.1	34.3	19.3	29.1
7	30.5	15.0	10.7	38.6	33.3	43.8

* NOTE: Cover types: *House*—residential house roofs, mainly red/brown tile. *Other*—other building roofs, high density residential, commercial, and industrial. *Road*—bitumen, dry. *Concrete*—mainly aged, footpaths and driveways. *Tree*—native trees, mainly eucalyptus. *Grass*—mainly cut grass, dry, southern summer.

In addition, the total vegetative percentage cover (GREEN) was predicted using all significant variables, resulting in the following equation:

$$\text{GREEN} = 72.6 - 110.2\left(\frac{R_5}{R_7}\right) + 13.5\left(\frac{R_7}{R_5}\right) + 0.452\left(\frac{R_5}{R_7}\right)(R_5^2 + R_7^2)^{1/2}$$

(multiple correlation coefficient, $r = 0.82$). The last variable in the equation is a product variable of a color ratio and a brightness vector, which can be shown to be geometrically equivalent to a measure of the difference between bands 5 and 7. A low correlation of -0.13 between grass and tree percentages was determined, which indicates that these cover variables are essentially orthogonal.

APPLICATION TO EXTENDED AREAS

In certain circumstances cover information over extended areas may be preferable to that determined in individual pixels. It would be expected that variance would be reduced by using average reflectance data so that higher multiple correlations could be achieved between average cover and average reflectance. The application to extended areas also raises the possibility of using textural type variables to predict surface cover. Todd and Baumgardner (1973), for example, have found that the standard deviations in the infrared bands aid in separating residential areas.

Average reflectance (and the various derived variables) over each ground truth area was used in a regression analysis to predict average percentage cover in the ground truth areas. In addition, textural variables, represented by reflectance standard deviation over each area and in each band, were also included as independent variables. All correlation coefficients were markedly increased from their single pixel equivalent, from a low of 0.63 for average concrete cover to a high of 0.91 for average tree cover; and in all cases apart from road and concrete cover, the standard deviations were seen to be secondary but significant predictors. The equation for the average house cover percentage (H_a) is as follows:

$$H_a = 136.6 - 57.3\,\frac{R_7}{R_6} - 105.5\,\frac{R_4}{R_6} - 0.643\sum_{i=4}^{i=7} SD_i + 82.8\,\frac{R_5}{R_7}, \qquad (1)$$

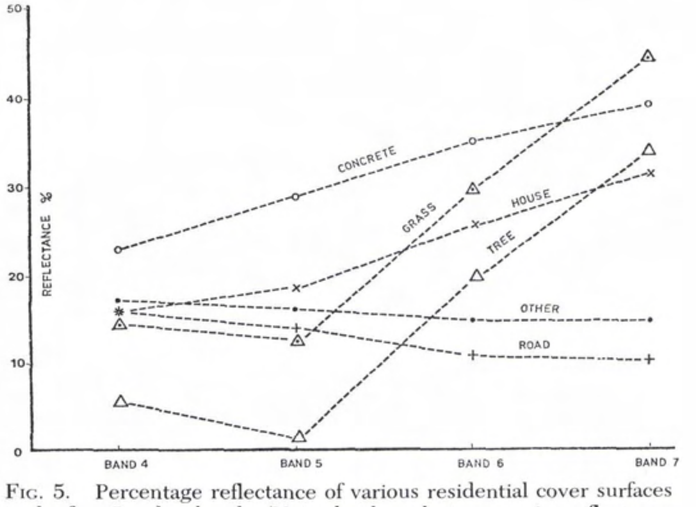

FIG. 5. Percentage reflectance of various residential cover surfaces in the four Landsat bands. (Note that lines between point reflectance values in each band are illustrative only and do not represent continuous reflectance values.)

