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L- and X-Band Like- and Cross-Polarized Synthetic Aperture Radar for Investigating Urban Environments

The X-band like-polarized data were the most useful, the L-band cross-polarized data were the least useful, and the texture calculations used in this study did not contribute toward urban cover type delineations.

Abstract: *Four synthetic aperture airborne radar data sets, L- and X-band like- and cross-polarizations, were spatially registered to a common map base for a portion of the Los Angeles basin. Texture calculations for the four SAR data sets were also obtained. Training sites for eight urban land-cover types were located, and statistics were determined for the eight data files. The training site statistics were examined for intraclass variability, the number of channels necessary for classification, and the best channels for classification using transformed divergence calculations. The X-band like-polarized data were the most useful, the L-band cross-polarized data were the least useful among the original data sets, and the texture calculations used in this study did not contribute toward urban cover type delineations.*

Introduction

The examination of radar data for the mapping and analysis of Earth surface features has considerably increased in the last few years. Much of this increase is a function of the recent availability of these data. The increase is also due to the awareness that radar has unique attributes, such as its all-weather and night and day capabilities, which may make it a very useful tool for resource inventory and analysis. There is, however, much which is still not understood about radar responses and how to use the data for resource analysis.

Previous studies have examined radar data of different bands and polarizations (Jensen *et al.*, 1977); from different platforms, i.e., aircraft and satellite (Wu, 1980); with different manipulations of the data, i.e., subtraction of one band from another (Bryan, 1982) and texture analysis (Fasler, 1980); and for different environments, i.e., geology (Ford, 1980), agriculture (Ulaby and Bare, 1980), land use (Henderson, 1979), and urban (Bryan, 1979). The purpose of this study was to examine two synthetic aperture radar (SAR) bands, L-band and X-band, at both like- and cross-polarizations in order to assess their usefulness for urban land-cover delineations. Rather than a visual analysis of images as has been done previously with similar data, this study examined the numerical data. The data were spatially registered to a common map base, thus allowing the extraction of data for the same surface features. The principal analytic tool used in this study was transformed divergence calculation. This calculation provides a quick inexpensive indication of the ability to classify numerically and correctly different land covers. The following sections describe the data, study area, research methodology, and study results.

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Data Acquisition

L-band like- (horizontal-horizontal, HH) and cross- (horizontal-vertical, HV) polarized data were collected for the Los Angeles basin in California on 7 March 1979 by the Jet Propulsion Laboratory (JPL) of the California Institute of Technology. The L-band sensor was on a NASA Convair 990 aircraft at 10,000-m (33,000-feet) altitude with a due north look direction and depression angles varying from 42° near range to 14° far range. The L-band sensor wavelength was about 23 cm and had an inherent resolution of 12 to 14 meters per pixel or picture element. The X-band sensor had a wavelength of 3.2 cm and an inherent resolution of 17 to 19 m. The like- (HH) and cross- (HV) polarization X-band data were collected by the NASA Johnson Space Center for the same area on 30 August through 2 September 1979. This sensor was on an RB-57 aircraft at 18,300-m (60,000-feet) altitude, also with a look direction of due north and depression angles varying from 49° near range to 30° far range.

Data Preprocessing

The four bands of radar data were spatially reprojected to fit 15-m grid cells on a Universal Transverse Mercator (UTM) map projection. This reprojection, or registration process, involved the selection of line and column identified control points from a computer display of each radar image and latitude and longitude coordinates of the same points from 1:24,000-scale topographic maps. The latitude and longitude locations were converted to UTM coordinates, and a mathematical relationship between the radar data and the UTM projection was established. Calculations were made for each radar data set of the best fit for the control points in order to determine the movement of all data elements to the projected map base grid (Clark, 1980; Bryant and Zobrist, 1977). This process provided a unique set of four spatially registered types of radar data. These data are part of a larger collection of multisensor and cartographic data assembled by the Earth Resources Applications Group of the Image Processing Laboratory at the California Institute of Technology's Jet Propulsion Laboratory in Pasadena, California. That entire data set is registered to the UTM projection to allow for multisensor, multispectral remotely sensed data analysis.

