RADAR AND OPTICAL DATA SENSOR INTEGRATION FOR LAND COVER EXTRACTION

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ABSTRACT

This study evaluated the advantages of combining traditional spaceborne optical data from the visible and infrared wavelengths with the longer wavelengths of radar. Several East African landscapes and one from Nepal including areas of settlements, natural vegetation and agriculture were examined. For these study sites, multisensor data sets were digitally integrated with training and truth information derived from field visits. Three general processing strategies were examined. The number of radar bands were expanded by use of texture measures to create new bands. Various spatial aspects of the data were examined including texture window size and post-classification filtering. Finally, different integration strategies including number of sensor bands, weighting of bands and principle components were explored. These results show that radar results can be improved by various manipulations such as derived texture measures and filtering and the potential of optical/radar merger for mapping basic land use/cover patterns in different environments. Given the range of landscapes examined, the results of this study should have wide applicability. The radar results can be improved by various manipulations such as derived texture measures and filtering. An important observation is that there are no consistent strategies for using radar and sensor integration that will provide the best results. As with independent optical data, the most productive processing strategies may be site and data specific.

INTRODUCTION

In a world with increasing population and the misuse of limited land resources, there is a greater demand for current, accurate spatial information. This issue of reliable information has taken on global dimensions as the world community has recognized the need to assess problems and tasks such as environmental studies, economic planning and resource management, in many diverse and separate geographical regions. Basic information concerning land use is, therefore, critical to both scientific analysis and decision making activities. Without this information scientists cannot complete valid studies and decision-makers will often fail to make the correct choices (Haack and English, 1996).

One significant method for providing current, reliable land surface information is spaceborne remote sensing. Traditionally, this has taken the form of multispectral systems, such as the Landsat Thematic Mapper (TM), which collect data at several discrete bandwidths within the visible and infrared regions of the electromagnetic spectrum (EMS). These systems have the advantage of being a mature technology, with a broad knowledge base achieved through several decades of experimentation and use (Gerstl, 1990). More recently Earth observation research has grown with the launch of several satellite systems capable of collecting radar data. Radar systems, which focus on the microwave region of the EMS, are of particular interest as they constitute a region far removed from, and potentially complementary with traditional multispectral sensors.

A difficulty with the analysis of radar as an independent sensor is that conventional radar spaceborne systems only collect data at a single wavelength with a fixed polarization. Only one component of the total surface scattering is thereby being measured, while any additional information contained within the reflected radar signal is lost (Zebker and van Zyl, 1991). Future systems will include an increased number of wavelengths and polarizations, but until then the goal of increased informational content may possibly be reached through simpler methods, such as the extraction of textural measures. Textural information may be used in addition to the spectral measurements of a single wavelength for analysis (Mauer, 1974).

Textural information may be as important as spectral information in radar images (Anys and He, 1995), as the information content of an image resides in both the intensity (spectral) of individual pixels and the spatial arrangement of those pixels. Standard image classification procedures, used to extract information from remotely sensed images, usually ignore this spatial information and are based on purely spectral characteristics. Such classifiers will be ineffective when applied to land use/cover classes such as residential and urban areas that are largely distinguished by their spatial, rather than their spectral, characteristics (Lee and Philpot, 1991).

The availability of remotely sensed data of the same geographic area obtained from separate sensors, operating in different portions of the electromagnetic spectrum, such as Landsat TM and RADARSAT, is increasing (Paris and Kwong, 1988). This, along with improved technology for the georectification and merging of such separate data sets has made the synergism of optical and radar data for land applications of greater practical importance (Leckie, 1990). This is done in an attempt to generate an interpretation of a geographic area that is not obtainable from any single sensor alone, or to reduce the uncertainty associated with data from a single source (Schistad, et al., 1994).

Generally, the traditional visible and infrared wavelength systems are recognized as being superior to radar data, due to their multispectral information content (Brisco and Brown, 1999). This is a strong argument for the utility of sensor fusion, as such multispectral systems are a fusion of several individual bandwidths of information. A problem with these systems is that spectral responses in the optical and infrared wavelengths are sensitive to differential scattering and absorption caused by chlorophyll, green leaf area and leaf structure, leaving some vegetation types that cannot be separated due to the similarity of their spectral responses (Raghavswamy, et al., 1996). Active microwave energy of radar responds to different terrain and dielectric factors, such as plant canopy roughness and structure, plant moisture content and sub-canopy conditions. As such, a combined sensor analysis could contribute information concerning both the leaf composition and the surface geometry, thereby greatly increasing the potential information content.