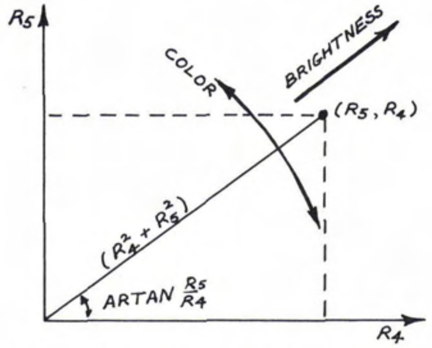

FIG. 6. An illustration of the relationship between reflectance values of a pixel being defined as rectangular coordinates (R_5, R_4) and alternative being defined as polar coordinates $\tan^{-1} R_5/R_4$ (color ratio) and $(R_4^2 + R_5^2)^{1/2}$ (brightness vector).

where SD_i is the standard deviation of reflectance over ground truth areas in bands $i = 4$ to 7.

An important result at this level of aggregation was that the prediction of total vegetative content was no longer dependent on the visible/infrared comparison apparent in single pixel analysis, but on the band 6/band 7 reflectance ratio, a measure of the steep vegetative gradient between these two bands, with a multiple correlation of 0.92. The equation relating total vegetative content over an extended area (AGREEN) to the reflectance ratio is as follows:

$$\text{AGREEN} = 315.0 - 282.1 \left(\frac{R_6}{R_7}\right), \; r = 0.92 \quad (2)$$

A cover related variable that is useful in urban studies is housing density, where housing density is the number of houses per unit area. This variable cannot be predicted in a single pixel situation except by means of its correlation with housing cover, as there is no reflectance measure that can discriminate whether the amount of house cover is due to a small number of large houses or a large number of small houses. However, over an extended area it might be expected that the variance of the reflectance in each band, and particularly in the infrared bands, might be greater the lower the number of houses per unit area, as these areas would tend to have cover and, thus, response substantially varying between pixels, whereas a high density area would be more homogeneous with respect to a pixel area.

Standard deviation in each of the four bands and various reflectance ratios were used in a multiple regression equation with N_a, the average number of houses per pixel, as the dependent variable. The equation predicting this variable was very significant ($r = 0.91$) but quite complex, as it represented a number of interacting effects. It was strongly dependent on the standar deviation in band 7, SD_7, and a non-linear effect of the standard deviation in band 4, SD_4. The predictive equation was as follows:

$$\begin{aligned} N_a & \text{ average number of houses per pixel} \\ &= -5.3 + 24.0 \left(\frac{R_5}{R_7}\right) - 0.62\, SD_7 \\ &\quad + 0.14 \left(\frac{R_6}{R_4}\right) (R_6^2 + R_4^2)^{1/2} \\ &\quad - 2.6\, SD_4 + 0.64\, (SD_4)^2 \\ &\quad - 0.23 \left(\frac{R_5}{R_6}\right) (R_5^2 + R_6^2)^{1/2} \qquad (3) \end{aligned}$$

Because it is not a cover variable, the potential to predict such a variable is an important result. The equation can be modified to give an average density of housing per hectare or per acre by dividing by pixel area. Note that this is an aggregate result and refers to the average density over a 40-pixel ground truth area.

It was shown previously that percentage house cover could be predicted using Landsat data at either the pixel or ground truth area level. Dividing predicted average percentage house cover by the average number of houses per pixel will give an estimate of the average percentage of pixel area covered by one house, that is, single level house size when multiplied by pixel area.

DERIVING HOUSE VALUES FROM LANDSAT DATA

The prediction of cover percentages at the pixel level, or cover percentages and housing density at the extended area level, can obviously have direct application in many urban studies. Of greater interest is the ability to predict characteristics of residential areas seemingly unrelated directly to these cover variables. Very little progress has been made using Landsat data in image surrogate applications to socio-economic differentiation of urban areas. This is in contrast to earlier work by Green (1957), Mumbower and Donoghue (1967), Metivier and McCoy (1971), and others using large- to medium-scale photographic sensors. Landini and McLeod (1979) suggest that one of the major difficulties to be overcome in the use of Landsat data for socio-economic studies is the development of techniques to increase the number of residential land-use classes.

In recent years the attention of researchers from many different fields including economics, geography, sociology, and planning has been directed to examining from which attributes of housing the consumer derives utility and whether these can be ranked in a meaningful way. It is argued that, if one house or group of houses has more desirable attributes than another, this higher valuation by the customer will be reflected in a higher ranked value.