The reprojected 15-m resolution data were aggregated to 30-m resolution by averaging each four picture element block. This resolution allowed for the inclusion of two-cell by two-cell texture calculations in the analysis and was also a smoothing function for the data. Averaging of pixel values to simulate resolution changes is simple and inexpensive. It will not, however, exactly replicate data as it would be obtained by different resolution sensors, but the differences were not expected to seriously influence this analysis (Sadowski *et al.*, 1977). The effect of changing resolution by this simple averaging was to lower the standard deviations of statistics for each training site. For a subset of six sample sites and one radar data file, the change from 15- to 30-m resolution did not change the mean data values and lowered the standard deviation by an average value of under 2.

Texture Determinations

Haralick (1978) has reviewed the use of texture in remote sensing analysis. Fasler (1980) and Clark (1980) have quantified texture values for Seasat SAR data. Fasler described texture as the spatial distribution and organization of the grey tone difference in an image which can be visually characterized as being fine, coarse, smooth, granulated, etc. Because both Fasler and Clark indicated improved data analysis with texture values, texture calculations were made for the four SAR data sets in this study. This study used the method of Clark (1980), who determined texture values as a function of variance or the frequency of change between the SAR data values of adjacent pixels. Land covers of a homogeneous return such as grassland should have a low variance or texture while land covers with a high frequency of change such as residential areas should have high variance or texture. The actual calculations were

$$\text{Texture} = (\overline{X^2}) - \overline{X}^2.$$

The value $(\overline{X^2})$ was determined by squaring the response value for each 15-m pixel cell and then obtaining the average for each two by two matrix or 30-m cell. The value, $\overline{X}^2$, was determined by aver-

Table 1. Radar and Texture File Identifications

File	Contents		
1	L-band	horizontal-horizontal polarization	LHH
2	X-band	horizontal-horizontal polarization	XHH
3	X-band	horizontal-vertical polarization	XHV
4	L-band	horizontal-vertical polarization	LHV
5	X-band	like polarization texture	XHHt
6	X-band	cross polarization texture	XHVt
7	L-band	cross polarization texture	LHVt
8	L-band	like polarization texture	LHHt

