Synergism of Synthetic Aperture Radar and Visible/Infrared Data for Forest Type Discrimination

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ABSTRACT: Five visible, three near-infrared, and one mid-infrared airborne MSS bands and eight airborne synthetic apeture radar (SAR) bands were acquired during summer over a forest test site near Chalk River, Ontario, Canada. The radar bands were X (3.2 cm) and C (5.6 cm) recorded with both vertical and horizontal transmit and receive polarization (i.e., X_{VV}, X_{VH}, X_{HH}, X_{HV}, C_{VV}, C_{VH}, C_{HH}, C_{HV}). Radiometric corrections were applied and the data were geometrically registered at a 10-m resolution.

Radar bands were better at discriminating softwood species than were the visible/infrared bands. Red and white pine had relatively low microwave backscattering, whereas jack pine and white spruce had high backscattering. The hardwoods tested had intermediate to high backscattering. Use of a near-infrared or mid-infrared band is important for distinguishing hardwoods from softwoods. Visible and mid-infrared bands are useful for discriminating open areas with either sparse, moderate, or dense ground vegetation from forested areas. No specific band was consistently better than others for differentiating young and mature stands of several different species. Maximum average classification accuracy for seven forest types was 74 percent. The best five bands in combination with each other for discriminating general forest stand types were a near-infrared band, a green band, a mid-infrared band, X_{VV}, and C_{HH}. Classification accuracy using these five bands was 67 percent.

Synergism of visible/infrared and radar data results in improved forest mapping capabilities.

INTRODUCTION

THE SYNERGISM of visible and reflected infrared (visible/infrared) and radar data for land resource applications is becoming of greater practical importance. The planned Japan Earth Resource Satellite will have both radar and visible/infrared sensors, while the European Earth Resources Satellite and Canadian Radarsat will provide radar data that can be combined with data from visible/infrared sensors on other satellite platforms. Advances in inertial navigation system technology and the use of this technology to geometrically correct imagery from both airborne optical and microwave sensors are making possible the combination of airborne multispectral scanner and radar data in a manner feasible for operational use.

There have been many studies investigating radar data for general land type mapping that examine broad forest categories. Some of these have addressed the benefits of combining visible/infrared and radar data (Eyton *et al.*, 1979; Guindon *et al.*, 1980; Toll, 1980; Ulaby *et al.*, 1983; Maeda and Sato, 1987). Although there have been numerous investigations of visible/infrared multispectral scanner data for detailed forest type determination, few radar studies have examined the forestry problem in detail (e.g., Shuchman *et al.*, 1978; Guindon *et al.*, 1980; Leckie, 1983; Churchill and Keech, 1984; Hoekman, 1985). These report specific species differences that are highlighted by radar data, but generally difficult overall forest type discrimination and mapping. Visible/infrared data are generally good for discriminating broad forest types but have difficulty discriminating specific species.

It is hypothesized that combining visible/infrared and radar data will improve forest type discrimination and mapping over use of either visible/infrared or radar data alone. This synergism is tested by comparing the usefulness of visible/infrared and X (3.2 cm) and C (5.6 cm) radar bands, and combinations of these bands, for discriminating forest types through examination of signatures, statistical measures of separation between classes, maximum likelihood classification accuracy, and examples from the literature. Specific cases were addressed: discrimination of different softwood species, different hardwood species, hardwoods versus softwoods, open areas from forest, open areas of different ground vegetation densities, and stands of similar species but different ages. As well, overall species discrimination and forest type mapping was examined. Analysis was undertaken on forest stands with densities and canopy structures typical of dense stands of each species and age class. It is the compendium of tree, stand, and site characteristics of the stands used that contribute to the response of the sensors. These responses are considered characteristic of the species and forest types examined. Results are therefore limited to the conditions and stand characteristics present in the test site during data acquisition.

SITE

The test site was a 2.5- by 10-km area of the Petawawa National Forestry Institute research forest centered at 46°00′N, 77°25′W, near Chalk River, Ontario, Canada. The test site consisted of natural stands of red pine (*Pinus resinosa* Ait.), jack pine (*Pinus banksiana* Lamb.), white pine (*Pinus strobus* L.), and white spruce (*Picea glauca* (Moench) Voss). Mixed stands of red and white pine were common. Plantations of these species ranging in age from three to 60 years of age also occurred. The dominant hardwoods were poplar (*Populus* L.), birch (*Betula* L.), and maple (*Acer* L.). The hardwoods were generally present in mature stands of mixed hardwood composition, although there were pure stands of poplar. Mixedwood stands were also common.

Relief in the area was low (generally less than 25 m), with most areas being flat, rolling, or gently sloping with slopes less than 4°. The soil was sand and sandy loam with an organic horizon of varying depth. There had been 8.1 mm of rain on 15 August, three days before the radar data were acquired. Soil and leaf samples were collected at nine locations within the test site during the period of the radar data acquisition in order to determine approximate moisture conditions. Soil moisture conditions were moderate, with average gravimetric soil moisture in the 0- to 5-cm layer of approximately 30 percent in forested

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stands and 15 percent in open areas with conifer regeneration or ground vegetation cover. Average leaf moisture content (mass of water/dry mass) of hardwoods was approximately 170 percent. Needle moisture averaged 140 percent, as did that of the leaves of ground vegetation. Moisture conditions will vary locally dependent on specific site conditions. This variability is not accounted for in this study. Wind speed during the radar flights was 2.3 m/s at 3.5 m.

DATA

Data Acquisition

The radar data were acquired between 1230 and 1545 h Central Daylight Time on 18 August, 1981 by the Canada Centre for Remote Sensing Convair 580 SAR system. Data were acquired in X (3.2 cm) and C (5.6 cm) band and both vertical and horizontal transmit and receive polarizations, that is, vertical transmit vertical receive (X_{VV}, C_{VV}), vertical transmit horizontal receive (X_{VH}, C_{VH}), horizontal transmit horizontal receive (X_{HH}, C_{HH}), and horizontal transmit vertical receive (X_{HV}, C_{HV}). Therefore, a total of eight bands were acquired in two separate passes, one for each transmit polarization. Each pass was flown at an altitude of 3000 m above ground level with the same flight line azimuth (240°) resulting in all radar look directions being the same. Nominal resolution of the single look data was 3.0 m in range and 4.0 m in azimuth. The data were acquired in medium swath mode, giving a ground swath of 7.1 km and look angles of 15°, 59°, and 69° at the near edge, center, and far edge, respectively. The data were optically processed to a 50 mm wide black-and-white positive transparency image. Image quality was good with no blurring of detail and good dynamic range. Exceptions were the C band cross polarized data, which were of only moderate quality with some blurring of detail. Negative results for C band cross polarized data may therefore not be conclusive.