Most of these studies can be grouped into one of four areas (Forster, 1975):

- Housing characteristic models ignore the locational and environmental characteristics of a neighborhood. They assume that house values are determined solely by the characteristics of the house itself.
- The most common models are those predicting house values on the basis of the trade-off between housing costs and transport. The accessibility models, of which Alonso (1964) is the most well known, predict that house values decline with distance from the central business district (CBD) and also that house values will be higher in areas having above average accessibility.
- Environmental or area preference models reflect researchers attempts to explain differences in house value in terms of neighborhood attractiveness. Richardson (1971) and others have put forward the hypothesis that the environmental attributes of an area determine the residential site choice.
- Universal models incorporate all of these factors that influence house value. They are usually disaggregated into locational and environmental effects with some measure of the socio-economic nature of the neighborhood and housing characteristics.

In this study the average house value over each ground area, at a specific time, was only considered. While it is considered that the absolute relationship between property values could vary quite quickly in times of rapid price increases, the underlying relative relationships are not as prone to rapid change (Timms, 1971, pp. 120–121). What are considered as *good* neighborhoods or *poor* neighborhoods do not change quickly but are subjected to historically quite long movements. These average values were examined using generalized universal models, which include some measure of location, environment, and average housing characteristics. Data were derived essentially from three main sources: actual house sales data, data sampled from aerial photographs, and satellite derived data.

The average area house values, P, as derived from the Valuer General's records were used as the dependent variable in a multiple regression analysis with all sampled housing characteristics, locational data, and terrain data as the independent variables. Quadratic values of distance to the CBD and number of rooms were also included with the independent variables as it was considered that these variables might not be linearly related to house value. Stepwise multiple regression was used with a minimum F-ratio criterion of 4.0 for each variable to enter the regression.

The most significant variable predicting average house value was found to be the number of rooms (squared) followed by distance to the nearest railway station. This latter variable was only marginally significant, with the multiple correlation coefficient, r, increasing from 0.86 to 0.88 as it entered the regression.

From a consideration of these results, it was expected that a measure of house size derived from the photographically sampled variables should also be a good predictor of average value. Such a variable can be derived by dividing H_a (average percentage of house cover per pixel) by N_a (average number of houses per pixel); therefore, house size percentage

$$HZ = \frac{H_a}{N_a}$$

where HZ = the average percentage of pixel area covered by one house.

In addition to HZ and HZ^2, all cover variables and locational variables were regressed with P (average house value) as the dependent variable. Only three variables were significant, HZ^2, HZ, and R_a (average percentage of road cover per pixel), the latter variable being the least significant variable to enter the regression equation. Multiple correlation, r, was 0.88. The derived equation was as follows:

$$P = 109.6 + 3.75\ HZ^2 - 34.0\ HZ - 0.5\ R_a$$

where P is in thousands of dollars (Forster, 1981b).

This is an equivalent result to that achieved using known housing characteristics. It is considered that R_a possibly represents a negative environmental effect or may also represent a locational effect because road cover percentage tends to be higher nearer the CBD.

The emergence of a measure of house size as the major predictor of average house value is an interesting result. This is not to say that the size of a house is the major reason for value differences, only that this variable incorporates many other factors. It could be argued, for example, that in environmentally attractive areas the original subdivisions were designed to appeal to a wealthy market, allotments were made larger, higher prices were paid, and larger houses were built to reflect the status of the occupant. Further relationships could be examined, but suffice to say that the house size variable has the potential to act as a surrogate for environmental and socio-economic factors.

A new variable HZ^1, representing the Landsat equivalent of HZ, was determined by dividing Equation 1 by Equation 3. The correlation between HZ and HZ^1 was found to be 0.70. While this correlation was lower than expected, it still represented a significant result. The regression equation between HZ and HZ^1 also shows that the relationship is essentially correct because the constant term is very close to zero, and the coefficient is very close to one as follows:

$$HZ = 0.19 + 0.98\ HZ^1$$

The new variables HZ^1 and $(HZ^1)^2$ and locational variables were regressed with P, average house value, as the dependent variable. Once again HZ^1 was the most explanatory variable, with average height above sea level of the ground truth area and distance to water bodies being just sufficiently significant to enter the equation. A multiple correlation coefficient of 0.62 was determined. While the latter two variables are different from those determined previously, they still represent a measure of location, although somewhat more environmentally related. The more elevated areas tend to be north of the CBD and western areas furtherest from the sea.