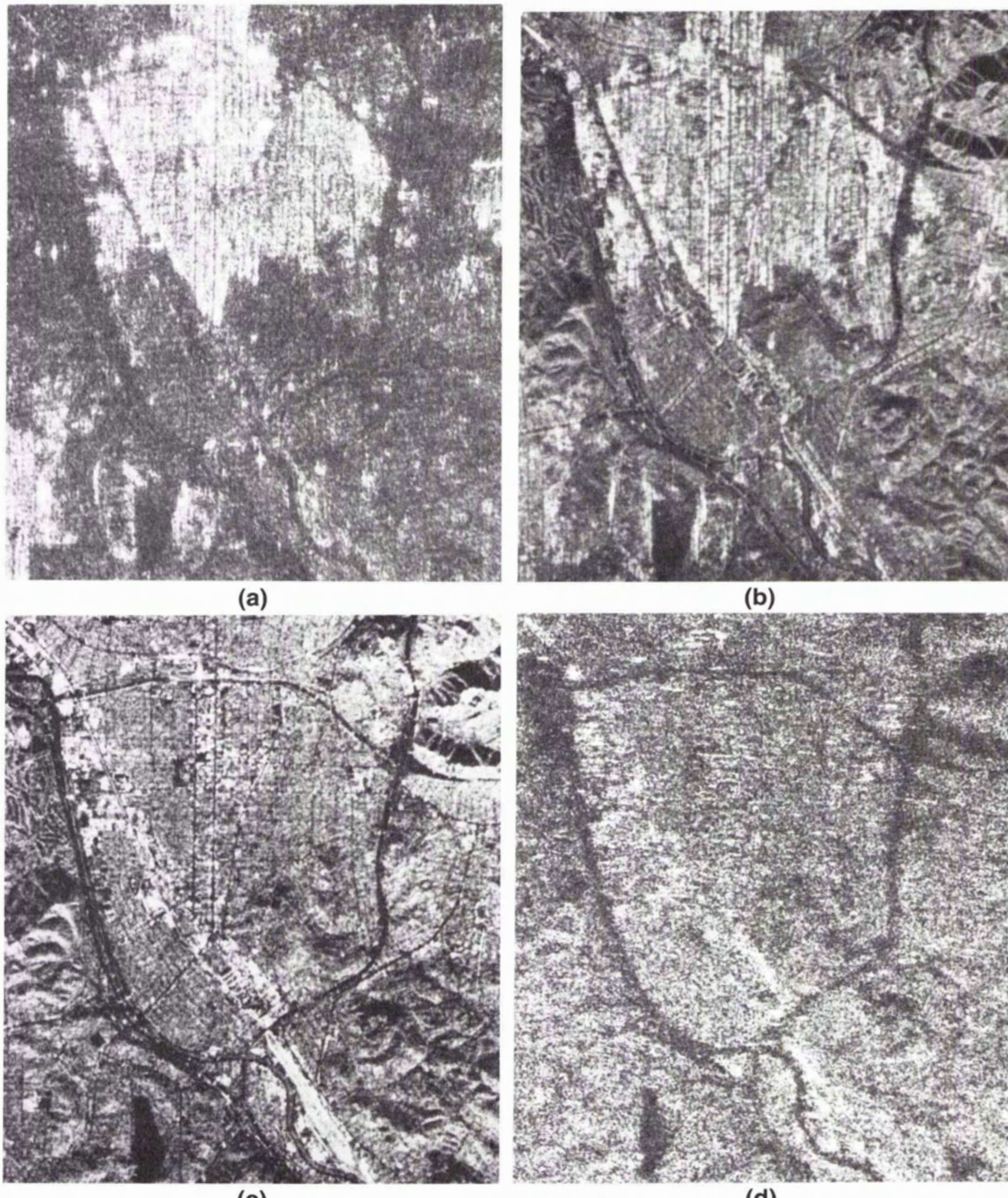

FIG. 1. Images of Glendale, California for Four Synthetic Aperature Radar Data Sets. (a) L-Band Like Polarization. (b) X-Band Like Polarization. (c) X-Band Cross Polarization. (d) L-Band Cross Polarization. Image Scale 1:96,500. North and radar look direction are towards the top.

aging two by two matrices of the original data and then squaring the result to get the square of the means. The eight files of spatially registered SAR data and associated texture values are listed in Table 1. Images of the SAR data for the study area are contained in Figure 1.

STUDY AREA AND TRAINING SITES

The study area as shown in Figure 1 is a segment of the Los Angeles basin. This area includes the city of Glendale, California, and portions of several surrounding cities in the north central portion of the

TABLE 2. TRAINING SITE DESCRIPTIONS

Site Numbers	Land Cover
1-2	Water
3-6	Residential
7-8	Transportation—railroad
9-10	Transportation—freeway
11-12	Grass—golf course
13-14	Grass—cemetery
15-17	Commercial—services
18-21	Industrial

basin. This is a relatively flat area containing mostly urban land-cover types. Most of the scene consists of an urban built-up area bordered by major freeways (dark tones). There are some hills in the northeast and west. There is also a large reservoir (dark tone) and a large railroad (light tone) easily observable in the lower portion of the X-band HV image. A visual examination of the X-band HV image provides the most recognizable features and the L-band HV image provides very little familiar information. On both the L- and X-band like-polarizations, the influence of street orientation on scene return is very apparent. In both images the areas where the street patterns are orthogonal to the look direction, the scene is lighter toned. Topographic shadowing in the northeast is evident in all four images.

Twenty-one training sites for eight different land cover types varying in size from 25 to 1396 15-m pixels were selected by interpretation of high altitude color infrared photography in association with topographic maps and the SAR imagery. Table 2 identifies the training sites, and Figure 2 locates them within the study area. The SAR file means and standard deviations for the training sites are contained in Table 3. The data in that table are in themselves interesting and are also useful in understanding some of the results in this study.

