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ANALYSIS OF URBAN AREA LAND COVER USING SEASAT SYNTHETIC APERTURE RADAR DATA

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16. Abstract
Digitally processed Seasat Synthetic Aperture Radar (SAR) imagery of the Denver, Colorado urban area is examined to explore the potential of SAR data for mapping urban land cover and the compatability of SAR derived land cover classes with the United States Geological Survey classification system defined by Anderson, et.al. The imagery is examined at three different scales to determine the effect of image enlargement on accuracy and level of detail extractable. At each scale the value of employing a simplistic preprocessing smoothing algorithm to improve image interpretation is addressed. A visual interpretation approach and an automated-machine/visual approach are employed to evaluate the feasability of producing a semi-automated land cover classification from SAR data. Confusion matrices of omission and commission errors are employed to define classification accuracies for each interpretation approach and image scale.

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PREFACE

OBJECTIVE

The objective of this study is to explore the capability of digitally processed L-band Seasat synthetic aperture radar (SAR) imagery for mapping urban land cover and the compatability of the SAR derived land cover classes with those described in the United States Geological Survey land use/ land cover classification system of Professional Paper 964 (Anderson, et.al., 1976).

SCOPE OF WORK

The Denver, Colorado, metropolitan area served as the study area for this investigation. To determine the level of land cover detail extractable the imagery was analyzed at three different scales. At the small scale (1:500,000) the entire Seasat scene was classified using Level I categories. At the medium scale (1:131,000) Level II categories were employed in interpreting a 367 km^2 area of urban land cover types. Finally, the data were subjected to maximum enlargement (1:41,000) and six study sites representative of all urban land cover conditions in the area selected for mapping at Level II detail. Two distinct approaches were employed in examining the data--a visual interpretation of the black-and-white imagery and an automated-machine/visual interpretation of the study areas. The purpose was to evaluate the feasibility of producing semi-automated land cover classifications with SAR data and to assess the contribution of each approach. To determine accuracy the SAR interpretations were evaluated through omission/commission matrices.

CONCLUSIONS

To obtain useful imagery for land cover analysis at the small or medium scale it was necessary to employ an averaging algorithm to reduce noise inherent in the data.

The raw data products were satisfactory for interpretation of the large scale imagery.

Until smoothing and averaging algorithms can be developed for incorporation into the data prior to level-slicing and color-coding it is believed density slicing will prove of little value for urban land cover analysis with Seasat SAR data.

Level I land cover classes can be delimited for synoptic mapping of urban areas.

At medium scale enlargement Level II category detail can be extracted, but the SAR derived land cover categories are not precisely comparable. New residential areas can be delimited as can the central business core, open space, and elements of industry and transportation. However, discrimination of small commercial zones and the precise boundaries of interior residential areas are imprecise. An overall accuracy of 87.9 per cent was achieved.

The most precise measurements of urban growth patterns can be made with the large scale imagery. Location and delimitation of the extent of urban growth is facile. Open space is readily identifiable, but defining its use is arduous. No single type or class of transportation is consistently visible.

At the large scale the highest interpretation accuracies (over 90 per cent) were obtained in the urban fringe areas while the poorest results (71 per cent) were obtained in the interior sections of the city where a complex mix of residential, commercial, industrial, and transportation activity is found.

The effects of radar azimuth on the land cover categories resulted in dissimilar tone/texture response for similar urban land cover categories.

RECOMMENDATIONS

Further work in developing pre-processing algorithms to smooth the data is recommended.

Urban areas in other settings (e.g., older cities, humid environments, different economic bases) should be analyzed to determine the consistency of land cover classification and detail.

The textural component and the susceptability of radar return to the angular, geometric patterns of man-made structures produce unique signal responses corresponding to the same or dissimilar urban land cover types. An effort must be made to precisely understand this relationship and develop more sophisticated algorithms to abet the interpretation process. This includes the examination of effects of wavelength, polarization, and look direction.

Research devoted to the possible synergetic effect of merging the textural component of SAR data with the spectral information available with multi-spectral scanner data deserves serious attention.

ACKNOWLEDGMENT

The author wishes to thank Stephen W. Wharton for his assistance in imagery generation with the Image 100 system and application of algorithms to the raw data tapes.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF TABLES

INTRODUCTION

Many new methods are being explored and developed to improve the urban data base. In planning for and monitoring the constantly changing urban mileau information is needed more rapidly and at a higher level of consistency, quality, and detail. Of the techniques being examined with this objective in mind, remote sensing systems are receiving considerable attention. Although much of the remote sensing effort to date has focussed on visible and near infrared sensor systems operating from aircraft and spacecraft platforms the potential of radar imagery also merits attention.

With the forthcoming launch of Shuttle-borne Space Imaging Radar (SIR) systems and the European Space Agency's "European SAR-580 Campaign", radar data will become more readily available to the user community. In certain instances where low-light or inclement weather conditions are extant radar may prove to be the only sensor capable of providing data. Equally if not more important is an assessment of the potential of radar imagery as a complement to other sensor systems. Radar is unique in that it is the only active imaging system. As such, the question arises as to what distinct contribution to urban data collection can be made by radar as a function of its sensitivity to texture, surface roughness, spatial orientation, background contrasts, and other system/environment related parameters. In short, what can radar offer?

To explore the advantages and potential of active sensor systems from space altitudes the National Aeronautics and Space Administration launched the Seasat satellite on 28 June, 1978. This was the first satellite dedicated to establishing the utility of microwave sensors for analysis of oceans and marine phenomena. Among the sensors on board was an L-band (23 cm wavelength) synthetic aperture radar (SAR) system with 25 meter (nominal) spatial resolution. As the spacecraft passed over the earth, the SAR, looking to the

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starboard side of the satellite, imaged a 100 km wide swath centered 23° off nadir. After some three months of operation a massive power failure forced the shutdown of the system on 10 October, 1978. However, during its operational life the satellite did provide considerable data for scientific examination and for input into the design and expected results of the upcoming Space Shuttle SAR systems.

The purpose of this study is to explore the capability of digitally processed L-band Seasat SAR imagery for mapping urban land cover and the compatability of the SAR derived land cover classes with those described in the United States Geological Survey land use/land cover classification system designed by Anderson, et.al. (1976).

STUDY AREA

The 6 August, 1978, 100 km x 100 km digitally processed SAR scene (Revolution 580, ascending pass) of the Denver, Colorado metropolitan area served as the study area (Figure 1).

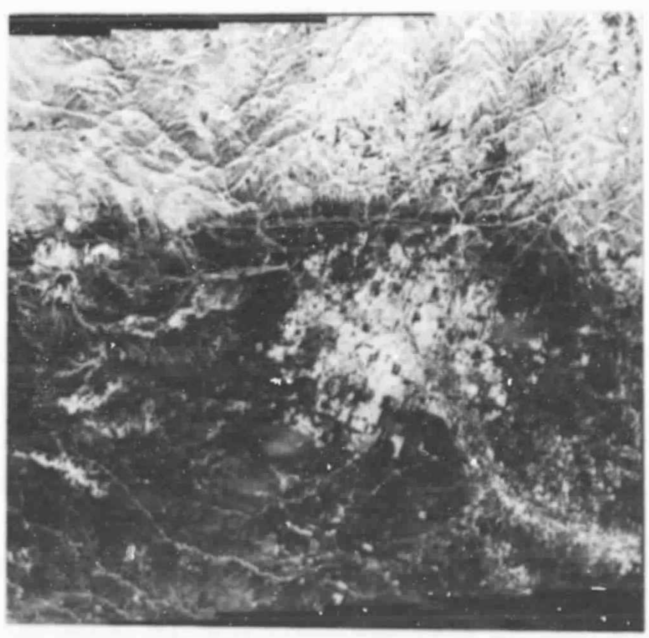

Figure 1. Digitally Processed SAR Scene of Denver, Colorado

Several factors contributed to the selection of Denver for examination. Denver is a rapidly growing urban area with a variety of urban land cover types including examples of several stages and ages of urban development. Considerable auxillary remote sensing and cartographic data were available to serve as ground truth. A photo mosaic was created from 1:24,000 scale black-and-white photography flown over the Denver area on 15 October, 1978. Color infrared photography flown in 1973 and 1978 (scale - 1:130,000) for portions of the area and a 1971 land use map compiled by the United States Geological Survey were available for verification of SAR analysis. The city is also one of the urban sites selected by the United States Bureau of the Census in their development of Geo-based Information Systems. As such, an extensive body of secondary information was accessible for checking actual ground land cover characteristics against the SAR interpretation.

Six sub-areas of the Denver SAR scene representative of Level II urban land cover categories extant in the area were identified for detailed analysis of land cover types (Figure 2). They were selected by examining the aerial photography and locating areas which contained examples of the following urban land cover: older residential area in the city interior; new residential areas on the urban fringe; single and multiple family housing; industrial; commercial and service; recreation and open space; and transportation.

METHODOLOGY

Black-and-white prints of the study area were generated from the digital tapes at three different scales using the Image 100 interactive processing system at Goddard Space Flight Center: 1) 1:500,000; 2) 1:131,000; and 3) 1:41,000. The first scale depicted the full SAR scene and the second scale provided an intermediate scale and area of coverage comparable to that of a high altitude aerial photograph.

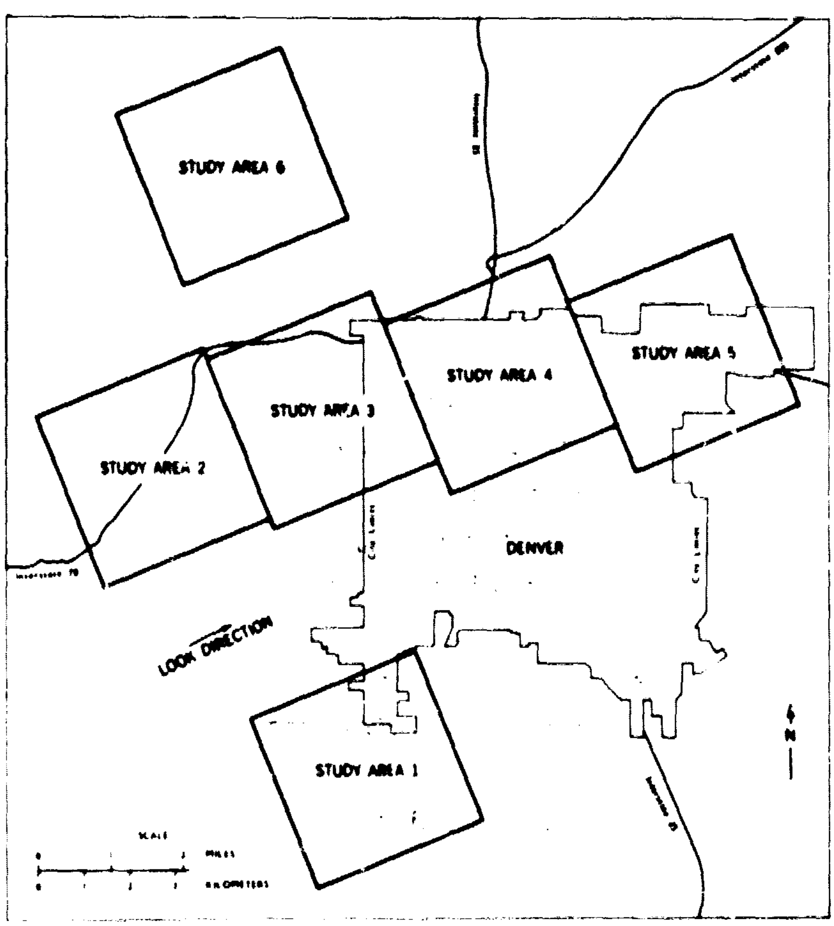

Figure 2. Location of Large Scale, Sub-scene Study Areas

The third scale was the maximum enlargement possible (512 x 512 pixels) on the Image 100 system without data resampling. Two distinct approaches were employed in examining the data--a visual interpretation of the black-and-white imagery and an automated-machine/visual interpretation of study areas. The purpose was to evaluate the feasibility of producing semi-automated land cover classifications with SAR data and to assess the contribution of each approach (i.e., visual or optical versus density-sliced imagery). The land cover classification system described by Anderson, et.al. in U.S. Geological Professional Paper 964 (1976) was adopted to provide a basis for systematic comparison of the data. To determine accuracy all SAR interpretation results were compared with aerial photography and existing land cover maps of the area.