The purpose of this study was to examine and improve upon the classification accuracy of specific land use/cover categories by utilizing these diverse, but complementary, portions of the electromagnetic spectrum for three study sites. Classification accuaracies were determined for the radar and optical data independently. Additional analyses were conducted to determine methods to improve the classification accuracy from radar. These methods included speckle reduction, texture measures, post-classification smoothing and various combinations of these techniques. The best radar manipulations were merged with TM data to determine classification improvements by sensor integration.

STUDY SITES AND DATA

Several different study sites were included in this study representing different surface conditions. These include two sites in East Africa and Kathmandu, Nepal. These multiple sites allow for comparison of procedures and results.

Kericho, Kenya

The Kericho study site is a complex geographic region, about 80 kms to the east of Lake Victoria and the port city of Kisumu, in western Kenya. The site covers an area approximately 20 kms by 20 kms that has an average elevation of 1500 m and a highly variable topography, with several steeply sloping features. Small, family owned and operated farms of mixed crops cover much of the region. This is a very intense agriculture, as field sizes are small and cropping patterns are complex. Most crops grown are for family consumption and include corn, various legumes, mixed vegetables, bananas, papaya and small plots of tea or coffee. These areas include some isolated large trees and structures. These inclusions further add to the complexity of this already diverse agricultural area. Such complexity in crop type, field size and structures make it nearly impossible to map individual crops in this region. Large tea plantations are located in the more elevated areas of the region. At the highest elevations is a third cover type of natural, broadleaf evergreen forests. These forests are quite mature and protected, providing a high green vegetation.

Limited areas of settlement constitute the final cover type located within this study site. Most housing in this region is associated with the small farms, and scattered throughout the mixed agricultural landscape. Though, these interspersed houses make up a majority of the dwellings, they are too small and isolated to be mapped, so the more concentrated areas of tea plantation settlements and the urban area of Kericho City were used for assessment. The housing for the employees of the large-scale tea estates is quite concentrated, interspersed among the tea plantations. Both the city of Kericho and plantation housing are very similar in tone and difficult to delineate from the bare soils of the mixed agricultural region. Such spectral confusion is cause for inadequate classification accuracies between these cover types.

The primary land use/cover types investigated as part of this study include the small, intense agricultural areas fallow during this date, tea plantations, natural forest and settlements. A RADARSAT scene from February 27, 1997 was used for this study. RADARSAT is C-band, 5.6 cm data, with a Horizontal-Horizontal (HH) polarization. The RADARSAT scene shows remarkably little difference in backscatter between the primary surface features. The natural forest has a higher tone, backscatter, as do the settlements but in general, there is little clear tonal separability in the primary land covers. Training and truth information obtained during field visitation, in June and July of 1997, were converted to a raster based geographic information system (GIS) layer and spatially fused to the imagery for signature extraction and comparison to the classification results.

Wad Medani, Sudan

The Wad Medani study site is situated along the Blue Nile River in central Sudan. It includes the second largest city in Sudan, Wad Medani, which is 160 kms southeast of Khartoum. Wad Medani has a population near 100,000 and is an extremely successful agricultural production area for cotton and sugar cane.

This region of Sudan is extremely flat and dry, and, with the exception of irrigated agricultural fields, contains very little vegetation. The natural vegetation is mostly riparian. Although there is a very limited amount of riparian vegetation in this subscene, because of its similarity of response to the crops, both of these features were included under the general cover classification of vegetation. The fields have defined geometric patterns for ease of identification. However, there are orchards near the river which merge directly into natural riparian vegetation.

Other land use/cover types include: water of the Blue Nile River, which transects the scene from the Northeast to the Southwest; urban areas, including villages and the city of Wad Medani; and areas of dry, bare soil. Wad Medani is not clearly identifiable in optical wavelengths because much of the material used in construction, primarily clay, is spectrally very similar to the areas of bare soil.

A Landsat TM scene from November 18, 1984 as well as radar data from the Shuttle Imaging Radar mission B (SIR-B) were used in this analysis. The SIR-B mission was flown in October 1984 and collected L-band (23.5 cm) Horizontal-Horizontal polarization synthetic aperture data. The digitally correlated data were obtained at a 12.5-m spatial resolution and fused with the 30-m TM data to the Universal Transverse Mercator coordinate system using a nearest-neighbor intensity resampling method. The RMS error for the geometric rectification was under one pixel. The Landsat TM thermal band at the coarser spatial resolution of 120 meters was excluded from the sensor integration. Ground information was obtained during a field visit in 1988. Using enlarged SIR-B and Landsat TM prints with limited available maps, samples of the various land use/covers were documented on overlays to the hardcopy imagery. This information was then converted to a raster-based GIS format and registered to the SIR-B/TM data set.