It was considered that an alternative to using the calculated value HZ^1, which is a rather cumbersome combination of reflectance derived variables, was to use reflectance values directly in a regression equation with *P*. House value as the dependent variable was regressed against reflectance, ratio, and textural type variables and a number of locational variables previously determined as the independent variables. The following equation resulted:

$$P = 167.6 - 5.8 \left(\frac{R_4}{R_5}\right) (R_4^2 + R_5^2)^{1/2} - 0.9 \text{ CBD}$$

where P = average house value, December 1972, in thousands of dollars (Australian),
and CBD = distance to the central business district, in km.

The overall correlation coefficient was 0.60 with a standard error of \$A16,200, the locational variable, CBD, being only marginally significant.

The value of *r* of 0.60 seemed somewhat low, and an examination of the residuals revealed that two areas had predicted values substantially below their measured values. These represented two unique areas within the data set. Average values for each were \$A115,000 and \$A127,000, while the balance of areas ranged in average value from \$A14,000 to \$A73,000. Equivalent values for 1983 would be approximately four or five times larger. The predicted values still indicated, however, that both areas were at the top of the value range with values of \$A62,000 and \$A75,000, respectively, but that many other undefined factors apart from house size and location contributed to average value. Both areas are commonly known as the two most exclusive areas in Sydney—Bellevue Hill and Vaucluse. These areas have a significant proportion of two-storied houses, which would result in the house size effect being underestimated. Removal of these two unique areas from the data set resulted in a substantially higher multiple correlation of 0.73.

The major explanatory variable in predicting average house value was a reflectance derived product variable of band 4 and band 5 color ratio and vector brightness variables. Response from bands 4 and 5 are usually considered so highly correlated that little information is contained in them. Forster (1980b), however, has shown that the difference between bands 4 and 5 is correlated with concrete percentage and to a lesser extent house percentage cover, and this may explain the correlation with house value. By a simple geometric manipulation, it can be shown that the product of the color ratio, R_4/R_5, and the brightness vector, $(R_4^2 + R_5^2)^{1/2}$, is a measure of the difference between the reflectance in bands 4 and 5. Thus, average house value can be approximately differentiated by the difference in the reflectance of these two bands.

House value predicted from Landsat data cannot be considered as a reliable source for detailed analysis; however, as Westerlund (1972, p. 39) suggests of Mumbower and Donoghue's (1967) photographically derived housing density, it has benefit for initial analysis. If five arbitrary classes of house value are assumed 0 to \$80,000 in steps of \$20,000 and greater than \$80,000, then the following results can be calculated. From the regression equation, 62 percent of the areas would be correctly classified from the predicted results, 33 percent would be one class either above or below their predicted class, and 5 percent would be removed by two class divisions. These results should generally satisfy the need for more residential classes as expressed by Landini *et al.* (1979, p. 104).

DERIVATION OF A RESIDENTIAL QUALITY INDEX

As Richardson (1971) suggests, house value difference may be explained in terms of environmental or area preference models. While there are some reservations to this hypothesis, it could be assumed that house value or a measure thereof is an indicator of residential environmental quality. In addition, many studies have shown a relationship between house value or rent and socio-economic status, classically represented by Hoyt's sector theory (see for example Timms (1971) for a discussion of this theory). It could be suggested, then, that house size as a surrogate for house value may be a measure of housing quality and social environment.

The percentage of grass and trees in an area can normally be associated with environmental quality, indicating open space and aesthetic qualities. Narigasawa and Fuchimoto (1979) have used a vegetation cover ratio determined from multispectral scanner data as one of a number of environmental themes. Green (1957) and Green *et al.* (1959) have also suggested the prevalence of industrial land use as a negative residential quality measure. While there are other factors contributing to residential quality, the purpose of this section is to demonstrate how a general quality index might be achieved.