Visual Interpretation: A black-and-white positive transparency of the entire 100 km x 100 km scene was generated from the digital data at a scale of approximately 1:500,000. An examination of the product indicated no meaningful land cover patterns could be discerned from this essentially raw data presentation due to excessive image noise believed inherent in the data. Consequently, a second image was produced by computing the average for all non-overlapping three by three windows in the original image. That is,the image was resampled with one third of the original number of pixels in each direction, each new pixel being the average of nine old pixels. The three by three averaging appeared to reduce the noise and land cover patterns were more apparent. Level I land cover categories (i.e., urban, agriculture, forest, rangeland, and water) were located and delimited on the transparency. The results were then compared with the aerial photography and United States Geological Survey map to evaluate the SAR classification accuracy. This synoptic view of the entire metropolitan area permitted an assessment of the detectability of general land cover; particularly the visibility of the rural-urban fringe, satellite communities, and the distinction between urban and non-urban land cover.

The intermediate scale image (1:131,000) was generated from the data tapes averaged in the same manner as the small scale (1:500,000) scene. Using aerial photography and the United States Geological Survey map as ground truth this 367 square kilometer area was interpreted at Level II land cover detail and a confusion matrix generated.

Black-and-white positive prints of each of the six large scale sub-scenes were generated and visually interpreted using Level II land cover categories as a guide. The averaging was not applied to the analyses of the six large scale sub-scenes as the image noise presented no problem at this scale. The resulting SAR land cover maps were compared with the aerial photography and the United States Geological Survey land use map to determine the accuracy of the SAR interpretation, instances and sources of error, and the level of detail and type of classification possible by this approach. Effects of system/environment variables such as specular reflection, incidence angle and system wavelength, street orientation, and land cover type on image classification were also examined. Confusion matrices were generated to aid in this process. Owing to time constraints Study Area 2 was excluded from analysis as its land cover patterns were similar to those found in Study Areas 1 and 6.

Machine/Visual Interpretation: The objective of the digital analysis was to determine the feasibility of discriminating land cover classes using density level slicing of the image frequency histogram. Level slicing as applied to a single band image is a means of identifying disjoint spectral categories by the selection of upper and lower response thresholds which define the pixel membership for each category. These thresholds should be selected so as to segment the image into meaningful groups or patterns. One method of accomplishing this is to consider a group as being represented by a peak in the frequency histogram, hence the thresholds should be located at the valleys between peaks. A second method is to interactively adjust the thresholds for a category until the member pixels form a meaningful pattern. Both methods were used in segmenting the SAR image scenes.

For illustration, the segmentation process for subscene Study Area 1 is described. Except for the spike at the maximum responses (255), the frequency histogram was relatively uniform. Hence, the first category, which corresponds to specular reflectors, consisted of all pixels with a response greater than 254. Since no other separable peaks were apparent, the second, interactive method was used to further segment the image. This process is defined as follows:

1. Start with 254 as the upper bound for the second category.
2. Using an interactive display, interactively adjust the lower bound until the member pixels form a meaningful pattern, correspond to a homogeneous land cover class by comparison with aerial photography of the area, or meet an arbitrary criterion.
3. Assign a unique color to the category and store it.
4. The lower bound (minus one) for the n^{th} category then becomes the upper bound for the $(n + 1)^{th}$ category.
5. Repeat steps 2 - 4 until the histogram is completely partitioned.

By comparing the SAR imagery with aerial photography, it was found that water and vegetation had relatively low responses, and that urban and developed areas had relatively higher responses. A lower bound (142) for the second category, which corresponds to developed areas, was found by locating the lowest threshold which minimized the inclusion of vegetation and water pixels. The next step was to segment the remaining pixels into water and vegetated categories. However, due to the overlap in responses for water and vegetated surface, no satisfactory threshold could be found. The next step was to further segment the urban and vegetation/water categories by attempting to break out meaningful patterns within each major category. Seven categories were so identified as shown in Table 1.

Table 1. Results of Level Slicing Sub-scene Study Area 1.

Category	% of Scene	Response Bounds
1. Specular Reflectors	5.96	255-255
2. High Return Urban	12.31	178-254
3. Low Return Urban	13.12	142-177
4. Fringe Vegetation	17.03	110-141
5. High Return Vegetation	25.69	76-109
6. Medium Return Vegetation	16.26	55-75
7. Low Return Vegetation	9.63	8-54

Color prints of each of the five density-sliced large scale sub-scene study areas were produced and land cover categories delimited at Level II detail. These SAR interpretations were then compared with the United States Geological Survey land cover maps and aerial photography to determine the classification accuracy. Confusion matrices were generated and compared with the results obtained from the optical interpretations of the corresponding black-and-white prints of each study area.

Density slicing was attempted for the small scale, entire scene image but no meaningful patterns could be defined. Consequently, analysis at this scale was confined to the visually interpreted black-and-white image. Time constraints prohibited an analysis of a density-sliced image at the intermediate scale.

ANALYSIS AND RESULTS

1:500,000 (small scale imagery): Examination of the black-and-white print derived from the raw data indicated that no meaningful land cover patterns could be discerned owing to excessive image noise. A three by three averaging algorithm was subsequently applied to the data and a second black-and-white film positive produced. At this scale the boundaries of urban built-up areas could be easily delimited owing to the high return of suburban housing in contrast to the darker tones of agriculture, rangeland, and other open space. Agricultural Land was identifiable only when several rectangular, cultivated fields were juxtaposed. At L-band wavelengths Rangeland generated a smooth, low return response (dark gray to black). Since the surface roughness, pattern, and morphology of this land cover type generally fell below the threshold necessary for more varied tone/texture response, Rangeland, pasture, and bare field borders were frequently indistinct. Forest Land was discernable in the mountains, along stream banks, and on lowland hills as textured, medium to light gray toned greas. Water was not consistently detectable at this scale. Small water bodies (less than 2 km^2) could not be delimited consistently from surrounding land cover of grass, beach, bare soil, and rangeland. Larger resevoirs often produced a salt-and-pepper response rather than the expected black, no return response owing to the L-band signal sensitivity to rough and choppy water. Density slicing the image at this scale proved of minimal value due to overlapping signal response among categories. The number of visual interpretation clues available to the interpreter were reduced as a result of level slicing and color coding the data.

These observations are not meant to imply that Seasat SAR imagery cannot be of use in small scale synoptic land cover inventory efforts. It is believed that the environment is a significant limiting factor and that more detail may be visible in other regions. The cultivation and land use patterns of the Denver area reflect the semi-arid climatic conditions. At this scale open space, bare ground, sparse range vegetation, sandy soils, and areally extensive agricultural field patterns do not offer sharp tonal contrasts at L-band wavelengths. However, Level I land cover can be mapped (Figure 3). While the distinction of non-urban land cover types is confined to broad generalizations the contrast between large concentrations of urban built-up land and

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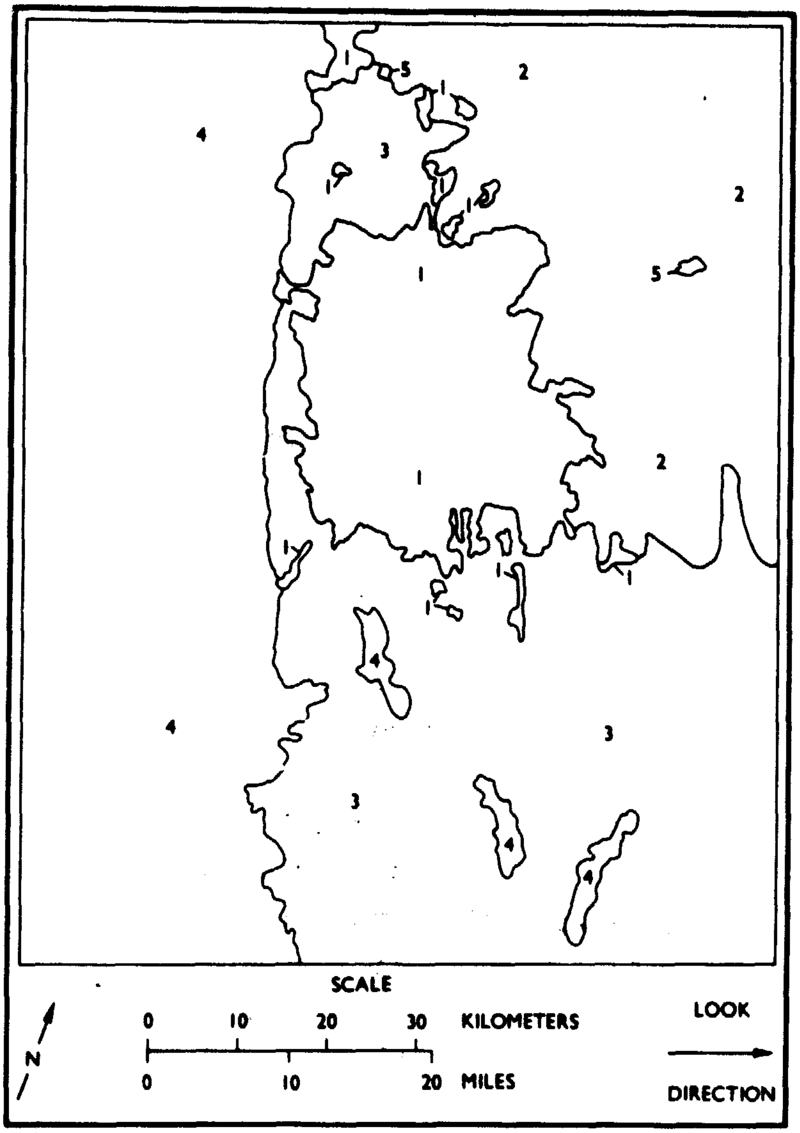

Figure 3. Level I Land Cover Map of Small Scale (1:500,000) SAR Scene

non-urban areas is quite distinct. In fact, the generalization afforded by such a synoptic view is a prime objective of such small scale imagery. In more humid environments and/or areas that are intensively cultivated more contrast and surface roughness (manifested as texture and gray tones on the imagery) would be expected as a function of crop diversity, field patterns, and spatial distribution of land cover. In such cases much more detailed land cover information should be obtainable from the Seasat SAR imagery. Too, the development of more sophisticated preprocessing algorithms will increase the level of information obtainable from the digital data and enhance subtle land cover contrasts that at present remain indistinct in all environments.

1:131,000 (medium scale imagery): At this scale the black-and-white image generated from the raw data (367 square kilometers) still contained excessive image noise obviating any interpretation attempts. Consequently, the data were smoothed as before to generate a useful product for examination. Level II land cover categories(e.g., residential, transportation, commercial) were employed at this stage of the analysis.

Recently constructed residential subdivisions were readily delimited by optical interpretation of the black-and-white print as were most older, interior residential areas (Figure 4). The commercial/industrial core of the city and the concentration of downtown commercial activity were also apparent. However, small commercial blocks in residential areas and the distinctions between the commercial core and interior residential areas were ambiguous. Confusion between commercial/service land cover and residential land cover was the cause of most of the error at this scale.