Kathmandu Valley, Nepal

The Kathmandu Valley is in the central region of Nepal and encompasses an area of approximately 30 by 35 kms. The generally flat floor of the valley is at an average elevation of 1,300 m and the sides of the valley are very steeply sloping to elevations of over 2,000 m. The floor of the valley consists of two primary landforms, broad river floodplains and elevated ancient lake and river terraces, locally called tars.

For this study, four land use/covers were examined. These include the dense, older urban core; the more recent expansions of the urban areas on the margins, suburban or new urban; agriculture which is primarily fallow at the time of year for the imagery examined; and a few areas of open grass. This is a limited number of classes but considered adequate for this study where the primary intent is the delineation of urban extent and also for an initial examination of analysis procedures. The more appropriate procedures from this study could be applied to a more complex set of classes of a future study. For the purposes of urban growth mapping, it may not be necessary to separate the old urban and new urban. The grass and agriculture are also not significantly different from a land use\cover perspective for urban delineations. In examining the results from this site, the new and old urban could be combined to urban and the grass and agriculture to a non-urban class.

A RADARSAT scene from November 19, 1998 was collected with an approximate 50-degree incident angle and a spatial resolution of about 25 by 28 meters. TM data from 4 November, 1999 were collected in six reflective spectral regions from the visible to the mid-infrared at a nominal spatial resolution of 28.5 m. A seventh band in the thermal-infrared was not included in this study, in large part because of the much larger spatial resolution and also the added complexity of thermal data.

The TM data were UTM registered and resampled to 20 meters. In this scene, the new urban regions are light, most of the core older urban features are darker grey because of different roofing materials, greater density and more shadows. This TM date was selected because it is a cloud free image and similar in date to the RADARSAT scene. The analysis of this image was done without one of the reflective bands due to a conversion difficulty. Band 7, the second mid-infrared band, was not available but its absence is not considered a significant issue in this study since the other mid-infrared band was available.

METHODOLOGY

The basic procedure for this study was to conduct a digital classification of selected surface classes using standard processing techniques applied to various combinations and manipulations of the merged optical and radar data sets, as well as the original data sets themselves. Spectral signatures were extracted for the various cover types using supervised training sites identified through fieldwork. After signature extraction, a maximum likelihood decision rule was employed to classify the data sets. Accuracy assessment was calculated from a comparison of the classifications obtained to a set of truth sites, separate from the training areas, also derived from field efforts. The results from this study consist of comparisons between the producers and users accuracy assessments from various classifications for the individual cover types, and for all of the cover types combined in an overall classification accuracy for the site

This study extends sensor fusion results from previous studies by these authors and others. One of these data sets had been examined using a parallelepiped decision rule and only the original data without any modification of radar either spatially or radiometrically (Haack and Slonecker, 1994). This study employed the more common, and generally more effective, maximum likelihood decision rule for classification and examined other radar derived measures. This study also extended previous efforts to compare different radar texture measures and texture window sizes which determined that the variance texture window at a 13 X 13 pixel window generally provide the best results (Haack and Bechdol, 1999). In addition, this study had a more comprehensive inclusion of several spatial and radiometric manipulations of the radar data. There was a focus on the radar manipulations because it is only a single band and single polarization data set in contrast to the multiband TM data. Most automated classification procedures improve with multiple bands rather than a single band. In addition, there is considerable more existing research with multispectral data such as the TM than radar.

This study began with a classification of the original radar data. Multiple independent radar derived values via spatial and/or radiometric procedures were then created and examined. Among the spatial procedures were speckle reduction and post-classification filtering. The radiometric derived procedures were radar texture measures with and without speckle reduction. These individual manipulations were then included in two and three band combinations to assess radar classification changes with additional bands. After evaluation of the radar data, the Landsat TM data were classified independently and then in combination with radar and radar derived bands.