An initial observation of the training site statistics in Table 3 brings out the small data values and relatively large standard deviations for the texture values. There is little discriminatory information between radar data types or training sites for these texture values. The range in training site mean values for the 21 classes is very similar for the original L-HH, X-HV, and L-HV data, i.e., the ranges are 73, 80, and 74, respectively, and is less, 58, for the X-HH file. This suggests less discrimination between cover types with this file. However, the range in standard deviations for the training sites is less for the L-HV data (12) than for the other SAR data files (19, 21, and 17), which will also influence discrimination.

There are considerable differences in the responses in all four SAR files for the two water sites (1 and 2). This may be in part related to the small size of site two (25 15-m pixels), due to the inclusion of some non-water pixels when aggregating cells, or possibly due to differences in wave height or orientation. For these reasons site 2 may not be a good site for analysis. There is also a very high standard deviation for the site 1 X-HH data. The two X-band means for site 1 are the lowest of all the training sites, as would be expected from water which is a specular reflector.

The four residential sites (3 through 7) have little variation in the X-HV file. The two sites with orthogonal street pattern and SAR look direction (sites 3 and 6) have higher response values in both the like polarization files. These differences in radar response due to street patterns will influence the ability to delineate this land cover.

The freeway sites (9 and 10) were not very similar training sites because they were interchanges where a variety of surfaces and angular relations made them quite different in their radar return values. This is particularly evident in both of the cross polarization files.

Because this area of California is quite dry during the summer, the urban vegetation is generally watered. Training sites from a golf course (11 and 12) and a cemetery (13 and 14) were selected to represent urban green areas or parks. These sites contained some trees as well as other features such as minor roads and tombstones. The SAR data files for the cemetery sites are fairly similar except for the low L-HV values for site 11.

The commercial and service areas are quite representative of their land-use class and have similar radar returns. The industrial sites consisted primarily of warehouses and were lacking in heavy industry and extensive stockpiling of raw materials. As with the residential sites, the industrial site with an orthogonal relationship (19) between street orientation and radar look direction has higher scene response values in both of the like polarization files.

ANALYSIS METHOD

Transformed divergence (TD) was the analytical tool used for this study. Transformed divergence, which is calculated from the means and covariance matrices of each spectral class or training site, is a measure of the statistical distance between class or site pairs of interest and provides information on their "separability." This separability is an indirect estimate of the likelihood of correct classification between groups of different channel combinations (Swain *et al.*, 1971). Such an estimate provides information usually obtained by the time consuming and expensive process of actual classification and accuracy evaluations. A discussion of transformed divergence, including some of its disadvantages, can be found in Swain *et al.* (1971), Swain and Davis (1978), and Latty and Hoffer (1980).

Transformed divergence can be used to examine intraclass variability, to examine how separability

TABLE 3. TRAINING SITE MEAN DATA VALUES AND STANDARD DEVIATIONS*

Training Site Number and Cover	SAR Data File							
	L-HH	X-HH	X-HV	L-HV	X-HH Texture	X-HV Texture	L-HV Texture	L-HH Texture
1 Water	41	187	158	61	7	6	7	5
	6	25	4	9	4	3	4	2
2 Water	56	235	206	89	6	8	12	8
	9	6	9	12	4	2	3	3
3 Residential	96	245	207	79	8	8	11	9
	14	4	8	11	4	3	5	4
4 Residential	57	225	208	99	8	7	11	7
	9	7	9	14	3	3	6	5
5 Residential	55	235	212	73	8	7	11	7
	9	7	7	11	3	3	6	4
6 Residential	79	241	206	81	8	8	12	10
	14	7	9	11	4	3	6	6
7 Transportation-	58	238	238	124	7	8	11	7
railroad	11	7	5	16	3	3	6	3
8 Transportation-	72	230	232	106	8	8	10	9
railroad	17	11	10	17	3	4	5	5
9 Transportation-	49	203	192	83	8	8	10	7
freeway	9	18	13	15	3	4	4	3
10 Transportation-	37	196	168	50	6	6	9	5
freeway	8	12	7	10	3	2	5	3
11 Grass-	38	199	191	53	8	8	8	5
golf course	7	10	11	12	3	3	4	2
12 Grass	46	207	190	75	9	7	11	7
golf course	7	15	11	17	4	3	6	4
13 Grass-	45	215	198	81	7	7	10	7
cemetery	7	19	8	14	3	3	4	3
14 Grass-	41	210	191	72	8	7	11	6
cemetery	8	10	12	12	2	3	5	4
15 Commercial-	110	243	213	85	8	9	12	9
services	20	7	14	14	3	4	6	5
16 Commercial-	97	241	205	78	8	8	11	9
services	25	7	13	14	4	4	6	5
17 Commercial-	103	244	211	84	8	9	13	9
services	16	6	16	17	4	4	8	5
18 Industrial	50	226	210	76	8	8	12	7
	15	16	21	21	4	4	8	5
19 Industrial	95	240	209	91	8	8	15	9
	21	12	18	21	4	3	7	5
20 Industrial	58	226	216	98	8	8	12	7
	14	12	16	17	3	3	6	4
21 Industrial	62	232	222	107	8	8	12	8
	13	12	14	17	4	4	6	4