Portions of major arterial roads could be inferred from the dark linears traversing the urban area but complete road networks were not visible. Open space was distinguishable owing to the sharp contrast between its dark, low return and the surrounding medium to light gray tones of built-up land cover. However, the exact use of the open space could not be consistently classified as recreation, cemeteries, or other open space categories. Instances where institutions, public facilities, or commercial buildings were surrounded by open space were also classified as simply open space from

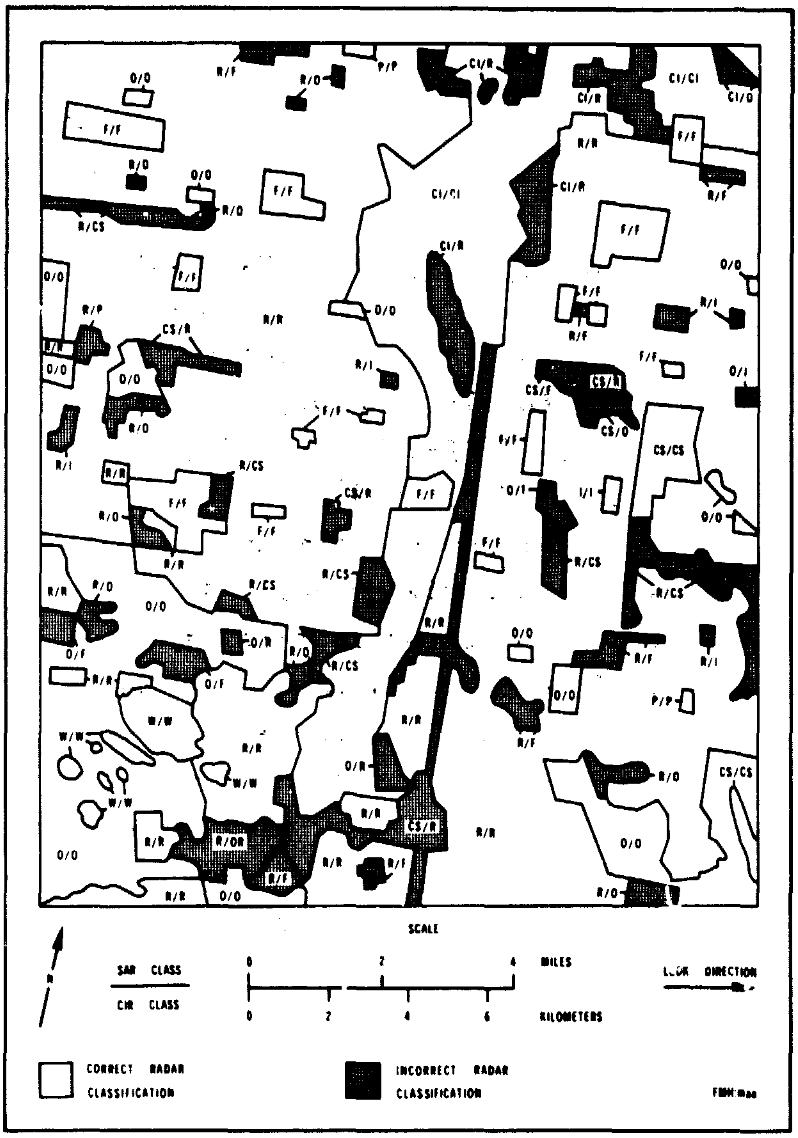

Figure 4. Comparison of 1:131,000 SAR Classification with Actual Land Cover

Key: (CI/I) commercial-industrial; (CS) commercial-services; (FOP) recreational-open-public; (R) residential; (W) water

the radar image. Table 2 (Appendix A) provides a summary of omission and commission errors for this scale.* Given the

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*% Omission = 100% - % correct

$$\% \text{ Commission} = \frac{\text{Total Number of Commission Errors}}{\text{Total Possible Responses} - \text{Total Possible Correct Responses}} \times 100$$

complexity of land cover types and the relatively low total percentage of incorrect identifications (12.1%) the potential of such SAR imagery for urban data extraction appears promising. Familiarity with the urban area land cover locations and types might enable more precise identification but cannot be documented at present.

1:41,000 (large scale imagery): Six sub-areas of the entire SAR scene that encompassed a range of urban land cover types including: older, interior and new residential areas; single and multiple family housing; industrial; commercial and service activity; recreation and open space; and transportation were selected for analysis. Each study area encompassed some sixty-four square kilometers. As can be seen in Figure 2, three of the study areas (3, 4, and 5) traverse the metropolitan area in addition to three areas located on the urban fringe (1, 2, and 6). Study Area 2 was subsequently omitted as its land cover pattern was redundant to that of Study Areas 1 and 6 and as a result of time constraints. Black-and-white prints of the raw data were generated for each area and the land cover classified according to Level II categories. The five images were then level sliced, color coded, and a color print generated. Level II land cover was then defined for each of these products.

On the black-and-white prints generated from the raw data, older, interior residential areas were less distinct than the new residential areas and confused at times with commercial and service activity and some industrial fringe areas owing to similar tone and texture responses on the imagery. Separate categories of recreation, cemeteries, and open space could not be consistently defined other than as open space. Institutions, schools, and public land were also confused with open space due to the low return of their grounds. The visibility of transportation elements was a function of their size, shape, orientation to flightline, and surrounding land cover. Only segments of major road networks were visible with sections of residential streets identifiable as dark lines or dashes in contrast to the higher return of surrounding housing structures. In commercial zones streets were generally obscured by the bright return and signal blooming (spectral response) from buildings.

The visibility of Commercial and Service activity was a function of size and location. The contrast between the Central Business District, industrial core, and surrounding residential land was detectable, but small commercial centers and commercial streets in residential areas were a major point of confusion. Using the raw data at this large scale the distinction between the business and commercial activity versus other land cover, particularly residential, was more pronounced than on the smaller 1:131,000 scale, smoothed data. However, isolated commercial/industrial buildings in open areas were still indistinct from residential development unless identification could be inferred from its spatial location and unusually bright signal response--a function of building size, complexity, and orientation to the flightline.

Given these general observations the next step was to examine the land cover maps created from the raw data and the density-sliced data for each of the five study areas. Confusion matrices were generated in each case using aerial photography and existing maps of the study areas as ground truth. Cells representing 1.6 hectares (4 acres) on the ground were selected as the recording unit of measurement as (1) it was the smallest cell from which land cover could be consistently and accurately recorded, (2) the area encompassed by each cell is the smallest areal unit for which the majority of urban land cover is recorded by urban planners and other users, and (3) it is a unit recommended by Anderson, et.al. (1976) for remote sensing systems. A systematic aligned sampling system (center dot) was employed to identify the land cover in each cell. It should be noted that there is some disagreement in the confusion matrix tables as to the boundary correlation and number of hectares among the five study areas. This is a result of limitations in the image generation and reproduction process and does not detrimentally affect the quality or validity of the data.

Preliminary examination had indicated that it was not possible to precisely distinguish specific types of land cover from each other. In compiling the confusion matrices the decision was made to combine some open space categories into one inclusive category as indicated in the tables. A second, modified group category was employed for commercial/service and commercial/industrial land cover. For purposes of brevity the interpretation and resulting land cover maps generated from the black-and-white prints of the raw data will be referred to as the <u>OPTICAL</u> interpretation and the results obtained from analysis of the density-sliced, color-coded data will be referred to as the <u>DENSITY</u> interpretation. Confusion matrices of each of the five study areas for each interpretation method can be found in Appendix A. Summary tables are provided in the text discussion along with maps illustrating the land cover and sources of error.

Study Area 1 is located on the urban fringe of the metropolitan area and consists chiefly of new single family residential housing, some small lakes and resevoirs, public land, and open space in the form of recreation (golf courses) and agricultural land awaiting urban development. The Optical interpretation of this study area produced an overall accuracy of 93.9 per cent. It was not possible to detect land cover devoted to extractive, public, or utilities activities, but these cover types comprised only 3 per cent of the total land cover. Ninety-five per cent of the residential land cover was correctly identified. The Density interpretation produced a lower overall accuracy of 89.5 per cent including a 12 per cent error in the residential category. Water was also less accurately identified, but other errors were similar to that of the Optical interpretation. Figures 5 and 6

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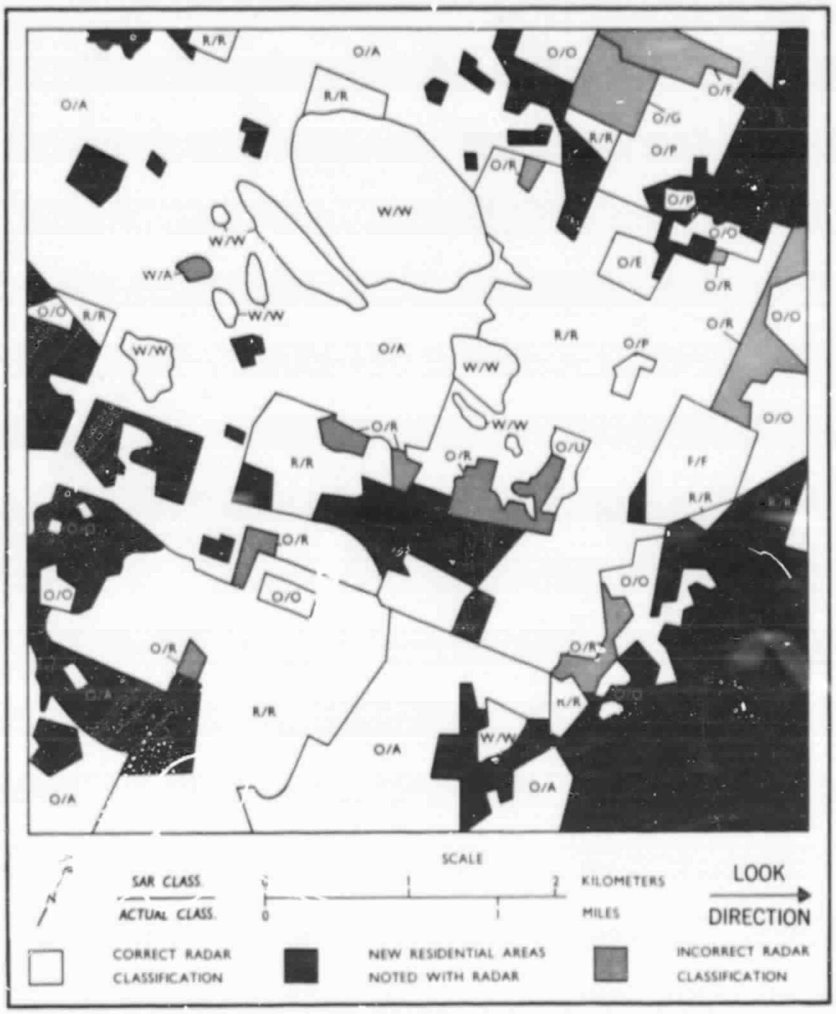

Figure 5. Comparison of Large Scale (1:41,000) Optical SAR Classification with Actual Land Cover for Study Area 1.

Key: (A) agricultural; (C) commercial; (CI) commercial-industrial; (CS) commercial-services; (E) extractive; (G) cemeteries; (I) industrial; (O) open; (P) public; (R) residential; (T) transportation; (U) utilities; (W) water; (F) recreation

provide an indication of the accuracies, sources of error, and ability of the SAR imagery to accurately detect new residential construction areas. Tables 3 and 4 in Appendix A contain the confusion matrices for this study area.