Airborne MSS data were acquired 17 August 1981 at an altitude of 1650 m above ground level with the Canada Centre for Remote Sensing Daedalus 1260 multispectral scanner (Zwick *et al.*, 1980). This gave a ground resolution of 4.1 m. The nine bands recorded are given in Table 1. The imagery was digitally recorded at 1635 h Central Daylight Time. The sun azimuth was 249°, its altitude 36.6°, and, with a 242° flight azimuth, this gave an angle of 83° between the sun azimuth and scan direction. The field-of-view of the scanner was ± 36.9° each side of nadir.

Data Preprocessing

Radar data. The optically processed data were digitized to eight bits with an Eikonix digitizing camera system. The resulting pixel resolution was 5.0 m. Radiometric trends occur across the range direction due to antenna pattern, attenuation of the radar signal, and changes of the backscatter of different surface types with look angle (Cosgriff *et al.*, 1960; Katz, 1963). A correction procedure was applied to the image of each band in order to account for these affects. An area of imagery over predominantly forest cover was selected and the mean pixel value of each column of pixels was calculated. These columns of pixels represent a line of data acquired along-track at a given look angle. A fourth-order polynomial was fit to these column averages and a correction factor ($F_i = P_m/P_i$, where P_m is the mean of the values of the polynomial curve across all columns and P_i is the value of the polynomial at column i) multiplied with the value of each pixel in column i.

Median filters are often used to reduce radar image speckle (Trevett, 1986). A median filter operating on a three-by-three pixel window was applied to the data. Several window sizes were investigated and the three-by-three window was found, by visual examination, to be the best compromise between speckle reduction and the retention of image detail, eliminating most of the speckle and retaining good image detail.

TABLE 1. VISIBLE/INFRARED SPECTRAL BANDS. RATIO AND DIFFERENCE FEATURES TESTED.

a) Visible/infrared bands.

Band	Wavelength (nm)
3 (475 nm)	450-500
4 (525 nm)	500-550
5 (575 nm)	550-600
6 (620 nm)	590-650
7 (665 nm)	630-700
8 (730 nm)	680-780
9 (835 nm)	770-900
10 (955 nm)	870-1040
11 (2150 nm)	1550-2750

b) Ratio and difference features derived from the radar bands.

Difference	Ratio
$X_{VV} - X_{VH}$	X_{VV}/X_{VH}
$X_{HH} - X_{HV}$	X_{HH}/X_{HV}
$X_{HH} - X_{VV}$	X_{HH}/X_{VV}
$X_{VV} - X_{HV}$	X_{VV}/X_{HV}
$X_{HH} - X_{VH}$	X_{HH}/X_{VH}
$C_{VV} - C_{VH}$	C_{VV}/C_{VH}
$C_{HH} - C_{HV}$	C_{HH}/C_{HV}
$C_{VV} - C_{HH}$	C_{VV}/C_{HH}
$C_{VV} - C_{HV}$	C_{VV}/C_{HV}
$C_{HH} - C_{VH}$	C_{HH}/C_{VH}
$C_{VV} - X_{VV}$	C_{VV}/X_{VV}
$C_{HH} - X_{HH}$	C_{HH}/X_{HH}
$X_{VH} - C_{VH}$	X_{VH}/C_{VH}
$X_{HV} - C_{HV}$	X_{HV}/C_{HV}

Airborne MSS data. Radiometric trends also occur on airborne MSS data. These result from the changing effect of path radiance, atmospheric attenuation, and bidirectional reflectances with illumination and sensor view angle. The latter factor is illustrated by the fact that, for the data of this study, the sun azimuth was 83° from the scanner view direction. For this reason, on one side of the image the sensor viewed slightly more of the sunlit side of the tree. A correction procedure similar to that used for the radar imagery was applied. Twenty-eight sample areas of dense mature red pine distributed across the image were defined. A quadratic polynomial was determined with the mean intensity of each sample area as the dependent variable and the position (number of pixels from nadir) of the centroid of the sample area as the independent variable. These polynomials represented the trend across the images well, with correlation coefficients of approximately 0.9 for the bands with the largest correction, while several bands did not show a significant trend. A correction factor equal to the difference between the polynomial at pixel i and the polynomial at nadir was added to each pixel value of column i of the image. A separate correction was determined and applied for each spectral band.

Geometric Correction and Image Registration. The airborne MSS data were registered to UTM coordinates using a third-order (ten-term) polynomial relating the image and UTM coordinates of 28 ground control points. The geometrically corrected image was output at a resolution of 5.0 m using cubic convolution resampling. Third-order polynomials were then used to register each of the eight median filtered radar bands to the geometrically corrected airborne MSS data. Thirty-three to 41 registration control points were used, depending on the availability of good reference points on each image. Residual errors for the control points ranged from 0.5 to 0.7 pixels in the pixel direction and 0.4 to 0.6 pixels in the line direction. The resulting 5.0-m registered

TABLE 2. COVER TYPE CLASSES.

#	Class	Description
1	jack pine	mature, dense
2	white spruce	mature, dense
3	mixed pine	mature, dense white and red pine in mixed and pure stands
4	young jack pine	dense jack pine approximately 20 years old
5	mixed hardwood	mature, dense hardwood of mixed species mainly maple (predominantly sugar maple (*Acer saccharum* Marsh.)), birch (predominantly white birch (*Betula papyrifera* Marsh.)), and beech (*Fagus grandifolia* Ehrh.)
6	aspen	mature, dense (predominantly largetooth aspen (*Populus grandidentata* Michx.))
7	young aspen	dense aspen (predominantly largetooth aspen) approximately 20 years old
8	wetland shrubs	dense, 1-1.5 m high shrubs (e.g., winterberry and black cherry)
9	open-low density	open areas of sparse ground vegetation[1]
10	open-moderate density	open areas with moderate density ground vegetation[1]
11	open-dense	open areas with dense ground vegetation[1]
12	water	lakes or rivers
13	radar shadow	zones of radar shadow at a boundary between treed and open areas
14	high backscatter edge	zones of high radar backscatter at a boundary between treed and open areas
15	red pine	mature, dense
16	white pine	mature, dense

[1] Ground vegetation on open areas was primarily grass, herbs, and ferns. Some have sedges and low shrubs.

airborne MSS and radar images were then resampled to a 10.0-m resolution to reduce any effects of image misregistration on subsequent analyses. A cubic convolution resampling kernel was used. The swath width of the radar imagery was greater than the airborne MSS data and, therefore, only the center portions of the radar images (from look angles of 45° to 50° on the near edge to approximately 65° on the far edge) were included in the final data set.