RESULTS

Kericho

Evaluation of the Kericho study site was accomplished by comparing classifications to areas of truth. For Kericho there were 16,780 truth pixels, which included four forest sites (8,848 pixels), five tea plantation sites (2,761 pixels), one urban site (114 pixels) and four sites of mixed agriculture (5,057 pixels). The low number of urban truth pixels was due to the lack of large urban areas within the scene. The city of Kericho was the only urban area available for the purposes of accuracy assessment. The differences in the size and number of the truth sites was of particular importance, as larger truth classes, such as the forest class, would contribute more substantially to an overall classification percentage, while a small class, such as the urban class will have little influence. This could result in misleading overall classification accuracies. For this reason, individual class accuracies were evaluated in addition to the overall percentage of correctly identified pixels.

Radar. Initial examination of the RADARSAT image for Kericho provided poor classification results. As can be seen in Table 1, the overall classification, as well as most of the individual class accuracies, were quite low. The more unique, higher backscatter areas of the urban/settlement class had the best producer's classification accuracy at approximately 67 percent, but provided a very low user's accuracy.

Table 1. Contingency table for Kericho RADARSAT.

	Forest	Tea	Urban	Mixed Ag	Total	**User Accuracy**
Forest	**2750**	541	19	525	3835	71.71 %
Tea	2696	**1094**	10	1530	5330	20.53 %
Urban	1756	108	**76**	84	2024	37.55 %
Mixed Ag	1646	1018	9	**2918**	5591	52.19 %
Total	8848	2761	114	5057	**16780**	
Producer Accuracy	31.08 %	39.62 %	66.67 %	57.70 %		**Overall Accuracy 40.75 %**

A larger number of pixels from each of the forest, tea and mixed agricultural classes were incorrectly included as part of the urban category (1948 out of 2024 total pixels) than were correctly classified as urban pixels. Though this misclassification did not affect the proportion of correctly identified urban pixels (76 out of 114), it did decrease the reliability of the urban class. The reliability was decreased because as the total number of pixels classified as urban features increased, the correctly identified urban pixels occupied an increasingly lower proportion of that total (76 out of 2024 pixels). This resulted in a much larger urban area than should have been present within the classification. The accuracy of the other classes decreased as well, as a number of pixels that should have been included within each of these classes were removed and instead classified as urban.

This was a particular problem within the forest class, which had the largest number of pixels incorrectly assigned as urban, though the incorrect classification of forest areas was not limited to this urban misclassification. The urban class occupied 20 percent (2696) of the forest truth pixels, but nearly 30 percent (2696 pixels) of the forest class was misidentified as tea plantations and 19 percent (1646) as mixed agriculture. These errors of omission decreased the producer's accuracy of the forest class and increased the total number of pixels assigned to the other classes, which in turn decreased their user's accuracy, or reliability.

Errors of omission and commission are directly related and overlap in effect. An individual class may possess one or the other, or it may possess both types of errors. The urban class had a fairly high producer's, or classification, accuracy with a very low user's accuracy, while the forest class had a fairly high user's, but a low producer's accuracy. The tea and mixed agricultural classes added to the errors associated with both the urban and the forest classes, but also had a more general confusion between themselves. Both the user's and producer's accuracies for these classes were low, as they had nearly the same number of pixels confused with the other classes as they have correctly classified.

These results are consistent with examination of the RADARSAT data. The RADARSAT spectral signatures for the forest, tea and mixed agriculture covers (urban class excluded) do not greatly differ, returning visually and spectrally similar responses. They have average digital number (DN) values of 139, 113 and 103 (respectively) and all possess high standard deviations. This creates areas of overlap in their spectral signatures, which causes confusion, and limits their spectral separability. The urban class has a much higher average DN value at 206, which improves its spectral discrimination, but also has a much higher standard deviation. This high standard deviation indicates that both high and low DN values may be included in the urban class, which accounts for the over-classification as many pixels values may fall within this signature range.

Landsat TM. Analysis of the Landsat TM data provided very good overall classification results but an extremely poor ability to map urban features. As shown in Table 2, a classification utilizing all of the TM bands (excluding the thermal band due to its coarse spatial resolution) only classified the urban areas at 28 percent accuracy, while other cover types were nearly perfectly identified. The low accuracy of the urban class was due to the similarity in spectral response to that of the mixed agriculture class at this time of year. This confusion can be identified in Table 2, as 82 out of the 114 urban pixels were classified as mixed agriculture. This accounted for 72 percent of the urban pixel misclassification.

Table 2. Contingency table for Kericho Landsat TM (bands 123457).