Study Area 3 is an older area of urban development,

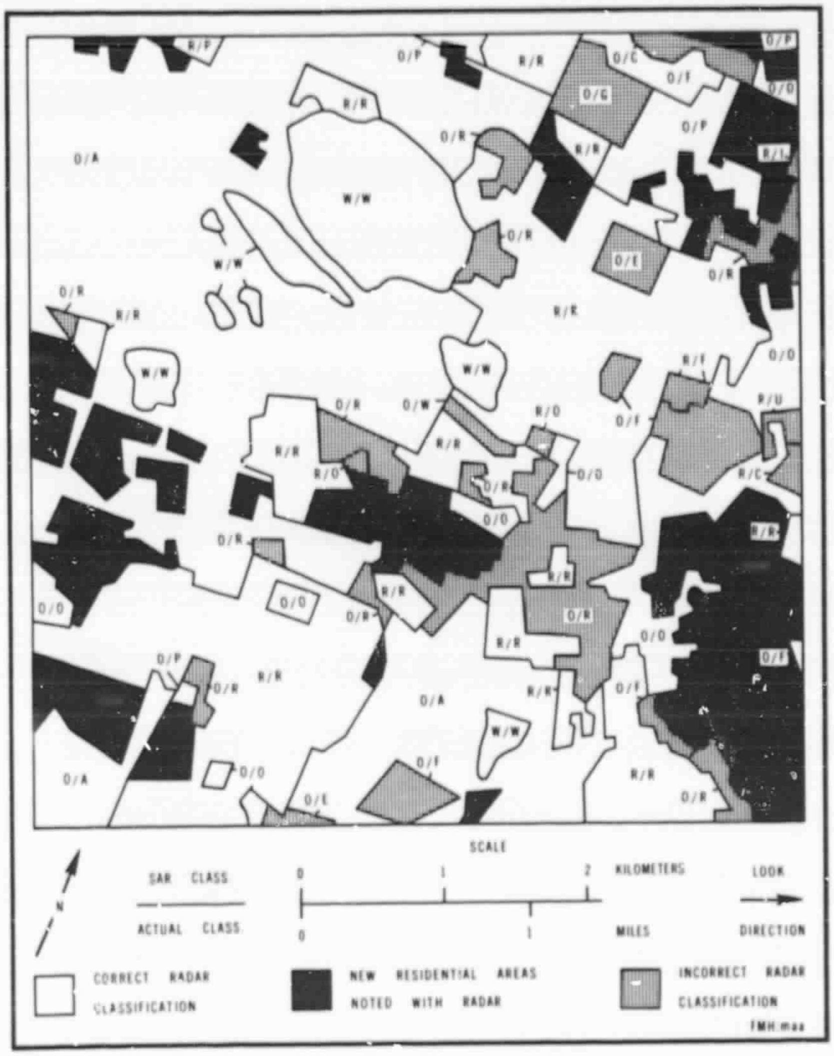

Figure 6. Comparison of Large Scale (1:41,000) Density SAR Classification with Actual Land Cover for Study Area 1.

Key: (A) agricultural; (C) commercial; (CI) commercial-industrial; (CS) commercial-services; (E) extractive; (G) cemeteries; (I) industrial; (O) open; (P) public; (R) residential; (T) transportation; (U) utilities; (W) water; (F) recreation

interior to the current urban fringe and includes a mix of more varied land cover activities. Approximately 14 per cent of the area is industrial/commercial activity in blocks and strips while some 70 per cent is residential--a mix of older, single family homes and apartments. The remaining land cover is comprised of transportation, utilities, public, and open space (Figures 7 and 8). The overall Optical interpretation accuracy was 84 per cent but dropped to 76.9 per cent for the Density interpretation. Although residential identification remained high in both cases there was considerable confusion with other categories, particularly commercial land cover

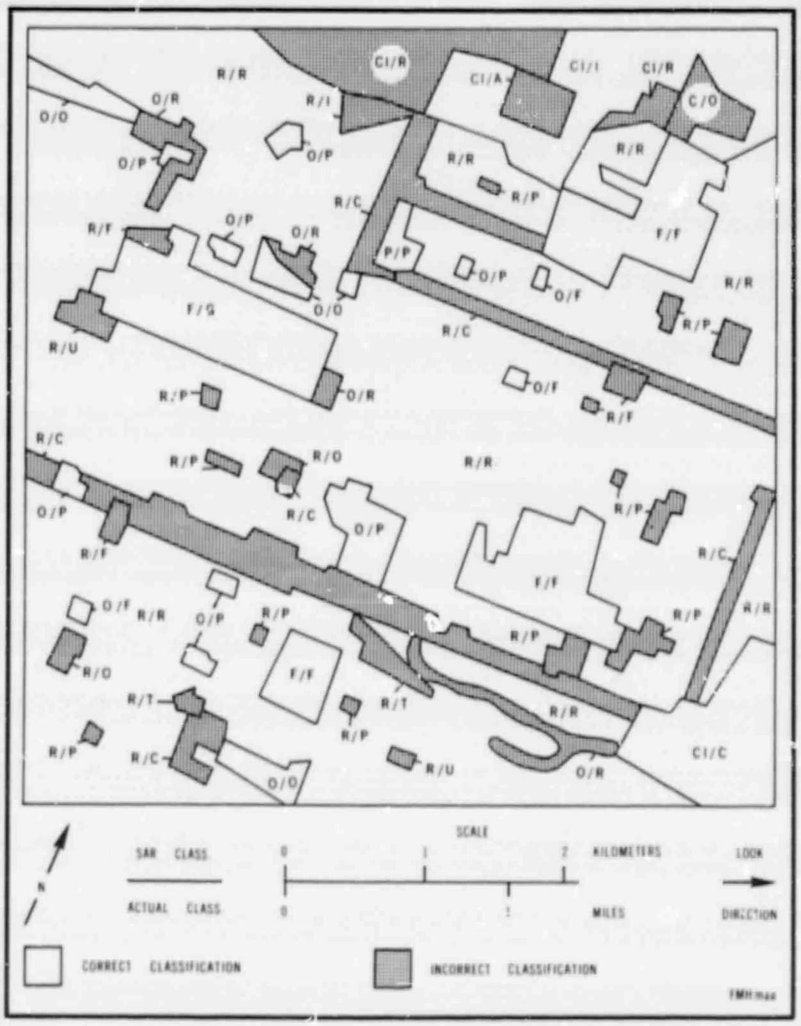

Figure 7. Comparison of Large Scale (1:41,000) Optical SAR Classification with Actual Land Cover for Study Area 3.

Key: (A) agricultural; (C) commercial; (CI) commercial-industrial; (CS) commercial-services; (E) extractive; (G) cemeteries; (I) industrial; (O) open; (P) public; (R) residential; (T) transportation; (U) utilities; (W) water; (F) recreation

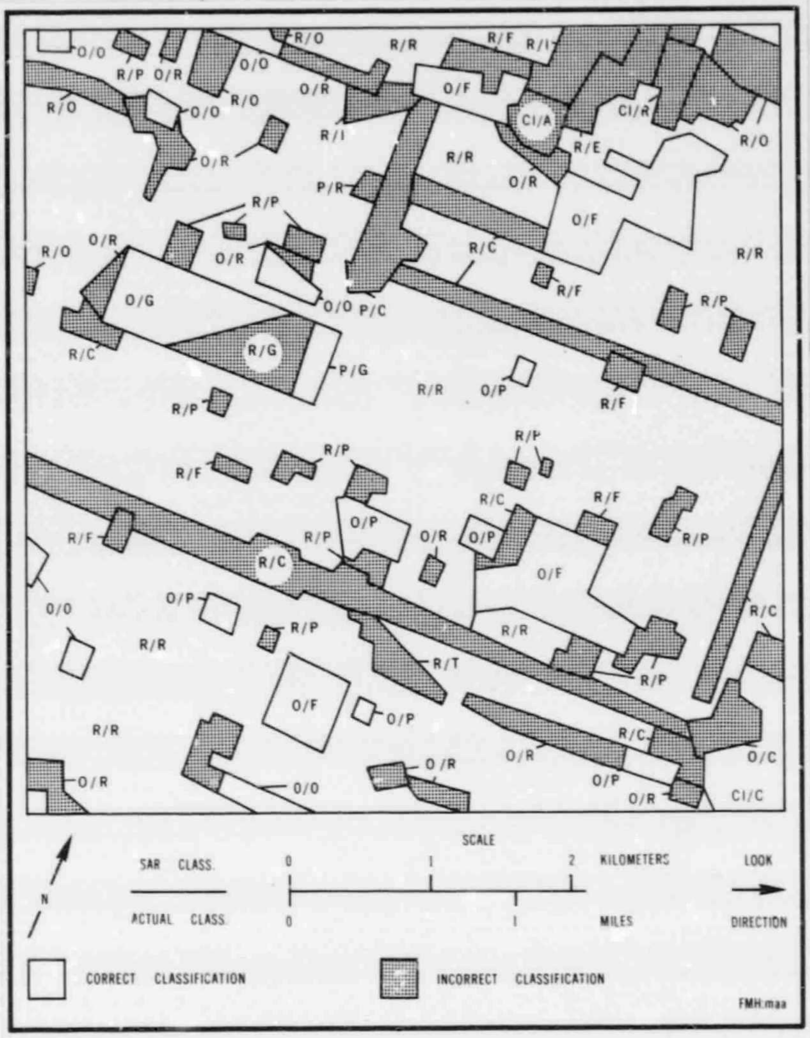

Figure 8. Comparison of Large Scale (1:41,000) Density SAR Classification with Actual Land Cover for Study Area 3.

Key: (A) agricultural; (C) commercial; (CI) commercial-industrial; (CS) commercial-services; (E) extractive; (G) cemeteries; (I) industrial; (O) open; (P) public; (R) residential; (T) transportation; (U) utilities; (W) water; (F) recreation

(Table 5, Appendix A). The Density interpretation also confused open space with residential activity more often than the Optical analysis (Table 6, Appendix A). Neither method was able to detect small parcels devoted to extractive, transportation, public, and utilities land cover activity.

The central business district, downtown commercial/industrial core, transportation hub, interior multi-family and single family housing, and city parks comprise Study Area 4. Residential land cover comprises only 41 per cent of the total while commercial/services and commercial/industrial activity account for 16 and 26 per cent respectively. The complex nature of this land cover mix presented diverse interpretation problems as many of the land cover categories were indistinct on the SAR imagery. This fact is reflected in the lower accuracies achieved--77.4 per cent for the Optical and 69.9 per cent for the Density analysis. As was the case in previous study areas the major problem using either method was the inability to distinguish small areal units devoted to transportation, public land cover and small parcels of open space devoted to parks, cemeteries, and idle land (Tables 7 and 8, Appendix A). A second factor was the similarity in appearance on the imagery between commercial/service and commercial/industrial land cover versus other land cover types, especially the older row housing and multi-story residential buildings (Figures 9 and 10). In spite of these problems the overall accuracy of the Optical method (77.4 per cent) indicates that SAR imagery can produce acceptable results for the major land cover types. Seventy-three per cent of the residential, 83 per cent of the commercial, and 100 per cent of the commercial/industrial land cover was correctly identified.