PROCEDURES

The capabilities of airborne MSS, radar, and combined airborne MSS/radar data for discriminating among forest types were analyzed by:

- examining the signatures of each forest type for the set of nine visible/infrared and eight radar bands;
- using the Bhattacharyya distance[1] (Kailath, 1967), a statistical measure of the distance between the probability density functions characterizing two classes, to determine the utility of each band and combinations of bands together for separating forest type pairs or groupings of forest types;
- determining the maximum likelihood classification accuracy of class pairs or groupings of classes using combinations of bands; and
- drawing upon examples from the literature.

The utility of ratio and difference features derived from the eight radar bands (Table 1) was also analyzed.

The primary forest types one may wish to discriminate can be categorized as follows: different softwood species, different hardwood species, hardwoods from softwoods, and open areas from forested areas. Age is another important parameter. Each of these categories is examined separately. Also important is discrimination of forested areas from other surface types or image features which may cause confusion (e.g., wetland areas, water, radar shadow zones, and zones of high radar backscatter from the edge of forest stands adjacent to open areas in the direction of the incoming radar beam).

Sixteen cover type classes were defined (Table 2) and classification training areas and classification test areas were determined for each class. Small sample areas of dense mature (60 years) red spruce and Scots pine (*Pinus sylvestris* L.), and young (20 years) red pine were also established from single stands. They provided some insight into the signatures of these forest types, but there was an insufficient number of independent samples for thorough statistical analysis. All sample areas of forest species were selected to have a dense canopy closure in order to reduce the influence of density on the signature of each forest species. An analysis of the effects of stand density and biomass distribution, or varying morphologic and physiologic characteristics of trees due to different provenances, climatic conditions, and soil characteristics, is beyond the scope of this study. Training and test areas were chosen to be typical of dense stands of each species in the region of the test site. Results are therefore limited to these conditions. Sample areas of wetland consisting of predominantly dense cattails (*Typha latifolia* L.) and other special cover types were also defined.

The classification training areas were comprised of approximately equal-sized segments from parts of at least three spatially distributed stands. The training areas generally contained 75 to 500 pixels, with most having greater than 250 pixels. Classification test areas consisted of 17 to 39 two-by-two pixel polygons whose locations were selected on a grid system placed over the 2.5- by 10-km test site. This ensured that the test areas were unbiased and evenly distributed about the image. The training areas were delineated and categorized using 1:11 000-scale photography, acquired simultaneously with the airborne MSS data, and various (leaf-off) normal color and color infrared photography at scales of 1:6 000 to 1:12 000 acquired before and after data collection for this study. The class of the test areas was also determined with these aerial photographs. The class and purity of all training areas and many of the test areas were confirmed by inspection on the ground.

Bhattacharyya distance (B-distance) was used as a metric of the separation of the signatures of classes. The separation among several classes was taken to be the average of the B-distances between each pair of classes. The "best" combination of bands for separating classes was taken to be as follows: that sequence of bands starting with the best single band for separating classes, followed by the band that, in combination with the best single

[1]There are several variants of the B-distance that have proven to be effective for feature selection (Kailath, 1967; Swain *et al.*, 1971). They are based on the Bhattacharyya coefficient (ρ) (Bhattacharyya, 1943), which for two populations represented by multivariate Gaussian probability densities $p_1(x)$ and $p_2(x)$ is given by $\rho = \int [p_1(x)p_2(x)]^{1/2}dx$. B-distance as used in this study is $-\ln\rho$. B-distance for two classes 1 and 2 is given by

$$B = 1/8[(\mathbf{u}_1 - \mathbf{u}_2)^T [(\mathbf{Z}_1 + \mathbf{Z}_2)/2]^{-1} (\mathbf{u}_1 - \mathbf{u}_2)] + 1/2 \ln[\det((\mathbf{Z}_1 + \mathbf{Z}_2)/2)/[\det\mathbf{Z}_1 \det\mathbf{Z}_2]^{1/2}]$$

where $\mathbf{u}$ are the class mean vectors and $\mathbf{Z}$ the covariance matrices (Kailath, 1967).

TABLE 3. SINGLE BAND B-DISTANCE FOR SELECTED GROUPINGS OF CLASSES.

General Forest Species		Softwood Species		jack pine vs white spruce		red pine vs white pine		mixed hardwood vs aspen		mature vs young aspen		mature vs young jack pine		mature vs young red pine	
Band	Avg. B-Distance	Band	Avg. B-Distance	Band	B-Distance	Band	B-Distance	Band	B-Distance	Band	B-Distance	Band	B-Distance	Band	B-Distance
835	0.727	C_{HH}	0.633	2150	0.328	C_{HH}	0.228	X_{VV}	0.430	X_{HH}	0.115	835	0.416	C_{VV}	0.130
2150	0.703	X_{HH}	0.587	X_{VV}	0.085	C_{HV}	0.178	X_{HH}	0.350	2150	0.094	620	0.408	C_{HH}	0.092
955	0.694	X_{VV}	0.542	C_{VH}	0.085	C_{VV}	0.167	C_{HH}	0.332	C_{HH}	0.084	955	0.357	730	0.091
730	0.624	C_{VV}	0.377	665	0.063	X_{HH}	0.148	C_{VV}	0.276	730	0.064	730	0.306	835	0.075
X_{VV}	0.407	X_{VH}	0.327	730	0.052	X_{VH}	0.118	X_{VH}	0.253	665	0.062	575	0.248	C_{VH}	0.067
X_{HH}	0.401	X_{HV}	0.313	620	0.044	X_{VV}	0.087	575	0.232	835	0.055	665	0.236	955	0.062
665	0.257	C_{HV}	0.206	525	0.041	2150	0.087	X_{HV}	0.199	955	0.054	525	0.181	620	0.062
C_{HH}	0.240	835	0.157	C_{HV}	0.035	575	0.079	525	0.191	575	0.046	2150	0.139	665	0.055
C_{VV}	0.192	2150	0.140	575	0.033	525	0.077	665	0.172	X_{VV}	0.038	X_{VV}	0.042	C_{HV}	0.053
X_{HV}	0.178	730	0.137	835	0.032	620	0.059	2150	0.162	525	0.037	X_{HV}	0.030	575	0.044
X_{VH}	0.174	955	0.136	C_{HH}	0.027	X_{HV}	0.053	620	0.142	620	0.028	C_{HH}	0.024	525	0.036
620	0.154	C_{VH}	0.111	X_{HH}	0.022	665	0.048	C_{HV}	0.142	C_{HV}	0.028	C_{HV}	0.018	X_{VH}	0.026
575	0.148	665	0.101	X_{HV}	0.019	C_{VH}	0.046	C_{VH}	0.139	C_{VH}	0.013	475	0.017	2150	0.018
525	0.136	525	0.084	C_{HH}	0.012	475	0.033	730	0.115	475	0.006	C_{VV}	0.014	X_{VV}	0.007
C_{VH}	0.095	575	0.078	X_{VH}	0.010	955	0.010	835	0.091	C_{VV}	0.003	X_{VH}	0.013	X_{HV}	0.007
C_{HV}	0.090	620	0.060	855	0.010	730	0.009	955	0.076	X_{VH}	0.003	X_{HH}	0.008	X_{HH}	0.006
475	0.074	475	0.042	475	0.009	835	0.004	475	0.048	X_{HV}	0.002	C_{VH}	0.005	475	0.005