* Mean/Standard Deviation

may change with an increase or decrease in the number of channels utilized, and to determine the spectral channels most useful for classifying specific class pairs. A transformed divergence value of 1500 or greater in this analysis generally indicates an acceptable separability of classes (Swain *et al.*, 1971). The maximum or saturated value is 2000.

INTRACLASS VARIABILITY

For each cover type in this analysis, a minimum of two training sites was selected. The number of available training sites was limited by the area for which the SAR data could be precisely registered. Transformed divergence values were obtained for all possible pairs of training sites for each cover type for all SAR files. The intent of these calculations was to assess intraclass variability for different SAR data sets. This information is useful prior to classification in indicating to the analyst those cover types with no significant intraclass variability so that they may be adequately represented by a single training site or that the training site statistics for that cover type can be merged. Similarly, for cover types with significant intraclass variability, the analyst must use

FIG. 2. Training Site Locations

several distinct training sites in representing those cover types. The examination of this variability by channels also provides the analyst with information on those channels most likely to minimize intraclass variability and thus allow a reduction in the number of site statistics used in classification.

The results of the transformed divergence calculations for intraclass variability are contained in Table 4. Each class with a separable training site pair, a TD value greater than 1500, is indicated for the file where the separability occurs. The two water classes are separable in the X-HH and X-HV

TABLE 4. INTRACLASS SEPARABILITY

Cover Type and Training Site Number	SAR Data File							
	L-HH	X-HH	X-HV	L-HV	X-HH Texture	X-HV Texture	L-HV Texture	L-HH Texture
Water (1-2)		x	x					
Residential (3-6)	x	x						
Transportation—railroad (7-8)								
Transportation—freeway (9-10)								
Grass—golf course (11-12)								
Grass—cemetery (13-14)								
Grass (11-14)								
Commercial-services (15-17)								
Industrial (18-21)								

Cover type training sites with intraclass transformed divergence values greater than 1500 are indicated by an X for each data file.

TABLE 5. MERGED TRAINING SITE MEAN DATA VALUES AND STANDARD DEVIATIONS*

Training Site Cover Type and Number	SAR Data File			
	L-HH	X-HH	X-HV	L-HV
Railroad (22)	68	232	234	111
	16	11	9	19
Freeway (23)	43	200	180	67
	10	16	16	20
Park (24)	43	209	193	73
	8	12	11	17
Commercial—services (25)	104	243	210	83
	21	7	15	15
Industrial (26)	64	230	215	94
	22	14	18	22

* Mean/Standard Deviation.

data. This is possibly a function of the radar return from these short wavelengths differing because o wave size or orientation. The residential sites are separated in the L-HH and X-HH data. Closer examination of the separability values indicates that the separability only occurs between sites 3 - 4 and 3 - 5 in the L-band and sites 3 - 4 in the X-band. An examination of the aerial photography for these sites indicates that site 3 has a very distinct orthogonal relationship between street orientation and SAR look direction, which is not true for sites 4 and 5. Bryan (1979) demonstrated that the radar look direction will cause variations in return from similar cultural land covers. This variation in the angular relationship between street patterns and radar look direction is then the cause of the intraclass variability of the residential sites. It is surprising that there is no intraclass separability in other cover types for the original data, indicating homogeneity within cover types for these data. It is not surprising that there is no intraclass separability in any of the texture files because of their low and very similar training site mean values.