Study Area 5 includes Denver's airport and the surrounding area. Transportation (26 per cent), commercial/industrial (21 per cent), open space (21 per cent), residential (19 per cent), and public (12 per cent) are the major cover types. This study area presented the most problems in interpretation and produced the greatest error (70.8 per cent accuracy for the Optical and 62.5 per cent accuracy for the Density interpretation). Although the inability to detect small land cover parcels remained a problem it was not the major cause of interpretation error. As can be seen in Figures 11 and 12 the

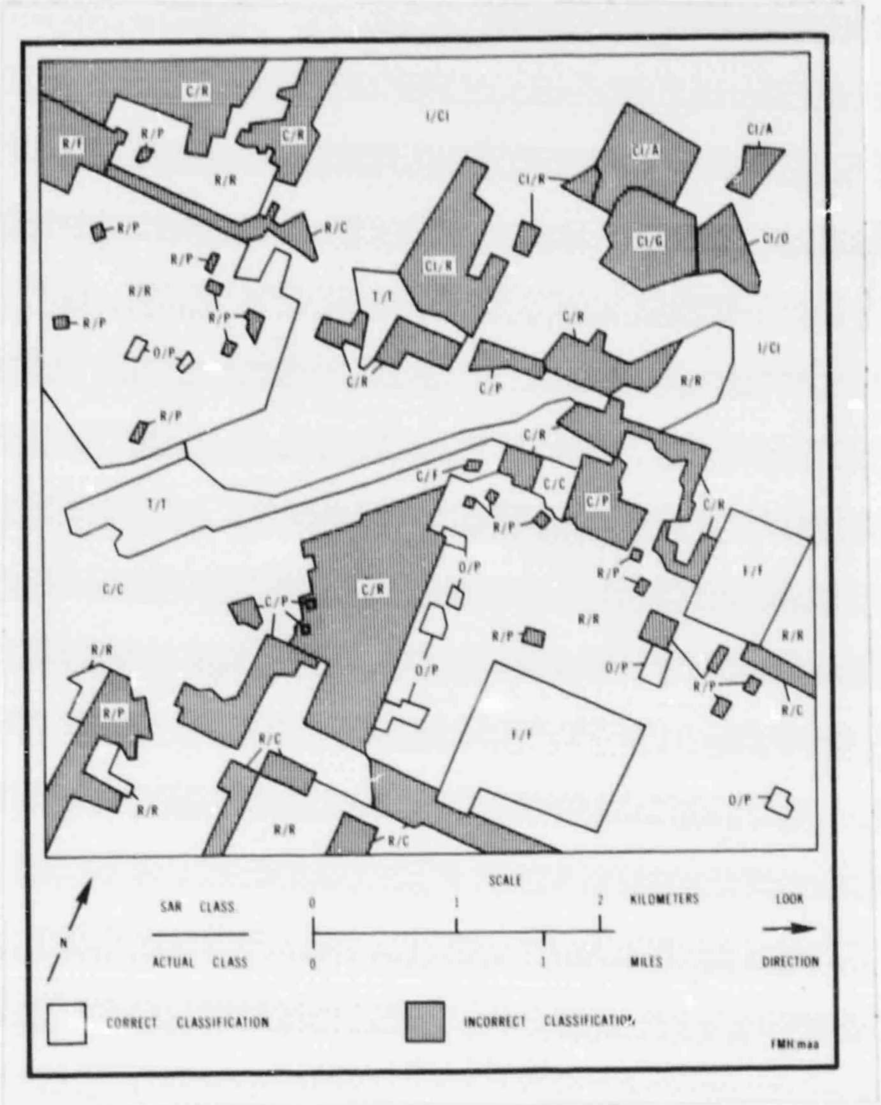

Figure 9. Comparison of Large Scale (1:41,000) Optical SAR Classification with Actual Land Cover for Study Area 4.

Key: (A) agricultural; (C) commercial; (CI) commercial-industrial; (CS) commercial-services; (E) extractive; (G) cemeteries; (I) industrial; (O) open; (P) public; (R) residential; (T) transportation; (U) utilities; (W) water; (F) recreation

areas adjacent to the airfield did not present distinct, identifiable tones and textures on the SAR imagery. While each of the major land cover categories was confused with other land cover the inability to accurately classify open space produced most of the error (Tables 9 and 10, Appendix A).

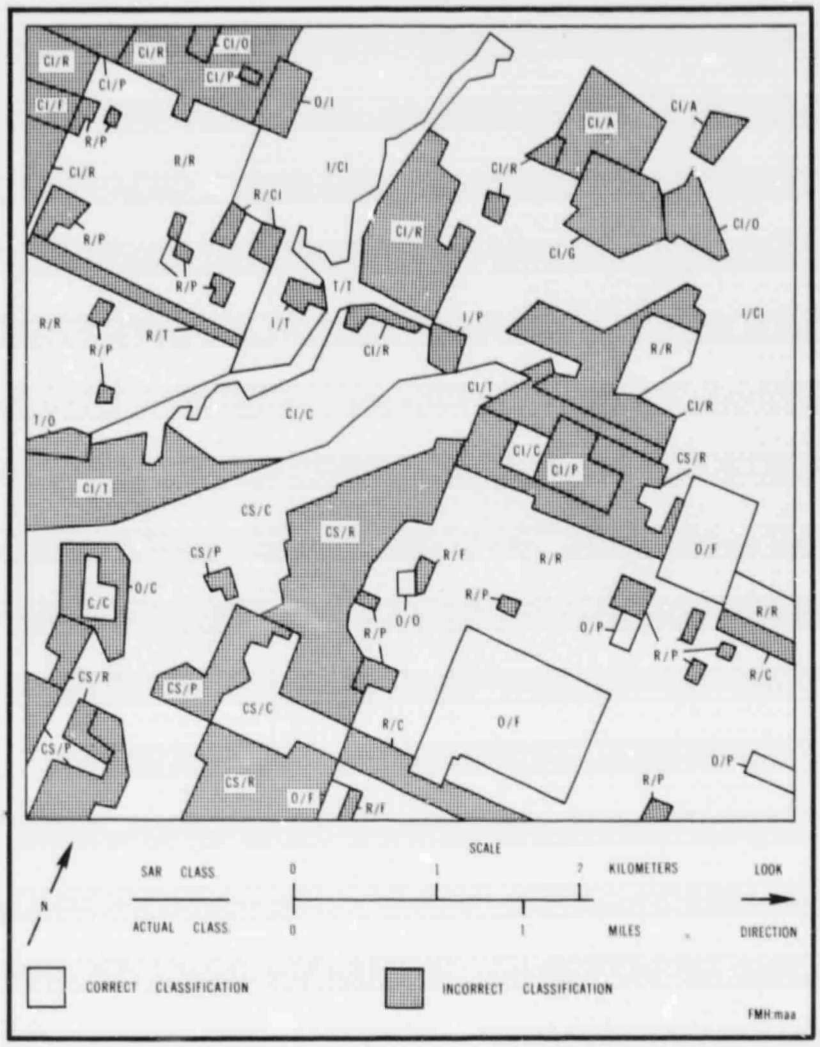

Figure 10. Comparison of Large Scale (1:41,000) Density SAR Classification with Actual Land Cover for Study Area 4.

Key: (A) agricultural; (C) commercial; (CI) commercial-industrial; (CS) commercial-services; (E) extractive; (G) cemeteries; (I) industrial; (O) open; (P) public; (R) residential; (T) transportation; (U) utilities; (W) water; (F) recreation

Transportation (94 per cent detected) and residential (99 per cent detected) land cover parcels were accurately identified. Still, the overall interpretation accuracy was the lowest of the five study areas. Comparison of the aerial photography with the SAR imagery and SAR land cover maps indicated three

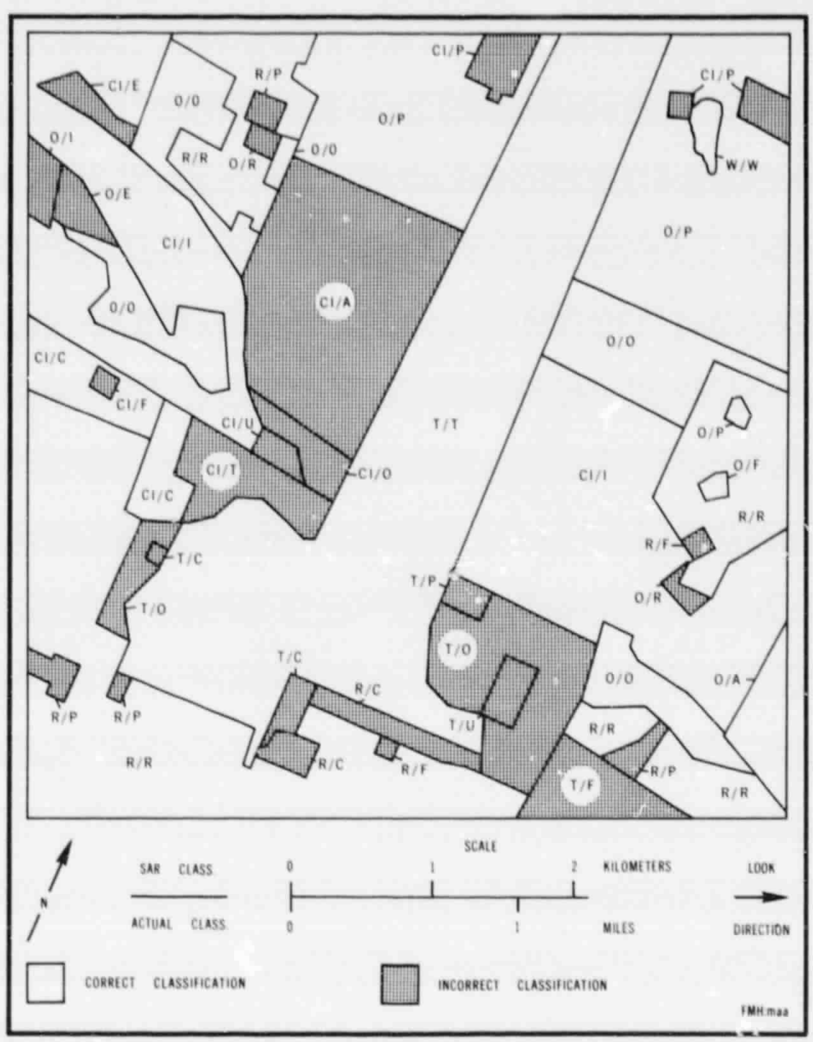

Figure 11. Comparison of Large Scale (1:41,000) Optical SAR Classification with Actual Land Cover for Study Area 5.

Key: (A) agricultural; (C) commercial; (CI) commercial-industrial; (CS) commercial-services; (E) extractive; (G) cemeteries; (I) industrial; (O) open; (P) public; (R) residential; (T) transportation; (U) utilities; (W) water; (F) recreation

factors were responsible. First was the inability to define the boundary of the airfield. Much of the grass field and open space around the runway was interpreted as transportation while the United States Geological Survey map classified it as open space r recreation. Second, commercial/industrial

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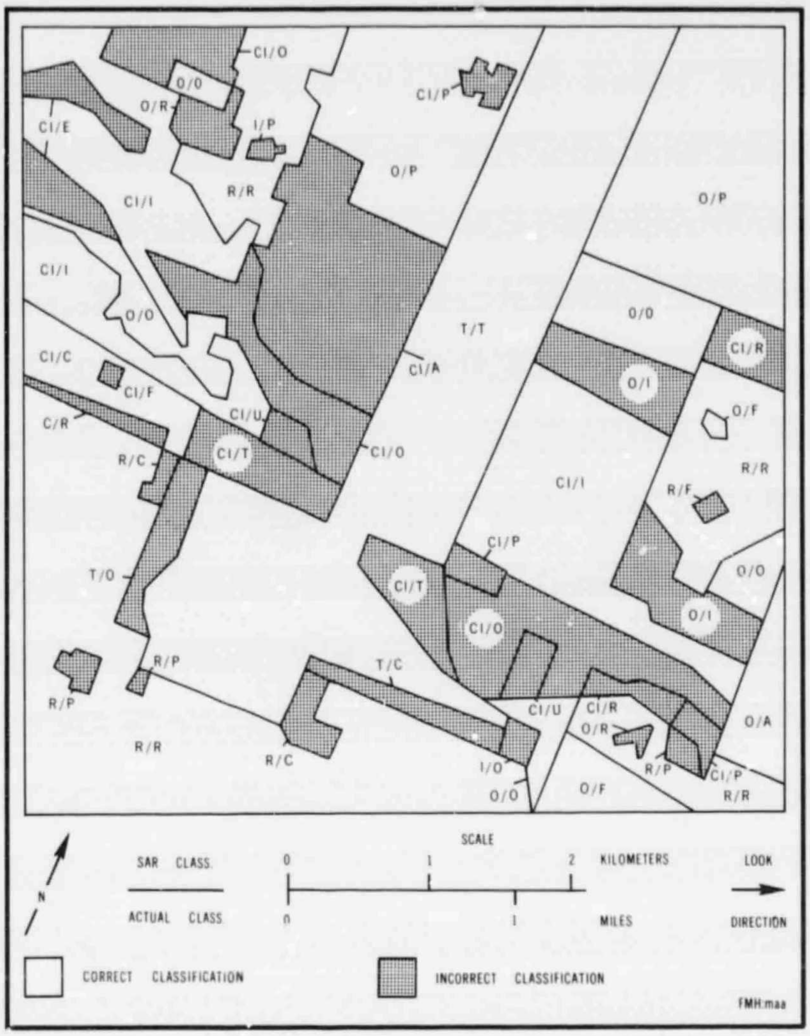

Figure 12. Comparison of Large Scale (1:41,000) Density SAR Classification with Actual Land Cover for Study Area 5.