TABLE 4. B-DISTANCES FOR COMBINATIONS OF BANDS FOR SELECTED GROUPINGS OF CLASSES AND BAND SETS.

Number of Bands[1]	General Forest Species: All Bands		General Forest Species: Visible Bands Only		General Forest Species: Radar Bands Only		Softwood Species: All Bands	
	Band[2]	B-distance[3]	Band[2]	B-distance[3]	Band[2]	B-distance[3]	Band[2]	B-distance[3]
1	835	0.73	835	0.73	X_{VV}	0.41	C_{HH}	0.63
2	575	1.28	575	1.28	C_{HH}	0.58	X_{HH}	0.93
3	2150	1.70	2150	1.70	X_{HH}	0.73	835	1.11
4	X_{VV}	2.07	620	1.82	C_{VV}	0.83	620	1.37
5	C_{HH}	2.29	730	1.97	C_{VH}	0.93	2150	1.56
6	665	2.42	525	2.03	C_{HV}	1.03	C_{VV}	1.71
7	620	2.56	665	2.10	X_{VH}	1.11	X_{VV}	1.88
8	X_{HH}	2.68	475	2.17	X_{HV}	1.19	C_{HV}	2.02
9	C_{VH}	2.81					730	2.17
10	C_{VV}	2.92					X_{VH}	2.29
11	C_{HV}	3.03					475	2.41
12	525	3.13					C_{VH}	2.51
13	X_{VH}	3.24					525	2.61
14	X_{HV}	3.34					665	2.71
15	475	3.43					X_{HV}	2.80
16	730	3.53					575	2.86

[1]Number of bands in combination of bands at each stage.
[2]Band which enters the combination of bands at each stage.
[3]Average B-distance for the band combination at each stage.

band, produced the highest average B-distance between classes, followed by the band that, in combination with the first two bands, provided the highest separation (B-distance) between classes, and so on for all bands. This forward selection procedure for determining the "best" band combinations will not necessarily give the same band combinations as the optimum band combination defined by examining all possible band combinations at each stage of 2 through n bands. For convenience, only 16 of the 17 bands (five visible, two near-infrared, one mid-infrared, and eight radar) were used in the final selection procedure. Because the three near-infrared bands were closely correlated, band 10, the near-infrared band of generally lowest capability for discriminating species and age classes (e.g., Table 3), was not included in the final B-distance analyses. Although the backscatter of cross polarized bands of the same radar frequency are equal (i.e., $\sigma_{HV} = \sigma_{VH}$), both cross polarized bands were included for redundancy. Parallel analyses were conducted of both the classification training areas and test areas in order to confirm results.

B-distance analyses were conducted for two main groupings of classes (or cases) plus other special groupings (e.g., Tables 3 and 4). The general species case is meant to determine the best bands for discriminating general forest species types and includes the following classes: jack pine, white spruce, mixed red and white pine (mixed pine), mixed hardwood, aspen, and young jack pine. The softwood species case included four softwoods: jack pine, white spruce, red pine, and white pine. It gave the best bands for discriminating these species amongst themselves.

Classification was determined by a maximum likelihood classifier using the signatures of the classification training areas. Accuracy was assessed by comparing the classification of pixels of the test areas with the true classes of the test areas. Classifications were tested for two primary cases: a general species case with 14 classes (Table 2, classes 1 to 14), and a softwood species case with

15 classes (the same classes as the general species case but with red pine and white pine classes added and the mixed pine class not included (Table 2, classes 1, 2, and 4 to 16)).

RESULTS

Softwood Species

Using observed radiances as an indicator of reflectance, it was noted that, among the softwood species, white spruce had low visible/infrared reflectances and white pine had high reflectances (Figure 1a). Red pine had low visible and mid-infrared reflectances but high near-infrared reflectances. Jack pine had low visible and near-infrared reflectances and a high mid-infrared reflectance. Sample areas of single stands of red spruce and Scots pine indicated that, relative to the other softwoods, red spruce had low visible/infrared reflectances and Scots pine high reflectances. Red and white pine had low radar backscatter, whereas jack pine and white spruce had higher backscatter (Figure 1b). The sample area of red spruce had high backscatter. The Scots pine sample area had backscatter intermediate between white pine and the higher backscatter of white spruce and jack pine. Exceptions were the C-band cross polarized bands that had high backscatter similar to jack pine. It is beyond the scope of this paper to determine the causes of the different backscattering of the softwood species of this study. Branching structure, needle distribution, and tree and stand biomass differ for each species. There was a notable strong trend of decreasing backscatter in both C and X band with increasing needle length. Needle lengths for the species examined, in order of increasing radar backscatter, were 10 to 15 cm for red pine, 6 to 10 cm for white pine, 4 to 7 cm for Scots pine, 2 to 4 cm for jack pine, 1.2 to 2 cm for white spruce, and 1.2 to 1.8 cm for red spruce.[2]

Shuchman *et al.* (1978) observed that, for spruce and pine of unspecified species, spruce stands had higher backscattering than pine stands on X_{HH} imagery but the reverse was true on X_{HV}, L_{HH}, and L_{HV} imagery. High C band backscatter was reported for dense black spruce (*Picea mariana* (Mill.) B.S.P.) stands (Leckie, 1983). Hoekman (1985), examining X band SLAR, noted different backscattering between two pine species (Scots and Austrian pine (*Pinus nigra* Arnold)) and higher backscatters for spruce (Norway spruce (*Picea abies* (L.) Karst) and Sitka spruce (*Picea stitchensis* (Bong.) Carr.)). Data of Churchill and Keech (1984) and Hoekman (1985) indicate little difference between Scots and Corsican pine (*Pinus nigra* var *maritima*) in X band, while Churchill and Keech (1984) reported good separation of these species on C band imagery.