If it is assumed that:

(i) house size is a measure of housing quality and social environment and would be positively related to a residential quality index,

(ii) the total vegetative content is a positive indicator of quality, and
(iii) the sum of road and other building percentages represents the negative influence of encroachment of non-residential land use and likely high noise and pollutant levels, then a residential quality index, RQI, can be represented by

$$\text{RQI} = \frac{(\text{House Size}) \times (\text{Average Tree} + \text{Grass\%})}{(\text{Average Road} + \text{Other\%})}$$

where house size is the average pixel percentage area occupied by a single dwelling, and was determined by dividing house percentage per pixel by the number of houses per pixel, both having been interpreted from air photographs over each ground truth area. The variable RQI was used as the dependent variable in a regression with various reflectance variables as the independent variables in order to give the following equation:

$$\text{RQI} = -130 + 674\left(\frac{R_6}{R_5}\right) + 113\left(\frac{R_5}{R_6}\right) - 1.8\left(\frac{R_4}{R_5}\right)(R_4^2 + R_5^2)^{1/2}$$

(multiple correlation, r = 0.87).

It should be noted that the major influence on the quality index comes from the infrared/visible ratio that correlates highly with vegetation content.

OTHER POTENTIAL URBAN APPLICATIONS OF DERIVED DATA

Very rarely can remotely sensed data be used as the sole source of information about an area. Any survey of an area must draw on all available data and then select a subset which in terms of cost, speed, and reliability can satisfy the defined goals of the survey. It is with this point in mind that potential applications are suggested.

(i) Urban catchment runoff studies require, as input, data on rainfall, slopes, and surface characteristics. A typical urban drainage system is made up of a number of elements which drain sub-catchment areas. Cover percentage determined from Landsat data at either the single pixel or extended area level could be used to derive aggregate coefficients of runoff. Over each area these coefficients could be used with slope data, derived from topographic maps or digitally held terrain models, and rainfall intensity data to calculate the rate and magnitude of surface runoff.

(ii) A number of researchers have suggested the application of Landsat data to population estimation. While predicted housing cover can be used as a surrogate for population density, it is preferable to use housing density as a measure of the number of families. Size of family also tends to vary between socio-economic groupings. If house size or house value is a surrogate for socio-economic status and is used in conjunction with housing density, both derivable from Landsat data, then the potential exists for a better estimation of population and its areal distribution.

Census data give very accurate estimates of population within each census district, but the boundaries of districts are generally not related to any stratification within the community or the landscape and so can contain mixtures of land use and housing types. In these circumstances, the population densities determined from the aggregated census district data may bear little relationship to actual densities in particular sub-areas. Landsat derived population estimates would help overcome this anomally.

(iii) Two major orthogonal factors that are cited from social area analysis of western industrialized cities are family status and social status. These factors appear to be reflected in the physical environment of the Sydney urban area. Percentage grass cover and percentage tree cover are uncorrelated, and when combined with measured house size and housing density might suggest themselves as surrogate variables for the orthogonal, family, and social status factors.

SUMMARY AND CONCLUSIONS

Multiple regression analysis was found to be a satisfactory method for determining cover reflectance from Landsat data, and also for determining significant single variable and multiple variable cover percentage predictive equations. A GREEN index representing percentage of total vegetative cover, with a multiple correlation of 0.82, was most reliably predicted at the single pixel level.

The correlation between cover and reflectance type variables was substantially improved when regression analysis was used with extended data, and was due to the reduction of variance and the addition of textural variables. The ability to predict the average number of houses per pixel from reflectance data and thus a measure of house dimension is considered an important result of the extended data analysis.

It has been demonstrated that the average house value in Sydney can be substantially predicted from Landsat derived reflectance data, with a readily available locational variable acting as a secondary predictor. It cannot be concluded that this type of analysis would be directly applicable to other cities. Nevertheless, while Sydney has many unique characteristics, it is not atypical of western industralized cities, and in population, size, residential density, morphology, and climate is quite similar to the western seaboard North American cities of Los Angeles and San Francisco. The emergence of the single variable house size as the primary predictor of value would suggest that these general results could be applicable in other similar cities. It must be stressed, however, that the results were for one city at one particular point in time and for residential areas that contined predominantly single level, single family housing.