The information in this table was used in some subsequent analyses. Those cover types without training site separability were merged to one statistical set of values for further examinations. The resulting means and standard deviations of these merged classes are contained in Table 5. The texture values, because of their low variability, are not included in this table. Site 24, park, is both the golf course and cemetery sites combined.

TABLE 6. TRANSFORMED DIVERGENCE VALUES AS A FUNCTION OF NUMBER OF DATA FILES

Number of Files	Average of Best Five File Combinations	Range of Best Five File Combinations
1	681	845
2	1290	201
3	1495	195
4	1646	50

NUMBER OF DATA FILES

Indications of the most desirable number of data files for classification can be obtained from transformed divergence values. These values provide information on the likelihood of correct classification as a function of the number of data types used. Table 6 contains the TD average and range of the best five files or file combinations for different numbers of files. These values are for the eight data files and the eleven classes determined from the examination of intra-class variability. These classes are two water, four residential, and combined classes for the other five cover types as found in Table 5. Because several training sites of the same cover type are included, which would be expected to have low TD values, the values in this table are conservative in estimating separability.

There appears to be sufficient information in four files for a good classification. A reasonable classification generally requires a TD value of at least 1500. Several of the three data file combinations also have TD values greater than 1500 and might also provide good classifications. The number of channels necessary for classification in this study is very similar to that found in previous studies with other, but multispectral scanner, data sets (Latty and Hoffer, 1980; Hoffer *et al.*, 1978).

CHANNEL SELECTION

In addition to determining the number of data files necessary for classification, divergence values are used for specific data selection. Table 7 identifies the best data or data combinations for different numbers of input files. These values are for the 11 classes previously identified. In examining this table, it should be remembered that only the best eight combinations are listed out of those possible; there are, for example, 90 possible four-file combinations. Because of this the range of separability or TD values between the combinations listed is often very small; for example, the transformed divergence value difference between the first and eighth best four-file combination is only 128.

It is apparent from Table 7 that, as expected from the training site means and standard deviations in Table 3, the texture values as used in this study (Files 5, 6, 7, and 8) do not significantly contribute towards urban cover delineations. Perhaps other means of quantifying texture or a variation of these texture values, such as histogram expansion, might improve their usefulness in urban cover separations. The most important single files for digital analysis from these calculations are the like polarization files 1 and 2. The least important non-texture file is the L-band cross-polarization, file 4, a fact which was visually suggested by the images.

TABLE 7. BEST DATA OR DATA COMBINATIONS AS DETERMINED BY TRANSFORMED DIVERGENCE CALCULATIONS FOR DIFFERENT NUMBERS OF INPUT FILES

	Number of Files			
	1	2	3	4
	2	1,3	1,2,3	1,2,3,4
	1	1,2	1,2,4	1,2,3,8
Best	3	2,3	1,3,4	1,2,3,7
Data	4	2,4	2,3,4	1,2,3,5
	8	1,4	1,3,8	1,2,3,6
	7	2,8	2,3,8	1,3,4,6
	6	2,7	1,3,7	1,2,4,8
	5	2,6	1,3,6	1,3,4,8

Data Identification: 1-LHH, 2-XHH, 3-XHV, 4-LHV, 5-XHHt, 6-XHVt, 7-LHVt, 8-LHHt

The combinations of two files indicates that the best combination is of different polarization L and X-bands. The only possible two file combination among the four SAR files not in Table 7 is the combination of L like-and cross-polarizations, files 3 and 4. The X-band like-polarization data, file 2, appear to be slightly more useful than the X-band cross-polarization data. This is in part determined in the two file combinations where the only original data file paired with a texture file are the X-HH data. Of the texture files they are paired with, they are most useful with the L-band like- and cross-polarized texture followed by the X-HV texture. Among those pairs listed, they are not paired with their own texture values.