Any one of the radar bands except C_{VH} were better than any

[2]Needle lengths were derived from samples taken from within the study test area.

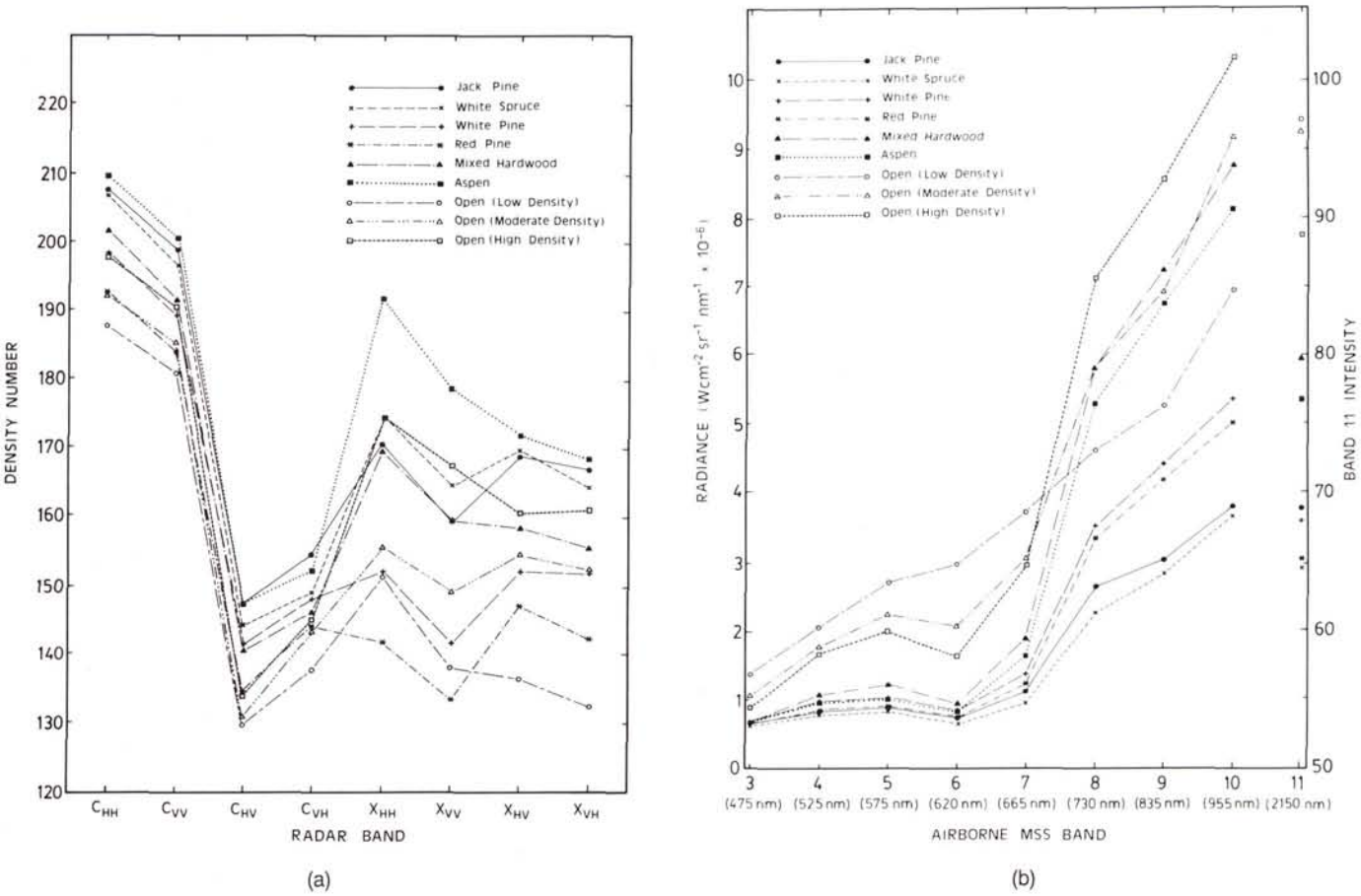

FIG. 1. Signatures of nine selected cover types represented by the classification training areas for the classes. Insufficient sensor calibration information was available to give the band 11 signature in terms of radiance. Standard deviations for the classes plotted ranged from approximately 1.7 to 3.5 for bands 3 and 6, 1.7 to 5.5 for bands 4 and 5, 3 to 10 for band 7, 6 to 11 for the near-infrared bands, and 3 to 7 for band 11. An exception was the low density open class which had standard deviations from 8 to 13 for the visible bands, and from 4 to 5 for the near-infrared bands and a standard deviation of 7 in the mid-infrared band. Also, the mixed hardwood class had higher standard deviations in each wavelength. The standard deviations for the radar bands ranged from approximately 5 to 7 for C_{HH}, C_{HV}, and C_{VH}; 4 to 5 for C_{VV}; and 8 to 13 for the X bands. Radar band density numbers are proportional to radar backscatter. (a) Visible/infrared bands. (b) Radar bands.

one of the visible/infrared bands for discriminating softwood species (Table 3, softwood species case). The importance of radar bands held for each pair of softwood species (except jack pine versus white spruce) with radar bands being at least the five best bands. The parallel polarized bands were of greater use, with C_{HH} and X_{HH} being the best. Of the visible/infrared bands, the infrared bands were best. Similar bands were identified as best for discriminating among seven softwood species (jack pine, white spruce, red pine, white pine, Scots pine, red spruce, and tamarack (*Larix laricina* (Du Roi) K. Koch)). The sequence of best combinations of bands for softwood species separation reflects the importance of these bands (Table 4), C_{HH}, X_{HH}, and the 835-nm band being the most important. The softwood species pairs with poorest separability (lowest B-distance) were jack pine versus white spruce and white pine versus red pine (Table 3).[3] No bands appeared particularly well suited for separating these classes.