The demonstration of the use of Landsat data for predicting a residential quality index and the suggested applications of reflectance derived cover data and cover related data indicates that the potential of satellite data as a tool in urban analysis is considerable, particularly when it is used in association with other readily available data. This potential will be considerably enhanced when data from the new generation of higher resolution satellite systems, such as Landsat 4 TM and SPOT, are available.

References

Alonso, W., 1964. *Location and Land Use: Toward a General Theory of Land Rents.* Harvard University Press.

American Society of Photogrammetry, 1975. *Manual of Remote Sensing.* Reeves, R. G. (ed.), Falls Church, Va.

Bailey, M. A., 1979. The Structure of the Urban Landscape as Defined by Data from Landsat. Paper presented at the First Australasian Landsat Conference, Sydney.

Binsell, R., 1967. *Dwelling Unit Estimation from Aerial Photography.* Remote Sensing Laboratory, Department of Geography, North Western University, Evanston.

Bowden, L. W., 1968. *Multi-sensor Signatures of Urban Morphology, Function and Evolutions.* Status Report II, Tech. Rep. No. 2, Department of the Interior, Washington, D.C.

Branch, M. C., 1948. *Aerial Photography in Urban Planning and Research.* Harvard City Planning Series, No. 14, Harvard University Press, Cambridge.

———, 1971. *City Planning and Aerial Information. Harvard University Press, Cambridge.*

Carter, P., 1977. Automated Land Use Mapping Using Aerial/Satellite Data. Report No. RRL77/543, Image Analysis Group, Atomic Energy Research Establishment, Harwell, England.

Collins, W. G., and P. W. Bush, 1969. The Use of Aerial Photographs in the Study of Derelict Land. *Journal of Town Planning Institute,* 55, pp. 246-255.

Collins, W. G., and Aly. H. A. El-Beik, 1971. The Acquisition of Urban Land Use Information from Aerial Photographs of the City of Leeds (Great Britain). *Photogrammetria,* Vol. 27, No. 2, pp. 71-92.

De Bruijn, C. A., W. G. L. De Haas, P. Hofstee, A. B. M. Hijland, and V. F. L. Pollé, 1976. Urban Survey with Aerial Photography: A Time for Practice. *Proceedings of Commission VII, 13th Congress, I.S.P.,* Helsinki, pp. 185-224.

Dye, R. H., 1975. Restoration of Landsat Images by Discrete Two-Dimensional Deconvolution. *Proceedings of the 10th International Symposium on Remote Sensing of Environment,* Vol. 11, Ann Arbor, pp. 725-730.

Ellefsen, R., L. Gaydos, P. Swain and J. R. Wray, 1974. New Techniques in Mapping Urban Land Use and Monitoring Change for Selected U.S. Metropolitan Areas, an Experiment Employing Computer Assisted Analysis of ERTS-1 MSS Data. *Proceedings of Symposium on Remote Sensing and Photo Interpretation,* International Society for Photogrammetry, Commission VII, Banff, Canada, pp. 51-63.

Erb, R. B., 1974. *ERTS 1 Urban Land Use Analysis.* Report for period July 1972—June 1973, in The ERTS-1 Investigation (ER-600), Vol. V, NASA TM X-58121.

Eyre, A. L., B. Adolphus, and M. Amiel, 1970. Census Analysis and Population Studies. *Photogrammetric Engineering,* Vol. 36, No. 5, pp. 460-466.

Forster, B. C., 1975. *The Derivation of an Urban House Price Model.* M.Sc. Thesis, University of Reading, U.K.

———, 1980a. Urban Control for Landsat data. *Photogrammetric Engineering and Remote Sensing,* Vol. 46, No. 4, pp. 539-545.

———, 1980b. Urban Residential Ground Cover Using Landsat Digital Data. *Photogrammetric Engineering and Remote Sensing,* Vol. 46, No. 4, pp. 547-558.

———, 1981a. *Some Measures of Urban Residential Quality from Landsat Multispectral Data.* Unisurv S18. (School of Surveying, University of New South Wales) 211 p.