An examination of the 3 and 4 file combinations confirms that the X-HH texture is the least useful texture value whereas the L-HH texture is the most useful. Somewhat surprisingly, the L-HV texture is the second most useful texture although the L-HV data are the least useful of the original data.

Table 7 indicates the low utility of the texture values used in this analysis and the best and worst of the original data files for classification. It also indicates that, in general, the best combinations of files are those of great dissimilarity. This is in agreement with similar studies using multispectral scanner data.

An important aspect of transformed divergence calculations is the examination of the separability values for training site or cover pairs because the average transformed divergence values from many pairs do not indicate classification confusions for specific cover types. Table 8 contains the paired transformed divergence values for the original four data files and the eleven training site statistics.

The first water site is separable (TD greater than 1500) from all other cover types but, somewhat surprisingly, water site 2 is not separable from residential sites 4 and 5. An examination of these sites in the color infrared photography offers no apparent explanation for this confusion unless, as suggested earlier, site 2 is not a reliable water site, particularly if in the pixel aggregation some non-water pixels were included in site 2.

As discussed previously, there are some cases of separability and non-separability within the residential classes primarily due to street orientation and resulting differences in radar response. Residential site 3 is also not separable from the commercial-services combined site 25. These two sites have similar street orientation which most probably accounts for their lack of separability. Residential site 4 is not separable from the combined industrial site 26. Site 4 and three of four industrial sites have similar street orientations. Residential site 6, as site 3, is confused with the commercial-services cover and also has the same street orientation as this combined site. The influence of street orientation on site separability is evident from Table 8.

The railroad site 22 is confused with the industrial cover while the freeway 23 is confused with park site 24. The freeway-park confusion is originally surprising but less so when Table 3 is examined where the SAR data files for the freeway and grass sites are similar.

The industrial site accounts for 6 of the 11 non-similar cover type separability problems. This is explainable because this cover type has the largest standard deviations of the training sites.

SUMMARY

The transformed divergence calculations used in this study have indicated that the most useful of the four SAR data sets examined for urban land cover delineations by digital analysis are the X-band like-polarization data. The least useful are the L-band cross-polarization data. The radar texture calculations used in this study did not provide useful information. Intraclass variability as determined in this analysis only existed for the water and residential classes. The variability of the residential classes was primarily due to differences in the angular relationship between street orientation and radar look direction. Data from four, or possibly three, channels would be adequate for classification. There are, however, significant classification confusions between some urban cover types caused by similarity of street orientations and the large response value standard deviations of the industrial training sites.

At our present understanding of radar returns, it is questionable if signature extraction and classification of radar data by itself is warranted. It seems more likely that the radar data would be more useful if combined with other remotely sensed data such as multispectral scanner data for classification. In this context it might also be advisable to consider using the radar data in a two or more stage classification strategy. Principal research extensions of this study include actual classification and accuracy analysis to verify the transformed divergence calculations, further examination of different SAR tex-

TABLE 8. PAIRED TRANSFORMED DIVERGENCE VALUES FOR FOUR SAR DATA VALUES

Training Site Number and Description		Training Site Number 2	3	4	5	6	22	23	24	25	26
1	Water	2000	2000	2000	2000	1999	2000	1933	1996	2000	1999
2	Water		1981	1106	1020	1674	1845	1999	1987	1992	1694
3	Residential			1973	1808	592	1978	1999	1999	665	1889
4	Residential				1236	1553	1648	1910	1546	1919	1105
5	Residential					1186	1860	1982	1785	1856	1457
6	Residential						1874	1989	1934	680	1303
22	Railroad							1946	1907	1813	1030
23	Freeway								538	1998	1607
24	Park									1994	1488
25	Commercial-Services										1231
26	Industrial										

ture calculations for different size matrixes, and the combination of the radar with other remotely sensed data for urban cover delineations.

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Erratum

It has been brought to our attention that the description of the December 1983 cover is incorrect. The prominent snow-covered peak in the lower right (southeast) corner is, in fact, Mt. Kilimanjaro. Mt. Kenya, with a very small snow cap, is located in the upper right (northeast) corner of the mosaic.