Maximum average combined classification accuracy for four softwood species (white spruce, jack pine, red pine, and white pine) was approximately 74 percent (Figure 2). There is a steady increase in classification accuracy with number of bands, up to approximately five. After five bands there is only marginal improvement in classification accuracy. The combination of visible/infrared and radar data is important. Maximum average classification accuracy of the four softwood species classes was 67 percent using only visible/infrared bands. If the mid-infrared band was not used, maximum average accuracy was approximately 60 percent. When only radar bands were used, maximum average accuracy was 41 percent. The better classification accuracy of only visible/infrared bands as opposed to only radar bands, despite radar bands showing better separation of softwood species (Table 3), is partially due to the usefulness of the visible/infrared bands in reducing confusion of softwoods with open areas as well as confusion between mature and young jack pine. For example, even for the radar band combination giving maximum softwood accuracy, there was still confusion (up to 17 percent) between some softwood and open classes. Using only the 835-nm and 575-nm bands, there was virtually no confusion of softwood and open classes, although confusion among the softwood species was much greater than using only the two radar bands C_{HH} and X_{HH}. The lower accuracy of radar bands only, for softwood species, was also due to confusion of mature and young jack pine. Confusion of these two classes was low when only visible/infrared bands were used.

Conclusions. Radar bands are greatly superior to visible/infrared bands for differentiating one softwood species from another. However, classification accuracy of softwood species relative to all forest types using only X and/or C band can be low due to confusion of softwoods with open areas. Use of visible/infrared bands with these radar bands will eliminate most of the confusion. There is a wide range of radar backscatters for softwoods. Red and white pine have low backscattering and jack pine and white spruce high backscattering. There was a relationship of increasing radar backscatter with decreasing species needle length. Parallel polarized bands were the best radar bands. The best visible/infrared bands were the near- and mid-infrared. The best combination of five visible/infrared and radar bands was bands C_{HH}, X_{HH}, 835 nm, 620 nm, and 2150 nm. This gave 68 percent classification accuracy for four softwood species. Maximum classification accuracy of the four species was 74 percent. Visible/infrared bands were needed to prevent confusion between softwood classes and open areas. Jack pine versus white spruce and red pine versus white pine were the most difficult softwood species to separate.

Hardwood Species

The hardwood species of this study were difficult to differentiate. Classification accuracies of the mixed hardwood class of maple, birch, and beech (*Fagus grandifolia* Ehrh.) and the aspen class were low. There was confusion of these classes (classification of aspen as mixed hardwood or vice versa) and further confusion of young aspen with mixed hardwood (e.g., Table 5). The range of radar backscatter for the hardwood species examined was not as large as that for differing softwood species. The backscatter of aspen was higher than that of the mixed hardwood in all bands whereas, in the visible/infrared, the mixed hardwood class had slightly higher reflectances (Figure 1). Hoekman (1985) reported higher X_{HH} SLAR backscatter from poplar than from oak (*Quercus robur* L.) and from poplar than from beech (*Fagus sylvatica* L.). Shuchman *et al.* (1978) observed slightly different X band backscattering from some hardwood species but could not definitely ascribe these differences to species composition.

Single band B-distances for the mixed hardwood class versus aspen class (Table 3) indicated that there may be radar bands particularly suited to detecting differences in hardwood species composition. X parallel polarized bands had high B-distances compared with the visible/infrared bands and most other radar

[3]The high B-distances of bands 11 and C_{VH} for jack pine versus spruce in Table 3 were perhaps an anomaly, as both bands had low capabilities for separating the test areas of jack pine and spruce. X_{VV}, however, was among the most useful of bands for both the training areas and test areas and could be considered the best band.

Table 5. Classification Accuracy for a Classification of 14 Classes (General Species Case) Using all 16 Bands. Percent of Test Area Classified as Each Class.

	Test Area Class													
	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1 jack pine	67.9	5.4	0.0	7.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	11.6
2 white spruce	8.3	73.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	3.8
3 mixed pine	13.1	8.7	92.9	1.5	2.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	4.2	3.8
4 young jack pine	3.6	2.2	2.5	89.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
5 mixed hardwood	1.2	7.6	2.5	0.0	67.4	12.9	19.5	0.0	0.0	0.0	8.9	0.0	1.4	3.9
6 aspen	0.0	0.0	0.0	0.0	10.9	65.9	19.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0
7 young aspen	0.0	0.0	0.8	1.5	17.9	15.9	60.2	5.3	0.0	0.0	1.8	0.0	0.0	3.8
8 wetland shrubs	0.0	0.0	0.0	0.0	0.0	0.0	0.0	92.9	0.0	0.0	1.8	0.0	0.0	0.0
9 open (low density)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	58.3	10.7	0.0	0.0	0.0	0.0
10 open (moderate density)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	6.3	66.1	7.1	0.0	0.0	0.0
11 open (dense)	0.0	0.0	0.0	0.0	0.6	0.7	0.0	0.0	2.1	10.7	71.5	0.0	0.0	0.0
12 water	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	83.3	0.0	0.0
13 radar shadow	3.6	0.0	0.8	0.0	0.0	0.0	0.0	0.0	2.1	0.0	0.0	10.0	83.2	0.0
14 high radar return edge	2.3	2.2	0.0	0.0	0.0	2.3	0.0	1.8	0.0	8.9	1.8	0.0	0.0	69.2
unclassified	0.0	0.0	0.5	0.0	0.6	2.3	0.8	0.0	31.2	3.6	7.1	6.7	11.2	3.9

bands. B-distances for mixed hardwood versus young aspen showed similar results. The near-infrared bands were poor for separating the mixed hardwood and aspen classes of this study (Table 3). Confusion between mixed hardwood and aspen in the maximum likelihood classification was approximately 8 percent using the best three or more radar bands for general species discrimination, 16 percent with the best three or more visible/infrared bands, and 14 percent for the best five combined visible/infrared and radar bands. Overall accuracy for these classes, however, was less for radar bands due to confusion of the hardwood classes with other forest types (e.g., white spruce and open areas). Average accuracy for mixed hardwood and aspen was 43 percent using all radar bands, 51 percent with all visible/infrared bands, 67 percent with all bands, and 53 percent with only the best five bands for general species discrimination. Depolarization did not appear to be a key factor in species discrimination. Ratio or difference features involving combinations of C_{HH}, X_{HH}, C_{VV}, and X_{VV} were distinctly better than any of the other band combinations tested, but these had much lower B-distances (0.184 was the highest) than some of the individual bands (Table 3).