	Forest	Tea	Urban	Mixed Ag	Total	**User Accuracy**
Forest	**8848**	0	0	0	8848	100 %
Tea	0	**2759**	0	2	2761	99.93 %
Urban	0	0	**32**	3	35	91.43 %
Mixed Ag	0	2	82	**5052**	5136	98.36 %
Total	8848	2761	114	5057	**16780**	
Procucer Accuracy	100 %	99.93 %	28.07 %	99.47 %		**Overall Accuracy 99.47 %**

Radar derived measure (texture). The high standard deviation associated with the RADARSAT's urban class suggested that measures of image texture could possibly increase the discriminatory ability of radar. Though the classes may have had similar average DN values, differences in their standard deviations indicate that actual values exist over varying ranges. Measures of Variance texture were applied to the original RADARSAT data over 13x13, 21x21 and 29x29 moving window sizes. Previous analysis with similar data had determined that the Variance measure of texture and these window sizes were most useful (Haack and Bechdol, 2000). The results indicate that texture does improve discrimination. Overall classification accuracies of 67, 72 and 71 percent (respectively) were achieved, improving over those of the original radar data by 26 percent or more.

Results achieved with use of the 21x21 texture window size were best. The effectiveness of this texture window size is closely related to the variability and areas of the ground features being observed. This window seems to have been a good average size for the variety of class areas within this scene. Table 3 contains the contingency matrix for these results. These texture based classifications greatly increased the overall accuracy and especially increased the accuracy and reliability of the forest and urban classes. The urban features were discriminated perfectly by the 21x21 texture image, eliminating all of the confusion and errors previously seen with that class. The confusion associated with the forest class (both errors of omission and commission) was also all but eliminated, with only minor confusion between it and the mixed agriculture and tea classes. The only remaining area of major confusion was isolated between the mixed agricultural class and the tea plantations. These two land covers seemed to be very similar in terms of radar backscatter value and spatial variability.

Table 3. Contingency table for Kericho 21x21 Variance texture RADARSAT.

	Forest	Tea	Urban	Mixed Ag	Total	**User Accuracy**
Forest	**8672**	410	0	99	9181	94.46 %
Tea	0	**1205**	0	2949	4154	29.01 %
Urban	0	0	**114**	0	114	100 %
Mixed Ag	176	1146	0	**2009**	3331	60.31 %
Total	8848	2761	114	5057	**16780**	
Producer Accuracy	98.01 %	43.64 %	100 %	39.73 %		**Overall Accuracy 71.51 %**

Sensor fusion. Both the Landsat TM and RADARSAT data were found to be incapable of accurately delineating all four of the primary cover types on their own. Each of these two sensors has its strengths and weaknesses. The Landsat TM data can accurately discriminate the forest, tea and mixed agriculture, but fails to identify a majority of the urban class and the best classifications of the RADARSAT data achieved excellent discrimination between the forest and urban class (at near perfect levels), while the tea and mixed agriculture classes were greatly confused. By combining these two separate data sources it may be possible to improve the discriminatory ability over that of either sensor alone. Several different types of combinations and fusion techniques were examined.

Generally, the combination techniques that included a subset of the TM bands as well as the radar texture images were best. A combination including six TM bands and one or two bands of radar put a disproportionate amount of weight on the TM data, whereas a subset of the TM data combined with a band of radar data is a more equal combination. This sensor fusion obtained over 98 percent correct classification for all cover types.

Wad Medani

Evaluation of the Wad Medani, Sudan study site analysis was accomplished by comparing the classifications to areas of known truth obtained during ground visitation. For Wad Medani, there were 9,625 truth pixels. These pixels included four areas of water (970 total pixels), three agricultural sites (1,621 pixels), three urban areas (3,435 pixels) and three areas of other ground cover or bare soil (3,599 pixels). The lower number of water and agricultural pixels is primarily due to the dry climate of this area and the resulting lack of moisture for these features. The only body of water within the study region was that of the Blue Nile River, which meanders across a thin section of the scene. Agricultural areas, too, were limited in this subscene as irrigation is needed to sustain crops. The riparian vegetation exists only at a very close proximity to the Blue Nile.

Radar. The SIR-B image of Wad Medani, Sudan provided poor overall classification results (~51 percent accuracy). Confusion was caused by similarities in the radar spectral responses between the urban and agricultural areas, as well as between the water and other/bare soil classes in this site. These areas of confusion are clearly demonstrated in Table 4 which contains the distribution of pixels and resulting classification accuracies for each of these individual classes.

Table 4. Contingency table for Wad Medani SIR-B.