Key: (A) agricultural; (C) commercial; (CI) commercial-industrial; (CS) commercial-services; (E) extractive; (G) cemeteries; (I) industrial; (O) open; (P) public; (R) residential; (T) transportation; (U) utilities; (W) water; (F) recreation

activity adjacent to the air terminal and transportation land cover were all similar in appearance on the SAR imagery and could not be differentiated. Third, a large agricultural field adjacent to the runway was classified as commercial/industrial on the SAR imagery owing to instances of bright spectral response surrounded by a dark gray area. This gave the impression of a group of buildings and grounds. In fact, the spectral return was caused by a series of low cultivated ridges oriented parallel to the flightline (perpendicular to look direction). These sources of error can be seen in Figures 11 and 12.

Study Area 6 was similar to Study Area 1 in that it was another urban fringe area comprised primarily of residential (45 per cent), open space and agricultural land (47 per cent), and water/resevoirs (8 per cent). As might be expected the detection accuracy was quite high for both interpretation methods, but the Optical method (92.1 per cent) was again more precise than the Density (88.8 per cent). The chief source of error was confusion of residential with open space land cover (Tables 11 and 12, Appendix A). However, note that detection of new residential land cover was again facile (Figures 13 and 14).

The average accuracy for all five study areas was 83.6 per cent using the black-and-white prints/Optical interpretation and 77.5 per cent for the level-sliced, color-coded/ Density interpretation. A summary of errors of omission and commission in terms of areal units for each category and each study area and the combined totals is provided in the confusion matrices of Tables 13 and 14. Tables 15 and 16 provide the same information in per cent figures.

In summary, newly constructed single family residential areas and housing developments on the urban fringe were readily visible on the large scale imagery as were most older residential areas in the interior of the city, although to a lesser extent. The distinct appearance of new fringe residential areas [illegible] the SAR image should prove advantageous in monitoring the extent, direction, and pattern of urban expansion. Other Level II land cover categories could not be separated precisely according to the United States Geological Survey classification system. It is apparent from the omission

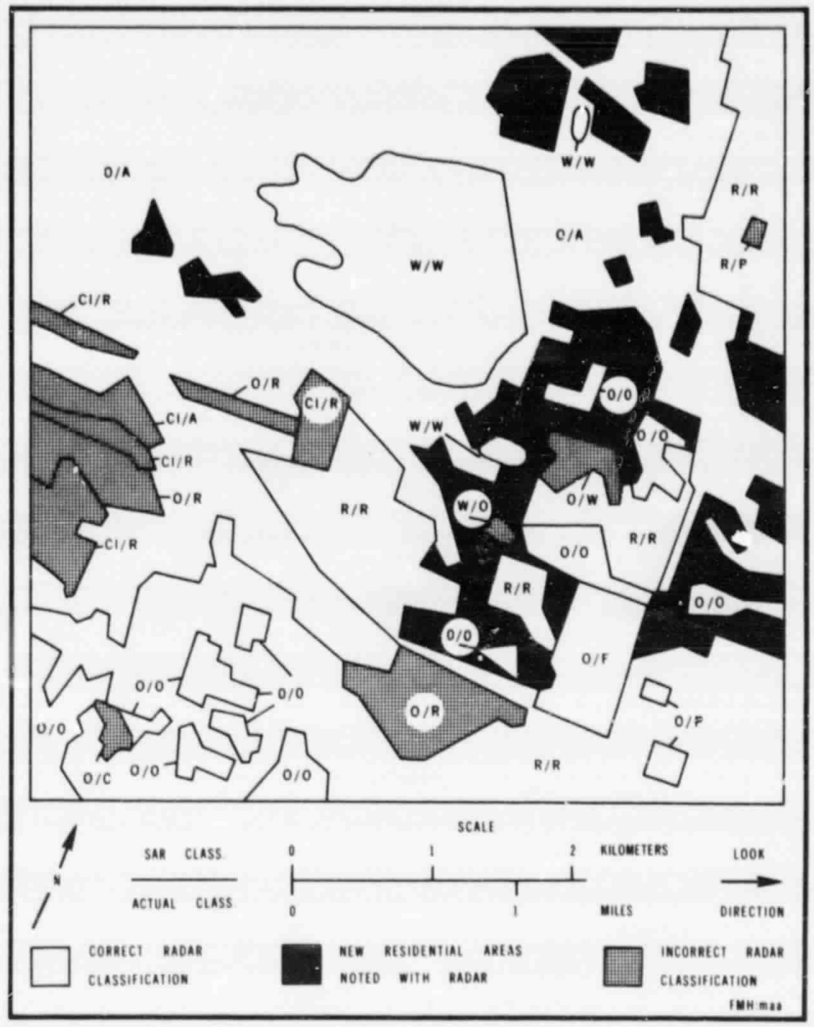

Figure 13. Comparison of Large Scale (1:41,000) Optical SAR Classification with Actual Land Cover for Study Area 6.

Key: (A) agricultural; (C) commercial; (CI) commercial-industrial; (CS) commercial-services; (E) extractive; (G) cemeteries; (I) industrial; (O) open; (P) public; (R) residential; (T) transportation; (U) utilities; (W) water; (F) recreation

figures that extractive, public, utilities, and transportation land cover could not be accurately identified from the SAR imagery. However, these parcels are usually very small in size (less than 3 hectares) and comprise a small portion of the total urban land cover. By modifying and combining

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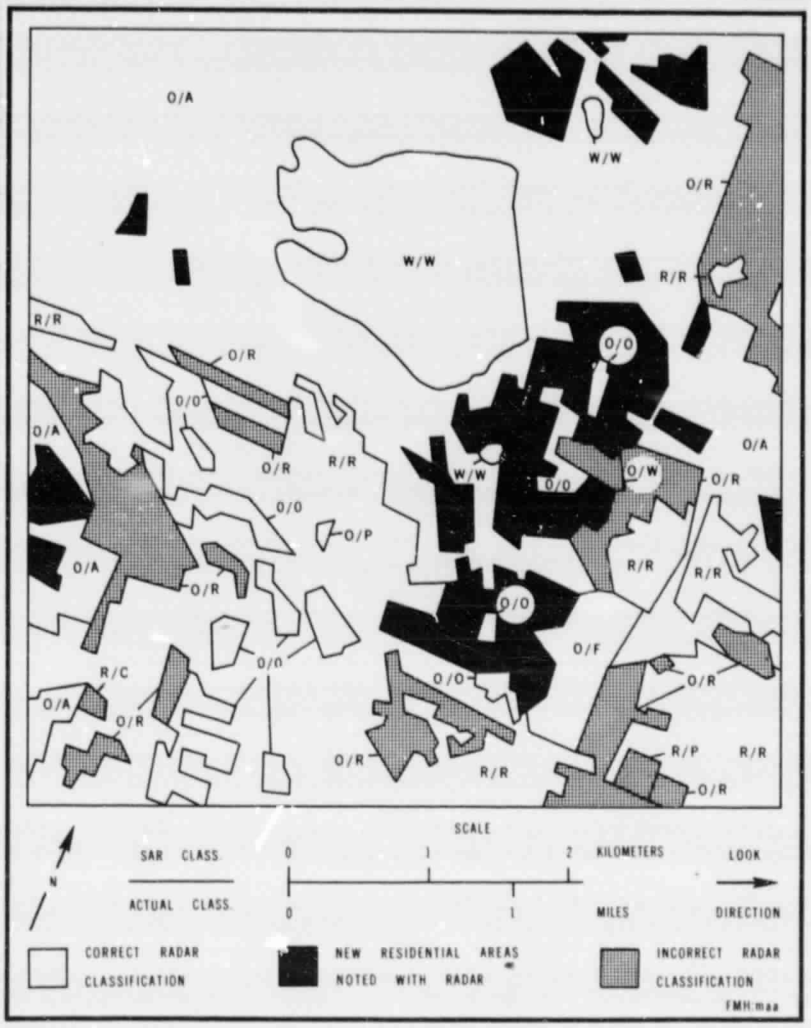

Figure 14. Comparison of Large Scale (1:41,000) Density SAR Classification with Actual Land Cover for Study Area 6.

Key: (A) agricultural; (C) commercial; (CI) commercial-industrial; (CS) commercial-services; (E) extractive; (G) cemeteries; (I) industrial; (O) open; (P) public; (R) residential; (T) transportation; (U) utilities; (W) water; (F) recreation

certain related categories a fairly realistic breakdown of urban land cover was possible. Separate categories of recreation and parks, cemeteries, agricultural land (adjacent to the urban fringe built-up areas) and undeveloped land could not be identified per se, but were identifiable as a combined

Table 13. Optical Interpretation Summary of Omission/Commission Error in Acres for Five Large Scale (1:41,000) Study Areas

Study Area	A1		A3		A4		A5		A6			
Land Cover	o	c	o	c	o	c	o	c	o	c	Totals (o)	Totals (c)
AFGO	8	424	120	200	356	0	808	780	56	292	1,348	1,696
C/CS	NA	NA	NA	NA	192	808	NA	NA	NA	NA	192	808
CI/I	NA	NA	440	260	0	356	120	700	12	212	572	1,528
E	28	0	NA	NA	NA	NA	48	0	NA	NA	76	0
P	180	0	176	0	296	60	832	0	28	0	1,512	60
R	192	0	284	616	792	412	16	132	380	8	1,664	1,168
T	NA	NA	32	0	0	0	100	352	NA	NA	132	352
U	24	0	24	0	NA	NA	40	0	NA	NA	88	0
W	0	8	NA	NA	NA	NA	0	0	40	4	40	12
Totals	432	432	1,076	1,076	1,636	1,636	1,964	1,964	516	516	5,624	5,624
Site Total Acres	7,052		6,724		7,224		6,724		6,560		34,284	

Key: (A) agricultural; (C) commercial; (CI) commercial-industrial; (CS) commercial-services; (E) extractive; (F) recreation; (G) cemeteries; (I) industrial; (O) open; (P) public; (R) residential; (T) transportation; (U) utilities; (W) water; NA = not applicable; o = error of omission; c = error of commission

Table 14. Density Interpretation Summary of Omission/Commission Error in Acres for Five Large Scale (1:41,000) Study Areas

Study Area	A1		A3		A4		A5		A6			
Land Cover	o	c	o	c	o	c	o	c	o	c	Totals	
AFGO	28	652	328	348	284	108	836	1,080	0	732	1,476	2,920
C	36	0	NA	NA	144	716	NA	NA	NA	NA	180	716
C/CI	8	0	652	56	40	1,028	292	1,244	8	0	1,000	2,328
E	60	0	52	0	NA	NA	92	0	NA	NA	204	0
P	152	0	228	104	364	0	932	0	20	0	1,696	104
R	[illegible]04	68	260	1,044	1,020	248	148	80	708	24	2,540	1,464
T	NA	NA	32	0	272	24	168	116	NA	NA	472	140
U	16	0	NA	NA	NA	NA	52	0	NA	NA	68	0
W	16	0	NA	NA	NA	NA	NA	NA	20	0	36	0
Totals	720	720	1,552	1,552	2,124	2,124	2,520	2,520	756	756	7,672	7,672
Site Total Acres	6,888		6,724		7,056		6,724		6,724		34,116	