———, 1981b. Analysis of Urban Residential Areas Using Landsat Derived Data as a Surrogate for the Determination of Average Relative House Prices. *Proceedings of 24th Australian Survey Congress,* Sydney. pp. 47-53.

Gibson, L. J., 1976. *The Use of Aerial Photography for Spoiled and Derelict Land Studies: with Special Reference to Glamorgan.* Unpublished Ph.D. Thesis, University of Aston. 283 p.

Green, N. E., 1957. Aerial Photographic Interpretation and the Social Structure of the City. *Photogrammetric Engineering,* Vol. 23, No. 1, pp. 89-96.

Green, N. E., and R. B. Monier, 1959. Aerial Photographic Interpretation of the Human Ecology of the City. *Photogrammetric Engineering,* Vol. 25, No. 5, pp. 770-773.

Hadfield, S. M., 1963. *An Evaluation of Land Use and Dwelling Unit Data Derived from Aerial Photography.* Chicago Area Transportation Study, Chicago.

Horton, F. E., and D. F. Marble, 1969. Housing Quality in Urban Areas: Data Acquisition and Classification Through the Use of Remote Sensor Imagery. Paper presented at the NASA-MSC Program Review, Houston, September, 1969.

Hsu, Shin Yi, 1970. Inter-Census Population Estimation by the Use of Photos and USGS Topographic Maps; a Sample Study of Population Change in the Atlanta Area. Paper presented at ASP-ACSM Annual Convention, Washington, D.C., March, 1970.

Kawata, Y., Y. Haba, T. Kusaka, Y. Terashita, and S. Ueno, 1978. Atmospheric Effects and their Correction in Airborne Sensor and Landsat MSS Data. *Proceedings of the 12th International Symposium on Remote Sensing of Environment,* Vol. 11, Manila, pp. 1241-1257.

Landini, A. J., and R. G. McLeod, 1979. Using Population Statistics for a First Look at the Utility of Landsat Data for Urban Areas. *Remote Sensing Quarterly*, Vol. 1, No. 1, pp. 80-105.

Mac Phail, D. D., and L. F. Campbell, 1970. The El-Paso (Texas-New Mexico) Study Area: A Comprehensive Analysis of Gemini 4 and Apollo 6 and 9 Space Photography. Paper presented at AAG Commission on Geographic Applications of Remote Sensing, East Tennessee State University, Johnson City.

Metivier, E. D., and R. M. McCoy, 1971. Mapping Urban Poverty Housing from Aerial Photography. *Proceedings 7th International Symposium on Remote Sensing of Environment*, Ann Arbor, University of Michigan, Vol. 2., pp. 1563-1570.

Moore, E. G., 1969a. *Collection of Housing Quality Data by Remote Sensor: The Los Angeles Experiment*. Remote Sensing Laboratory, Dept. of Geography, Northwestern University, Evanston.

———, 1969b. *Application of Housing Aggregates to Quality Classes: The Potential of Photographic Sensors*. Remote Sensing Laboratory, Dept. of Geography, Northwestern University, Evanston.

———, 1970. *Application of Remote Sensors to the Classification of Areal Data at Different Scales: A Case Study in Housing Quality*. Remote Sensing Laboratory, Dept. of Geography, Northwestern University, Evanston.

Mumbower, L. and J. Donoghue, 1967. Urban Poverty Study. *Photogrammetric Engineering*, Vol. 33, No. 6, pp. 610-618.

Narigasawa, K., and M. Fuchimoto, 1979. Urban Environmental Survey by Remote Sensing. Presented Paper, Thirteenth International Symposium on Remote Sensing of Environment, Ann Arbor.

Richardson, A. J., and C. L. Wiegand, 1977. Distinguishing Vegetation from Soil Background Information. *Photogrammetric Engineering and Remote Sensing*, Vol. 43, No. 12, pp. 1541-1552.

Richardson, H. W., 1971. *Urban Economics*. Penguin.

Thrower, N. J., R. H. Mullens, and L. W. Senger, 1968. Analysis of NASA Color Infrared Photography of Los Angeles, in *Mission 73 Summary and Data Catalog*, (R. F. Pascucci, and G. W. North (eds)). National Aeronautics and Space Administration.