	Water	Ag	Other/ bare	Urban	Total	**User Accuracy**
Water	**326**	84	1200	114	1724	19.91 %
Agriculture	0	**594**	0	1366	1960	30.31 %
Other/ bare	602	185	**2313**	285	3385	68.33 %
Urban	42	758	86	**1670**	2556	65.34 %
Total	970	1621	3599	3435	**9625**	
Producer Accuracy	33.61 %	36.64 %	64.27 %	48.62 %		**Overall Accuracy 50.94 %**

The water class is most representative of the confusion associated within the scene as it has both the poorest producer's (~33 percent) and user's accuracies (~20 percent), indicating a high degree of both errors of omission and commission. More water areas were incorrectly classified as other/bare than were classified as water (602 versus 326 pixels). These incorrect pixels accounted for approximately 62 percent of the actual water areas. More pixels were also identified as water (errors of commission), than were correctly identified as water (1,398 pixels). The majority of these pixels should have been assigned to the other/bare cover class (1,200 pixels).

Conversely, the pixels incorrectly included as part of the other/bare cover class should almost entirely have been assigned as water pixels (2,313 pixels), and though this class has the highest producer's (~64 percent) and user's (~68 percent) classification accuracies, these incorrectly included water pixels make up over 60 percent of the area identified as other/bare. Confusion similar to that between the water and other/bare classes was found between the agriculture and urban areas. Agricultural areas were commonly classified as urban features (~47 percent of the time) and the urban features were often misclassified as agricultural areas (~40 percent of the time).

Such confusion can be expected from the examination of the October 1984 SIR-B radar image. Both the agriculture and urban areas are represented by similarly high backscatter values with high standard deviations, while the water and other/bare classes are both represented with similarly low backscatter values and relatively low standard deviations. As such, radar spectral values alone were not enough to discriminate between these land cover classes.

Landsat Thematic Mapper (TM). The Landsat TM data provided generally good overall classification results, achieving an overall classification accuracy of approximately 79 percent. The water class was nearly perfectly discriminated, while slight confusion existed between the urban and both the other/bare and the agriculture classes. As can be seen in Table 5, the lower class accuracies of the agriculture, other/bare and urban classes were due to the over-classification of the urban areas creating errors of urban area commission (where more urban areas are identified than should be present) and corresponding errors of omission in the agriculture and other/bare class. This was primarily due to the wide variation in urban class spectral response. As the areas of other/bare soil are spectrally most similar to certain areas of the urban class, it was most often misclassified as urban. As such, this class achieved a low degree of discrimination.

Table 5. Contingency table for Wad Medani Landsat TM.

	Water	Ag	Other/ bare	Urban	Total	**User Accuracy**
Water	**968**	0	0	0	968	100 %
Agriculture	0	**1247**	0	0	1247	100 %
Other/ bare	0	1	**2044**	57	2102	97.24 %
Urban	2	373	1195	**3378**	4948	68.27 %
Total	970	1621	3599	3435	**9625**	
Producer Accuracy	99.79 %	76.93 %	66.80 %	98.34 %		**Overall Accuracy 79.35 %**

Radar texture. Due to the differences in spectral standard deviations between these classes and the inability of original radar to accurately discriminate the land cover classes, it was felt that information besides that of spectral values must be included. Variance texture measures extracted at a 21x21 textural window size did improve the class discrimination within this scene. An overall classification accuracy of 71 percent was achieved.

Sensor fusion. Each of these sensors has its strengths and weaknesses. The Landsat TM data can accurately discriminate water features, but experiences some confusion between the agriculture, other/bare and urban classes. The radar texture measures achieved excellent discrimination of other features. Various sensor merges including different band combinations and fusion techniques were explored. All sensor merges improved accuracies over those achieved by either sensor alone.

Generally, combinations that included the first three Principle Components Analysis (PCA) bands derived from all six of the TM bands and the radar texture data were best. Combinations that simply added all six TM bands to the radar data were poorest as particularly shown by the agricultural class accuracies. This is likely due to the decreased weight given to the radar data in such a combination. Two bands of radar data out of eight bands total gives a disproportionate share of the spectral information to the TM data. The TM subset was also found to be inferior to the TM PCA when combined with radar data, most likely due to the loss of key spectral information when only a portion of the TM bands are used. The PCA of both the radar and TM data combined was found to be a generally better combination. The best accuracy was achieved with a combination that included the best speckle filtered radar image (5x5 Median filtered), the best single radar texture band (5x5 Median filtered 21x21 Variance texture), and the PCA of the TM data (Table 6)..