Key: (A) agricultural; (C) commercial; (CI) commercial-industrial; (CS) commercial-services; (E) extractive; (F) recreation; (G) cemeteries; (I) industrial; (O) open; (P) public; (R) residential; (T) transportation; (U) utilities; (W) water; NA = not applicable; o = error of omission; c = error of commission

Table 15. Optical Interpretation Summary of Omission/Commission Error in Per Cent for Five Large Scale (1:41,000) Study Areas

Study Area	A1		A3		A4		A5		A6	
Land Cover	o	c	o	c	o	c	o	c	o	c
AFGO	0.3	9.6	14.4	3.4	49.7	0.0	57.4	14.7	1.8	8.4
C/CS	NA	NA	NA	NA	16.8	13.3	NA	NA	NA	NA
CI/I	NA	NA	46.8	4.5	0.0	6.6	8.5	13.2	100.0	3.2
E	100.0	0.0	NA	NA	NA	NA	100.0	0.0	NA	NA
P	100.0	0.0	88.0	0.0	100.0	0.9	100.0	0.0	100.0	0.0
R	5.2	0.0	6.0	30.4	26.9	9.6	1.3	2.4	13.0	0.2
T	NA	NA	100.0	0.0	0.0	0.0	5.8	7.0	NA	NA
U	100.0	0.0	100.0	0.0	NA	NA	100.0	0.0	NA	NA
W	0.0	0.1	NA	NA	NA	NA	0.0	0.0	7.6	0.1

Key: (A) agricultural; (C) commercial; (CI) commercial-industrial; (CS) commercial-services; (E) extractive; (F) recreation; (G) cemeteries; (I) industrial; (O) open; (P) public; (R) residential; (T) transportation; (U) utilities; (W) water; NA = not applicable; o = error of omission; c = error of commission

Table 16. Density Interpretation Summary of Omission/Commission Error in Per Cent for Five Large Scale (1:41,000) Study Areas

Study Area	A1		A3		A4		A5		A6	
Land Cover	o	c	o	c	o	c	o	c	o	c
AFGO	1.0	15.9	41.6	5.9	45.5	1.7	63.7	20.0	0.0	19.6
C	100.0	0.0	NA	NA	15.4	11.7	NA	NA	NA	NA
C/CI	100.0	0.0	89.6	0.9	2.1	20.0	22.8	22.9	100.0	0.0
E	100.0	0.0	100.0	0.0	NA	NA	100.0	0.0	NA	NA
P	100.0	0.0	100.0	1.6	100.0	0.0	100.0	0.0	100.0	0.0
R	12.0	1.9	5.3	57.2	36.7	5.8	9.7	1.5	22.2	0.7
T	NA	NA	100.0	0.0	60.2	0.4	11.0	2.2	NA	NA
U	100.0	0.0	NA	NA	NA	NA	100.0	0.0	NA	NA
W	3.5	0.0	NA	NA	NA	NA	NA	NA	3.8	0.0

Key: (A) agricultural; (C) commercial; (CI) commercial-industrial; (CS) commercial-services; (E) extractive; (F) recreation; (G) cemeteries; (I) industrial; (O) open; (P) public; (R) residential; (T) transportation; (U) utilities; (W) water; NA = not applicable; o = error of omission; c = error of commission

class of "open space". Institutions and schools were often mistaken for open space due to the low return of their grounds. The visibility of transportation elements was dependent upon their size, shape, and surrounding land cover. For example, the major airport was visible owing to the low return of the field and runway, its shape, location in the urban area, and the bright return and shape of the terminal, but the exact boundaries of transportation land cover versus open space and commercial/industrial activity was not distinct. While sections of major roadways were identifiable a complete network delineation was not possible. Small residential streets could be detected at times as dark lines or dashes between the higher (light gray to white) return of housing and other structures, but a road's visibility remained a function of surrounding land cover and orientation to the flightline.

Commercial and Service and Industrial activities were identifiable in certain instances. Broad, linear high returns often indicated such activity but had to be analyzed in relation to their size and spatial location in the urban area. Small shopping centers and commercial blocks or streets in residential areas were not consistently identifiable, but the contrast between the central business district, the fringe transition zone, and adjacent inner city residential land cover was visible. However, the exact boundary between such categories was indistinct. From SAR imagery it was impossible to determine if a cluster of two or three story row houses were residences, commercial and service establishments, or a combination of both. A distinctive pattern of light to dark return (a function of building size, shape, orientation to the flightline, and the presence of parking or storage facilities) was indicative of a commercial/industrial zone, but consistent, accurate (greater than 90 per cent) separation of commercial/service, commercial/industrial, and residential land cover was not possible in the interior urban built-up areas.

A factor throughout the analysis having significant bearing on this problem of confusion was the specular return of structures. As reported by Bryan (1979), the orientation of streets and walls of structures relative to the radar look direction is a critical factor in the appearance of low commercial and residential land cover. Using airborne radar systems he found that when the angle between the radar look direction and street or structure orientation was less than 10° to 15° a bright return would result. At other angles a darker return might indicate the same land cover type. Examination of the Denver Seasat SAR data supported Bryan's conclusion. All cases of specular reflection were noted in the five large scale study areas and located on the aerial photography. In every instance, if the residential housing/street orientation was within 10° of a line perpendicular or parallel to the SAR look direction specular reflection occurred. This condition was observed when as few as three adjacent houses met the criterion. Similarly oriented railroad lines, warehouses, multiple-story buildings, greenhouses, and other large urban structures also acted as specular reflectors, but their precise orientation to the flightline/look direction could not be determined. This phenomenon is certainly a problem to be confronted when automated and semi-automated data analyses of such data are conducted as it contributed to the confusion in selecting classification levels and break points in the density-sliced imagery.

The density-sliced images of the five large scale study areas were judged of minimal value compared to the optically interpreted black-and-white prints of the raw data--particularly in light of time and costs. Considerable information was lost by the assignment of spectral class ranges and colors to the data. Although urban related categories (e.g., high return/urban commercial and residential) could be extracted, the density range for each class varied among the study areas. Choppy water in resevoirs and small lakes resulted in a non-uniform response range and overlap with other land cover categories. Interpretation and land cover classification of the density-sliced image did not improve accuracy when compared with the optical data. Rather, tonal and texture clues of benefit in interpretation of the image were reduced and the overlap and confusion among land cover categories increased. While the extent of urban growth was easily detected by this level-slicing, generalization step the total amount of land cover information available on the image was more difficult to collect and it was less accurate. However, it is believed that reducing image noise by the incorporation of smoothing and averaging algorithm into the data before density-slicing may increase the amount and quality of information obtainable.

CONCLUSIONS

Seasat SAR data digitally processed at three different scales were examined in this study. To obtain useful imagery for analysis of the entire 100 km x 100 km scene (scale - 1:500,000) and a medium scale (1:131,000) image it was necessary to employ an averaging algorithm to reduce noise inherent in the data tapes. However, the raw data products were very satisfactory for interpretation of the large scale (1:41,000) imagery.

Until smoothing and averaging algorithms can be developed for incorporation into the data prior to level-slicing and color-coding it is believed density-slicing will prove of little value for urban land cover analysis. Much valuable image texture and tone information is lost when slicing and coding techniques are employed. No improvement in accuracy or level of detail observable was apparent at any of the scales examined when such data were compared with results of the Optical interpretation of the black-and-white images generated from the data.

The merits of each of the three scales examined for urban land cover analysis can be summarized as follows:

Small scale (1:500,000): Level I land cover classes can be delimited for synoptic mapping of urban areas. Agricultural Land, Forest Land, and Rangeland adjacent to urbanized areas can be identified for incorporation into general planning inventories of growth direction and land cover change. The extent of urban built-up can be defined within acceptable mapping accuracies of this scale. As is the case with any data generated at this scale, little detail is apparent.

Medium scale (1:131,000): More precise delimitation of the urban infrastructure is possible at this scale as Level II land cover category detail can be extracted. New residential areas can be delimited as can the commercial-services/industrial core, but small, isolated commercial streets or blocks and the discrimination of older, interior residential areas from adjacent commercial zones (e.g., transition zone) is tenuous. At this scale open space is detectable and its use (e.g., recreation or parks) at times inferred from its size, shape, and spatial location in relation to the urban area--but not consistently. Elements of the transportation network are not always identifiable other than the large airport complex.

Large scale (1:41,000): At this scale the most precise measurement of urban growth patterns can be made. The location and extent of growth on the urban fringe is facile due to the contrast between recent residential development and surrounding open space. Even small, isolated, low density housing developments can be detected. The contrast between older interior residential versus commercial activity is generally apparent, but the similarity in gray tone/texture response still remains a problem. However, this indistinction is not unique to radar systems. Buildings in such sections of cities are frequently used for either or both activities and often require ground observation to precisely identify the correct land use. Open space is readily identifiable at this large scale but defining its use is arduous. Classification of open space as to public, institutional, utilities, and extractive land use is imprecise. Transportation elements are visible and more of the transportation network is visible or can be inferred than at any other scale. However, no single type or class of transportation is consistently visible. At this large scale there is a loss of certain spatial association clues inherent at the medium scale, but this problem can possibly be mitigated by mosaiking several large scale images.

In general, some improvement in classification accuracy was possible compared to the medium scale enlargements. At first glance the accuracy of the medium scale image (87.9 per cent) appears higher than the average for the five large scale scenes (83.6 per cent) (Table 17). However, the medium scale image did not include Study Area 5, the airport scene, where detection accuracy was the lowest. In addition, some small land cover parcels not visible on the medium scale image were visible on the large scale scene but were incorrectly identified. Still, the overall merit of the large

Table 17. Summary of Large Scale Study Area Land Cover Interpretation Accuracy

Interpretation Method	Study Area 1	Study Area 3	Study Area 4	Study Area 5	Study Area 6	Average
Optical Interpretation	93.9%	84.0%	77.4%	70.8%	92.1%	83.6%
Density-Sliced	89.5%	76.9%	69.9%	62.5%	88.8%	77.5%

scale imagery should be judged in light of costs and information sought. Although the results are not conclusive it is suggested that a better synoptic view and comparable interpretation accuracies can be obtained with the 1:131,000 scale image, but for a more exact delimitation of urban growth extent and direction the large scale images may be preferable.

The results of this study appear promising, but additional work is requisite prior to a definitive statement on SAR's potential for urban land cover analysis. A relatively new urban complex in a semi-arid environment was examined in this effort. The question remains as to whether similar results could be expected in a more humid environment, an older urban settlement, one predicated on a different mix of economic activities, or in a smaller or larger metropolitan area. Digitally processed SAR imagery does provide useful information on the urban environment. Medium and large scale enlargements provide distinct but complementary urban data. The textural component and the susceptability of radar return to the angular, geometric patterns of man-made structures produce unique signal responses corresponding to urban land cover types. An effort must be made to precisely understand this relationship and develop more sophisticated preprocessing algorithms to abet the interpretation process. Equally as important, research devoted to the possible synergetic effect of merging the textural component of SAR data with the spectral information available with other sensors (e.g., digitally processed multi-spectral scanner data) certainly merits serious attention.