Conclusions. Radar bands are important for distinguishing between some hardwood species. X parallel polarized bands were best for discriminating mixed hardwood from aspen. The range of radar backscatter from the hardwoods in the test area was not as large as the range for the different softwood species. The mixed hardwood class and the aspen class were difficult to differentiate.

Hardwoods versus Softwoods

The well known phenomenon of low near-infrared reflectance of softwoods and high reflectance of hardwoods (e.g., Figure 1a) makes the near-infrared bands best for separating softwoods from hardwoods. B-distances for both the mixed hardwood and aspen classes versus the softwood classes indicated that near-infrared bands were the best single bands for separating hardwoods from softwoods. There was almost no confusion of the hardwood and softwood classes if only one band (a near-infrared band) was used in a classification. Confusion of these classes actually increased with added visible/infrared or radar bands (e.g., Table 5). The mid-infrared band (2150 nm) had higher reflectances for hardwoods than softwoods and was of almost equal value as the near-infrared bands for distinguishing softwoods from hardwoods.

There can be considerable confusion between softwoods and hardwoods if only radar bands are used. Even using all eight radar bands, there was 15 percent confusion of the mixed hardwood class with white spruce and 4 percent confusion with both mixed pine and spruce, whereas confusion of aspen with jack pine and white spruce was 4 percent to 5 percent. There was no confusion between aspen and mixed pine. There were similarities and overlaps of the range of backscatter for different hardwood species (e.g., mixed hardwood and aspen) versus the range of backscatters for different softwood species (e.g., red pine, white pine, jack pine, and white spruce) (Figure 1b), although aspen had higher backscattering than the softwood species in most bands. B-distance analysis indicated that the X parallel polarized bands were the best radar bands for discriminating mature aspen from each of the softwood species (average B-distances of 0.797 and 0.675 for X_{VV} and X_{HH}, respectively, and 0.256 and 0.189, respectively, for C_{HH} and C_{VV}, the next best radar bands).

Drake and Shuchman (1974) with X band data and Leckie (1983) with C band data could not consistently discriminate hardwoods from softwoods. Knowlton and Hoffer (1981) showed a good separation of hardwood from pine (mainly slash pine) on X_{HH} imagery with less separation on X_{HV}, pine having the lower backscatter. Generally higher X_{HH} backscatter for hardwood versus softwood areas were noted by Hoekman (1985), whereas Shuchman *et al.* (1978) reported good separation of softwoods and hardwoods on X_{HH} imagery due to high backscatter from the softwoods.

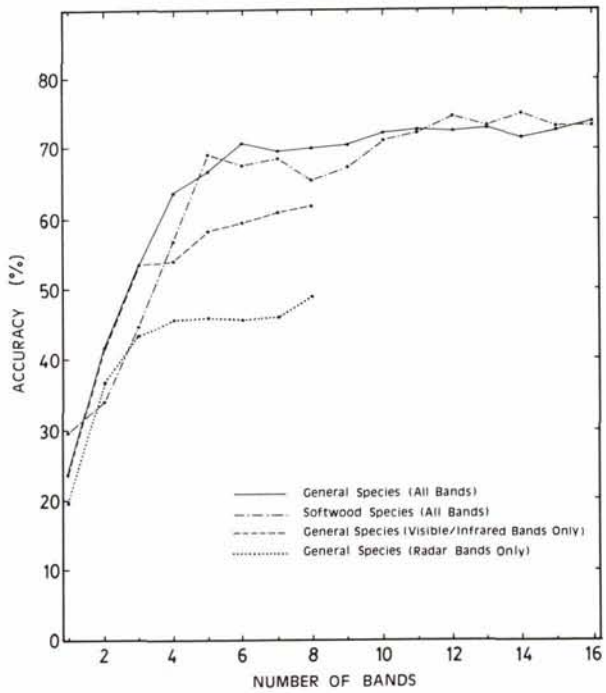

FIG. 2. Classification accuracy versus number of bands for two cases.
(1) The average classification accuracy for seven general species classes (jack pine, white spruce, mixed pine, young jack pine, mixed hardwood, aspen, and young aspen) using the best band combinations for discriminating these classes (Table 4). Fourteen classes (classes 1 to 14 of Table 2) were used in the classification. Three sets of band combinations are given: (a) combined visible/infrared and radar bands, (b) visible/infrared bands only, and (c) radar bands only.
(2) The average classification accuracy for four softwood species classes (jack pine, white spruce, red pine, and white pine) using the best combination of visible/infrared and radar bands for discriminating these four classes (Table 4). Fifteen classes were used in the classification (classes 1, 2, and 4 to 16 of Table 2).

There appeared to be more depolarization of the X band backscatter for the softwood species tested than the hardwoods and open areas (i.e., greater differences between X_{HH} and X_{HV}, and X_{VV} and X_{VH}) (Figure 1). B-distance analysis, however, indicated that separation of hardwood species from softwood species by features derived from the ratio or difference of these bands was not greater than the better single radar bands or the ratio or difference features best for general species differentiation (i.e., ratio or difference of C_{HH} and X_{HH}, and C_{VV} and X_{VV}).

Conclusions. The radar backscattering of the hardwood classes was either similar to backscattering of the softwoods with high backscattering, or intermediate between the low and high backscattering of softwood. Aspen had higher X parallel polarized backscatter than any of the softwoods. The radar band best suited for discrimination of hardwoods from softwoods will depend on the actual species involved. The best distinction is clearly through the use of near-infrared or mid-infrared bands. Confusion can be high if only radar bands are used. It is thus very useful to include visible/infrared data, particularly an infrared band, with radar data for differentiating softwoods from hardwoods.

Open Forest Areas

Reflectance of open areas increased in the visible part of the spectrum and decreased in the near- and mid-infrared as ground vegetation density decreased (Figure 1a). Although there is overlap between the near-infrared reflectance of open areas and forested stands, the visible bands and mid-infrared band should be successful at discriminating between forested and open areas. Confusion of open and forest classes was minimal using only visible/infrared bands. For example, for a classification with one band from each of the mid-infrared (2150-nm band), near-infrared (835-nm band), and visible (575-nm band) spectral regions, there was on average 3 percent (maximum 7 percent) misclassification of open areas as one of the forest species classes and on average less than 1 percent (maximum 2.5 percent) classification of forest species test areas as one of the open classes. Results were similar using only the 835-nm and 575-nm bands, the first two bands of the sequence of best combination of visible/infrared and radar bands for general species determination.