Table 6. Radar and Landsat TM sensor merger for Wad Medani.

	Water	Ag	Other/ bare	Urban	Total	**User Accuracy**
Water	**969**	0	0	0	969	100 %
Agriculture	0	**1461**	0	0	1461	100 %
Other/ bare	0	0	**3595**	0	3595	100 %
Urban	1	160	4	**3435**	3600	95.42 %
Total	970	1621	3599	3435	**9625**	
Producer Accuracy	99.90 %	90.13 %	99.89 %	100 %		**Overall Accuracy 98.29%**

Kathmandu

Radar. Initial examination of the RADARSAT data for Kathmandu provided poor classification results. As can be seen in Table 7, the overall classification, as well as most of the individual class accuracies, were quite low. The more unique, higher backscatter areas of the old urban class had the best producer's classification accuracy at approximately 77 percent, but provided a very low user's accuracy (42 percent). The primary confusion was between old and new urban. If these classes were combined, the results would be much better. There was, however, also considerable confusion between agriculture and new urban (1,081 erroneously classified truth pixels) and thus poor results for new urban. These results are not surprising for a single wavelength of any remote sensing data and especially radar. This traditional spectral signature extraction and matching classification procedure may not be the best processing strategy for radar. Other procedures, such as scattering models, may provide better radar results but the procedure used in this study allows for comparison and integration of sensors.

Table 7. RADARSAT original data results for Kathmandu.

	Grass	Agriculture	Urban_old	Urban_new	Total	User
						Accuracy
Grass	**337**	1257	0	115	1709	19.72%
Agriculture	112	**2882**	44	1081	4119	69.97%
Urban_old	0	6	**1086**	1499	2591	41.91%
Urban_new	0	185	284	**1594**	2063	77.27%
Total	449	4330	1414	4289	**10482**	
						OVERALL
Producer	75.06%	66.56%	76.80%	37.16%		**56.28%**

Landsat TM. Analysis of the Landsat TM data provided reasonable overall classification results (Table 8) and an improvement over the original radar results. Given the time of year and the amount of bare soil that is spectrally similar to the urban areas, the results are surprisingly good. These results are, however, less than several of the radar derived and radar combinations.

Table 8. LANDSAT TM original results for Kathmandu.

	Grass	Agriculture	Urban_old	Urban_new	Total	User
						Accuracy
Grass	**138**	450	20	240	848	16.27%
Agriculture	111	**3424**	20	257	3812	89.82%
Urban_old	25	119	**995**	1104	2243	44.36%
Urban_new	175	337	379	**2688**	3579	75.10%
Total	449	4330	1414	4289	**10482**	
						OVERALL
Producer	30.73%	79.08%	70.37%	62.67%		**69.12%**

Radar texture. Measures of Variance texture were applied to the original RADARSAT data over a 13x13 moving window. The results indicate that texture does improve discrimination with an overall classification accuracy of 75 percent, improving over those of the original radar data by about 20 percent. The effectiveness of this window size is related to the variability and spacing of the ground features being observed such as field size and building spacing particularly in the new urban locations. Table 9 contains the contingency matrix for these results. The confusions are within the two non-urban and the two urban classes. Class combinations would improve results greatly. The almost identical mean texture values for grass and agriculture (22 and 21) explain their classification confusion. Similarly, there are large texture differences between the two urban and two non-urban classes that allow their easy discrimination with texture measures.

Table 9. RADARSAT 13x13 pixel Variance texture for Kathmandu.

	Grass	Agriculture	Urban_old	Urban_new	Total	User Accuracy
Grass	**62**	624	88	46	820	7.56%
Agriculture	213	**3594**	2	0	3809	94.36%
Urban_old	122	112	**801**	791	1826	43.87%
Urban_new	52	0	523	**3452**	4027	85.72%
Total	449	4330	1414	4289	**10482**	
						OVERALL
Producer	13.81%	83.00%	56.65%	80.48%		**75.45%**

Sensor fusion. To assess issues such as the weight associated with each band and each sensor (the TM data consists of multiple bands; while the radar data consists of only one or two bands), several different types of combinations and fusion techniques were examined. These included combinations of original TM and radar or radar derived data; a subset of TM bands and radar data; PCA of the TM bands and radar data; and the PCA of the TM data combined with the radar. The best results were achieved through the combination of the individual radar texture image (RADARSAT 13x13 Variance) and the TM data (Table 10).

Table 10. RADARSAT + TM sensor merger for Kathmandu.