APPENDIX

Table 2. Confusion Matrix of SAR Interpretation Accuracy at 1:131,000

SAR Interpreted Land Cover

Actual Ground Cover	CI/I	CS	FOP	R	W	Total Actual Area
CI/I	4,435.5h (10,960a)		121.8h (301a)	155.4h (384a)		4,712.7h (11,645a)
CS		410.4h (1,014a)		887.1h (2,192a)		1,297.5h (3,206a)
FOP	66.4h (164a)	188.2h (465a)	5,500.2h (13,591a)	931.2h (2,301a)		6,686.0h (16,521a)
R	898.0h (2,219a)	1,197.5h (2,959a)	121.8h (301a)	22,421.3h (55,403a)		24,638.6h (60,882a)
W					388.1h (959a)	388.1h (959a)
Total Area By SAR	5,399.9h (13,343a)	1,796.1h (4,438a)	5,743.8h (14,193a)	24,395.0h (60,280a)	388.1h (959a)	37,722.9h (93,213a)

Key: (CI/I) commercial-industrial; (CS) commercial-services;
(FOP) recreational-open-public; (R) residential; (W) water
h = hectares; a = acres

Table 3. Confusion Matrix of Study Area 1 (Optical Interpretation)

SAR Interpreted Land Cover

Actual Ground Cover

	AFGO	E	P	R	U	W	Total Actual Area
AFGO	1,060.3h (2,620a)					3.2h (8a)	1,063.5h (2,628a)
E	11.3h (28a)						11.3h (28a)
P	72.8h (180a)						72.8h (180a)
R	77.7h (192a)			1,422.9h (3,516a)			1,500.6h (3,708a)
U	9.7h (24a)						9.7h (24a)
W						195.9h (484a)	195.9h (484a)
Total Area By SAR	1,231.8h (3,044a)			1,422.9h (3,516a)		199.1h (492a)	2,853.8h (7,052a)

Key: (A) agricultural; (E) extractive; (F) recreation; (G) cemeteries;
(O) open; (P) public; (R) residential; (U) utilities; (W) water
h = hectares; a = acres

Table 4. Confusion Matrix of Study Area 1 (Density-Sliced)

SAR Interpreted Land Cover

Actual Ground Cover	AFGO	C	E	I	P	R	U	W	Total Actual Area
AFGO	1,118.6h (2,764a)					11.3h (28a)			1,129.9h (2,792a)
C	13.0h (32a)					1.6h (4a)			14.6h (36a)
E	24.3h (60a)								24.3h (60a)
I						3.2h (8a)			3.2h (8a)
P	56.7h (140a)					4.8h (12a)			61.5h (152a)
R	163.5h (404a)					1,201.1h (2,968a)			1,364.6h (3,372a)
U						6.5h (16a)			6.5h (16a)
W	6.5h (16a)							176.4h (436a)	182.9h (452a)
Total Area by SAR	1,382.6h (3,416a)					1,228.5h (3,036a)		176.4h (436a)	2,787.5h (6,888a)

Key: (A) agricultural; (C) commercial; (E) extractive; (F) recreation; (G) cemeteries; (I) industrial; (O) open; (P) public; (R) residential; (U) utilities; (W) water; h = hectares; a = acres

Table 5. Confusion Matrix of Study Area 3 (Optical Interpretation)

SAR Interpreted Land Cover

Actual Ground Cover	AFGO	C/CI/I	P	R	T	U	Total Actual Area
AFGO	288.1h (712a)	30.8h (76a)		17.8h (44a)			336.7h (832a)
C/CI/I		202.3h (500a)		178.1h (440a)			380.4h (940a)
P	40.5h (100a)		9.7h (24a)	30.8h (76a)			81.0h (200a)
R	40.5h (100a)	74.5h (184a)		1,785.5h (4,412a)			1,900.5h (4,696a)
T				13.0h (32a)			13.0h (32a)
U				9.7h (24a)			9.7h (24a)
Total Area by SAR	369.1h (912a)	307.6h (760a)	9.7h (24a)	2,034.9h (5,028a)			2,721.3h (6,724a)

Key: (A) agricultural; (C) commercial; (CI) commercial-industrial; (F) recreation; (G) cemeteries; (I) industrial; (O) open; (P) public; (R) residential; (T) transportation; (U) utilities

h = hectares; a = acres

Table 6. Confusion Matrix of Study Area 3 (Density-Sliced)

SAR Interpreted Land Cover

Actual Ground Cover	AFGO	C/CI/I	E	P	R	T	Total Actual Area
AFGO	186.2h (460a)	11.3 (28a)		8.1h (20a)	113.3h (280a)		318.9h (788a)
C/CI/I	13.0h (32a)	29.1h (72a)		30.8h (76a)	220.2h (544a)		293.1h (724a)
E					21.0h (52a)		21.0h (52a)
P	37.2h (92a)				55.0h (136a)		92.2h (228a)
R	90.7h (224a)	11.3h (28a)		3.2h (8a)	1,877.8h (4,640a)		1,983.0h (4,900a)
T					13.0h (32a)		13.0h (32a)
Total Area by SAR	327.1h (808a)	51.7h (128a)		42.1h (104a)	2,300.3h (5,684a)		2,721.2h (6,724a)

Key: (A) agricultural; (C) commercial; (CI) commercial-industrial; (E) extractive; (F) recreation; (G) cemeteries; (I) industrial; (O) open; (P) public; (R) residential; (T) transportation

h = hectares; a = acres

Table 7. Confusion Matrix of Study Area 4 (Optical Interpretation)

SAR Interpreted Land Cover

Actual Ground Cover	AFGO	C	I/CI	P	R	T	Total Actual Area
AFGO	145.7h (360a)	1.6h (4a)	92.3h (228a)	24.3h (60a)	25.9h (64a)		289.8h (716a)
C		385.3h (952a)			77.7h (192a)		463.0h (1,144a)
I/CI			752.7h (1,860a)				752.7h (1,860a)
P		56.7h (140a)			63.1h (156a)		119.8h (296a)
R		268.7h (664a)	51.8h (128a)		872.5h (2,156a)		1,193.0h (2,948a)
T						105.2h (260a)	105.2h (260a)
Total Area by SAR	145.7h (360a)	712.3h (1,760a)	896.8h (2,216a)	24.3h (60a)	1,039.2h (2,568a)	105.2h (260a)	2,923.5h (7,224a)

Key: (A) agricultural; (C) com[illegible]cial; (CI) commercial-industrial; (F) recreation; (G) cemeteries; (I) industrial; (O) open; (P) public; (R) residential; (T) transportation

h = hectares; a = acres

Table 8. Confusion Matrix of Study Area 4 (Density-Sliced)

SAR Interpreted Land Cover

Actual Ground Cover	AFGO	C/CS	I/CI	P	R	T	Total Actual Area
AFGO	137.6h (340a)		100.4h (248a)		4.9h (12a)	9.7h (24a)	252.6h (624a)
C/CS	24.3h (60a)	320.5h (792a)			23.0h (84a)		378.8h (936a)
I/CI	9.7h (24a)		754.4h (1,864a)		6.5h (16a)		770.6h (1,904a)
P	9.7h (24a)	66.4h (164a)	35.6h (88a)		35.6h (88a)		147.3h (364a)
R		223.4h (552a)	189.4h (468a)		710.6h (1,746a)		1,123.4h (2,776a)
T			90.7h (224a)		19.4h (48a)	72.8h (180a)	182.9h (452a)
Total Area by SAR	181.3h (448a)	610.3h (1,508a)	1,170.5h (2,892a)		811.0h (2,004a)	82.5h (204a)	2,855.6h (7,056a)

Key: (A) agricultural; (C) commercial; (CI) commercial-industrial; (CS) commercial-services; (F) recreation; (G) cemeteries; (I) industrial; (O) open; (P) public; (R) residential; (T) transportation; h = hectares; a = acres

Table 9. Confusion Matrix of Study Area 5 (Optical Interpretation)

SAR Interpreted Land Cover

Actual Ground Cover

	AFO	C/CI/I	E	P	R	T	U	W	Total Actual Area
AFO	242.8h (600a)	204.0h (504a)			4.9h (12a)	118.2h (292a)			569.9h (1,408a)
C/CI/I	13.0h (32a)	522.9h (1,292a)			25.9h (64a)	9.7h (24a)			571.5h (1,412a)
E	9.7h (24a)	9.7h (24a)							19.4h (48a)
P	286.5h (708a)	22.7h (56a)			22.7h (56a)	4.9h (12a)			336.8h (832a)
R	6.5h (16a)				501.8h (1,240a)				508.3h (1,256a)
T		40.5h (100a)				652.4h (1,612a)			692.9h (1,712a)
U		6.5h (16a)				9.7h (24a)			16.2h (40a)
W								6.5h (16a)	6.5h (16a)
Total Area by SAR	558.5h (1,380a)	806.3h (1,992a)			555.3h (1,372a)	794.9h (1,964a)		6.5h (16a)	2,721.5h (6,724a)

Key: (A) agricultural, (C) commercial; (CI) commercial-industrial; (E) extractive; (F) recreation; (I) industrial; (O) open; (P) public; (R) residential; (T) transportation; (U) utilities; (W) water
h = hectares; a = acres

Table 10. Confusion Matrix of Study Area 5 (Density-Sliced)

SAR Interpreted Land Cover

Actual Ground Cover	AFO	C/CI/I	E	P	R	T	U	Total Actual Area
AFO	192.6h (476a)	309.2h (764a)			3.2h (8a)	25.9h (64a)		530.9h (1,312a)
C/CI/I	79.3h (196a)	399.8h (988a)			17.8h (44a)	21.0h (52a)		517.9h (1,280a)
E		37.2h (92a)						37.2h (92a)
P	339.9h (840a)	25.9h (64a)			11.3h (28a)			377.1h (932a)
R	17.8h (44a)	42.1h (104a)			560.1h (1,384a)			620.0h (1,532a)
T		68.0h (168a)				548.8h (1,356a)		616.8h (1,524a)
U		21.0h (52a)						21.0h (52a)
Total Area by SAR	629.6h (1,556a)	903.2h (2,232a)			592.4h (1,464a)	595.7h (1,472a)		2,720.9h (6,724a)

Key: (A) agricultural; (C) commercial; (CI) commercial-industrial;
(E) extractive; (F) recreation; (I) industrial; (O) open;
(P) public; (R) residential; (T) transportation; (U) utilities
h = hectares; a = acres

Table 11. Confusion Matrix of Study Area 6 (Optical Interpretation)

SAR Interpreted Land Cover

Actual Ground Cover	AFO	CI	P	R	W	Total Actual Area
AFO	1,218.9h (3,012a)	21.0h (52a)			1.6h (4a)	1,241.6h (3,068a)
CI	4.9h (12a)					4.9h (12a)
P	8.1h (20a)			3.2h (8a)		11.3h (28a)
R	89.0h (220a)	64.8h (160a)		1,031.2h (2,548a)		1,184.9h (2,928a)
W	16.2h (40a)				195.9h (484a)	212.1h (524a)
Total Area by SAR	1,337.1h (3,304a)	85.8h (212a)		1,034.4h (2,556a)	197.5h (488a)	2,654.8h (6,560a)

Key: (A) agricultural; (CI) commercial-industrial; (F) recreation;
(O) open; (P) public; (R) residential; (W) water
h = hectares; a = acres

Table 12. Confusion Matrix of Study Area 6 (Density-Sliced)

SAR Interpreted Land Cover

Actual Ground Cover	AFO	C/CI	P	R	W	Total Actual Area
AFO	1,207.6h (2,984a)					1,207.6h (2,984a)
C/CI				3.2h (8a)		3.2h (8a)
P	1.6h (4a)			6.5h (16a)		8.1h (20a)
R	286.5h (708a)			1,002.0h (2,476a)		1,288.5h (3,184a)
W	8.1h (20a)				205.6h (508a)	213.7h (528a)
Total Area by SAR	1,503.8h (3,716a)			1,011.7h (2,500a)	205.6h (508a)	2,721.1h (6,724a)

Key: (A) agricultural; (C) commercial; (CI) commercial-industrial;
(F) recreation; (O) open; (P) public; (R) residential; (W) water
h = hectares; a = acres

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