Thrower, N. J., R. H. Mullens, L. W. Senger, and K. J. Walton, 1970. *Satellite Photography as a Geographic Tool for Land Use Mapping of the South Western U.S., 1 July 1968—31 January 1970*. Technical Report 69-3, East Tennessee State University, Johnson City.

Timms, D., 1971. *The Urban Mosaic*. Cambridge Geographical Studies, Cambridge University Press.

Todd, W., and M. F. Baumgardner, 1973. *Land Use Classification of Marion County, Indiana, by Spectral Analysis of Digitized Satellite Data*. LARS Information Note 101673, Purdue.

Todd, W., P. Mausel, and M. F. Baumgardner, 1973. *An Analysis of Milwaukee County Land Use by Machine Processing of ERTS data*. LARS Information Note 022773, Purdue.

Turner, R. E., 1975. Signature Variations due to Atmospheric Effects. *Proceedings of the 10th International Symposium on Remote Sensing of Environment*, Vol. 11, Ann Arbor. pp. 671-682.

Turner, R. E., W. D. Malila, and R. F. Nalepka, 1971. Importance of Atmospheric Scattering in Remote Sensing or Everything You've Wanted to Know About Atmospheric Scattering but were Afraid to Ask. *Proceedings of the 7th International Symposium on Remote Sensing of Environment*, Vol. 111, Ann Arbor, 1651-1695.

Turner, R. E., and M. M. Spencer, 1972. Atmospheric Model for Correction of Spacecraft Data. *Proceedings of the 8th International Symposium on Remote Sensing of Environment*, Vol. 11, Ann Arbor. pp. 895-934.

Tuyahov, A. J., S. Davies, and R. K. Holz, 1973. Detection of Blight Using Remote Sensing Techniques, in *Remote Sensing of Earth Resources*, Vol. 2, (ed.) F. Shahrokhi, Space Institute, University of Tennessee. pp 213-226.

Wellar, B. S., 1968a. *Generation of Housing Quality Data from Multiband Aerial Photographs*. Technical Letter NASA-119, NASA Manned Spacecraft Center, Houston.

———, 1968b. *Hyperaltitude Photography as a Data Base in Urban and Transportation Research*. Remote Sensing Laboratory, Department of Geography, Northwestern University, Evanston.

———, 1969. The Role of Space Photography in Urban and Transportation Data Series. *Proceedings of the 6th Symposium on Remote Sensing of Environment*, Vol. 11, Ann Arbor. p. 831.

Westerlund, F. V., 1972. *Remote Sensing for Planning: a Bibliography and Review of Literature*. Urban Planning/Development Series, No. 10, Department of Urban Planning, University of Washington, Washington.

Witenstein, M. M., 1954. Photo Sociometrics. The Application of Aerial Photography to Urban Administration and Planning Problems. *Photogrammetric Engineering*, Vol. 20, No. 3, pp. 410-427.

———, 1955. Uses and Limitations of Aerial Photography in Urban Analysis and Planning. *Photogrammetric Engineering*, Vol. 21, No. 4, pp. 566-573.

———, 1956. A Report on Application of Aerial Photography to Urban Use Inventory, Analysis and Planning. *Photogrammetric Engineering*, Vol. 22, No. 4, pp. 656-664.

———, 1957. A Review of Aerial Photographic Interpretation and the Social Structure of the City. *Photogrammetric Engineering*, Vol. 23, No. 2, pp. 97.

Wray, J. R., 1960. Photo Interpretation in Urban Area Analysis, in *Manual of Photographic Interpretation* (R. N. Colwell, ed.) American Society of Photogrammetry, Washington, D.C. pp. 667-703.

———, 1970. Census Cities Project and Atlas of Urban and Regional Change. *Proceedings of Third Annual Earth Resources Program Review*, Vol. 1, Houston, pp. 2–1-2–16.

Zobrist, A. L., N. A. Bryant, and A. J. Landini, 1976. IBIS-A Geographical Information System That Can Use Satellite Data for Urban Analysis. Paper presented URISA National Conference, Atlanta, Georgia.

(Received 12 June 1982; revised and accepted 29 June 1983)