	Grass	Agriculture	Urban_old	Urban_new	Total	User Accuracy
Grass	**156**	8	0	4	168	92.86%
Agriculture	221	**4288**	0	12	4521	94.85%
Urban_old	0	0	**1097**	569	1666	65.85%
Urban_new	72	34	317	**3704**	4127	89.75%
Total	449	4330	1414	4289	**10482**	
						OVERALL
Producer	34.74%	99.03%	77.58%	86.36%		**88.20%**

SUMMARY

Both the Landsat TM and the RADARSAT data have been shown to be independently incapable of accurately delineating all of the land use/cover types for these sites. This is generally not surprising in part because the spectral confusion between urban features and bare soil is common in the optical bands and the radar data are more responsive to shape and form than tone. The single band radar is often a limiting factor as well.

Radar derived bands generally improve the utility of radar for land cover classes, at least for some features such as settlements. Various spatial and spectral manipulations of the radar were examined and in most cases Variance texture measures were found to be advantageous. The strategies for using radar that provide the best results may not be consistent. As with optical data, the most productive processing strategies may be site and data specific. Fusion of separate radar images was found to increase the accuracy over that of a single image alone. Even with additional bands, radar data were still incapable of accurate discrimination of all land covers.

Combinations of radar with optical data improve results, achieving good classification of most individual classes for all sites. These results show the potential of optical/radar merger for mapping basic land use/cover patterns. More case studies will contribute to an improved understanding of useful radar analysis techniques. Future applications of this project will include a comparison of the parallelepiped accuracy with that of a maximum likelihood and other classifiers, including a hierarchical approach, and an extension of basic land use/cover to more complex classification schemes. The systematic strategy of this study, determination of the best individual procedure before introducing the next method, was effective in managing a very complex, almost infinite set of analysis possibilities.

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REFERENCES

Anys, H. and He, D. C. (1995). Evaluation of textural and multipolarization radar features for crop classification. *IEEE Transactions on Geoscience and Remote Sensing*, 33(5), 1170-1181.

Brisco, B. and Brown, R. J. (1999). Mulitdate SAR/TM synergism for crop classification in Western Canada. *Photogrammetic Engineering and Remote Sensing*, 61(8), 1009-1014.

Gerstl, S. A. (1990). Physics concepts of optical and radar reflectance signatures. *International Journal of Remote Sensing*, 11(7), 1109-1117.

Haack, B. and Bechdol, M. (2000). Integrating multisensor data and radar texture measures for land cover mapping. *Computers and Geosciences*, 26, 411-421.

Haack, B. and Bechdol, M. (1999). Multisensor remote sensing data for land use/cover mapping. *Computers, Environment and Urban Systems*, 23, 53-69.

Haack, B. and English, R. (1996). National land cover mapping by remote sensing. *World Development*, 24(5), 845-855.

Haack, B., Slonecker, E. (1994). Merged spaceborne radar and Thematic Mapper digital data for locating villages in Sudan. *Photogrammetric Engineering and Remote Sensing* 60 (10), 1253-1257.

Leckie, D. G. (1990). Synergism of synthetic aperture radar and visible/infrared data for forest type discrimination. *Photogrammetric Engineering and Remote Sensing*, 56(9), 1237-1246.

Lee, J. H. and Philpot, W. D. (1991). Spectral texture pattern matching: a dassifier for digital imagery. *IEEE Transactions on Geoscience and Remote Sensing*, 29(4), 545-554.

Mauer, H., (1974). Quantification of textures: textural patterns and their significance for classification of agriculture crop types from colour aerial photographs. *Photogrammetria*, 30, 21-40.

Paris, J. F. and Kwong, H. H. (1988). Characterization of vegetation with combined Thematic Mapper and Shuttle Imaging RADAR (SIR-B) image data. *Photogrammetric Engineering and Remote Sensing*, 54(8), 1187-1193.

Raghavswamy, V., Gautam, N. C., Padmavathi, M., and Badarinath, K. V. (1996). Studies on microwave remote sensing data in conjunction with optical data for land use/land cover mapping and assessment. *Geocarto International*, 11(4), 25-30.

Schistad, A., Jain, A., and Taxt T. (1994). Multisource classification of remotely sensed data: fusion of Landsat TM and SAR images. *IEEE Transactions on Geoscience and Remote Sensing*, 32(4), 768-778.

Zebker, H. A. and Van Zyl, J. J. (1991). Imaging radar polarimetry: a review. *Proceedings of the IEEE*, 79, 1581-1606.