Radar backscatter of open areas varied from low for areas with little ground vegetation to high for densely vegetated open areas (Figure 1b). For X band, this range straddled the range of backscattering of forest species. The C band backscatter from open areas was lower in relation to other forest types than the X band backscatter, the backscattering of even the densely vegetated areas being lower than that of species with high backscattering (e.g., hardwoods, jack pine, and white spruce). This is likely due to greater penetration of the ground vegetation cover in C band.

There is, therefore, potential for confusion between open and forested areas if only X and C band radar imagery is used alone. Use of C band data can reduce this. Classification results showed that, even for classifications using all the X bands, there was still confusion of open versus forest areas (on average 41 percent of open areas were classified as a forest class, and 15 percent of forest was classified as one of the three open classes). Confusion was less for a classification using all C bands (29 percent and 13 percent error, respectively). Combining X and C bands improved classification of open versus forest species (e.g., 23 percent and 6 percent error, respectively, using all radar bands, and 27 percent and 11 percent error, respectively, using the best four radar bands for general species discrimination (Table 4, radar bands only case)). C band data aided discrimination of open areas from forest species with high backscatter. X band differentiated the densely vegetated open areas from the forest species with low backscattering confused in classifications using only C band data. A combination of visible/infrared and radar bands greatly reduced confusion of forest and open classes. For example, bands 835 nm, 575 nm, X_{VV}, and C_{HH}, the set of two best combined visible/infrared and two best combined radar bands for general species discrimination (Table 4, visible/infrared only and radar only general species cases), greatly improved classification of the open versus forest classes (1 percent and 0.8 percent error, respectively) over using only radar bands.

Several authors have reported better discrimination of new clear-cuts from surrounding forest with cross polarized data as opposed to parallel polarized data (Knowlton and Hoffer (1981) with X band data and Leckie (1983) with C band data). The B-distances of the low density open class versus forest classes indicated better separation of sparsely vegetated areas (similar to recent clear-cuts) from forest with X cross polarized than parallel polarized bands. B-distance analysis of C band data did not conclusively indicate whether cross or parallel polarized data were better.

Precise discrimination of different classes of open areas amongst themselves is difficult due to the continuum of vegetation densities, from nil to dense ground vegetation, and the variety of ground vegetation types that may be present. Open areas of predominantly low shrubs and areas of low density hardwood and/or softwood regeneration had radar backscattering and near-infrared reflectances generally similar to the dense and moderate density open areas. Their mid-infrared and visible band reflectances were lower than even the dense open areas. It was also observed that visible/infrared reflectances of the wetland shrub areas were very similar to those of a wetland area of predominantly cattails. C band backscatter was also similar, but X band backscattering was distinctly lower. B-distance analysis indicated separation of the two classes was best in the X bands. For discrimination of the three open classes of this study (low, moderate, and high density ground vegetation) among each other, the best single visible/infrared spectral regions were the near-infrared (e.g., 835-nm band), blue (475-nm band), and red (620-nm band) with average B-distances between classes of 1.30, 0.56, and 0.55, respectively. The mid-infrared (2150-nm) band had an average B-distance of 0.35. The best radar bands were the X bands, X_{VV} being the best with an average B-distance of 0.52. The best C band was C_{HH} with an average B-distance of 0.27.

Conclusions. The bands with major differences among the range of possible signatures for open areas and forested areas are in the visible and mid-infrared where the reflectance of open areas is higher than that of forested areas. The visible and mid-infrared reflectances of the open areas of varying densities of grasses, herbs, and ferns were higher than the reflectances of open areas of low shrubs and low density hardwood and softwood regeneration. There can be confusion of open and forested areas if only radar data are used. Confusion is most severe in X band. Confusion in C band was mainly with forest types such as red and white pine that have low C band backscatter. The X band backscattering of the dense to sparsely vegetated open areas straddled the range of backscattering for softwood species, but X band data did help differentiate the densely vegetated open areas from the softwoods with low backscatter. Use of visible/infrared bands resulted in minimal confusion of open and forest areas.

The near-infrared bands were best for discriminating open areas of sparse, moderate, and dense ground vegetation from each other. The best radar bands were the X bands, but they were not nearly as useful as the near-infrared bands. Unique capabilities for separating certain types of open areas exist within specific radar bands (e.g., X band for discriminating wetlands dominated by low shrubs from those of predominantly cattails).

Age

Capabilities of bands for discriminating stands of similar species but different ages were examined for three cases: mature versus young jack pine, red pine, and aspen. In each case the mature class was greater than 40 years old and the young class approximately 20 years. Age differences are not directly detected; rather, it is the different tree and stand characteristics (e.g., foliar vigor, quantity and distribution, height, stem and branch size, standing biomass, and canopy structure) of different aged stands that will result in different signatures.

Separation between mature and young aspen classes was low (Tables 3 and 5). X_{HH} was the best band for discriminating young and mature aspen. Among the visible/infrared bands the mid-infrared (2150-nm), near-infrared (730-nm, 835-nm, 955-nm), and 665-nm bands were best. Radar backscattering of the young aspen was slightly lower than that from mature aspen, whereas the visible/infrared reflectances were higher. There was considerable confusion (approximately 15 percent to 20 percent) between young aspen and both mature aspen and mixed hardwood (Table 5).

The visible/infrared bands were much superior to radar bands for discriminating mature and young jack pine (Table 3). Their radar backscatters were similar (Figure 1b). The reflectance of young jack pine was higher than mature jack pine in the visible/

infrared bands (Figure 1a). The higher reflectances in the near-infrared bands and 620-nm band were particularly important, as these bands were the most useful for separating mature and young jack pine.

C-band, particularly the parallel polarized bands, was best for discriminating mature and young red pine (Table 3). X-band was poor, with strong similarities in their backscatter. The near-infrared band was the best visible/infrared band.

Conclusions. There does not appear to be one visible/infrared wavelength region or radar band or polarization that is best for discriminating age classes. Each species had different bands. For some species, certain radar bands were much better, although still not providing high separability, indicating that, for given species, specific radar bands may be sensitive to differences in the characteristics of individual trees or structure of stands of different ages.

General Forest Type Discrimination

This paper has so far examined discrimination among specific forest types. The following section discusses factors relevant to general forest type mapping in which many combinations of species types must be discriminated and confusion with all surface types and image features (such as radar shadow zones) must be minimized. Bands and band combinations suitable for discriminating among classes of a general forest species case (jack pine, white spruce, mixed white and red pine, young jack pine, mixed hardwood, aspen, and young aspen) were determined. Confusion of classifications of forest stands caused by presence of other surface types and image features was examined, as were the relative importance of different radar parameters such as frequency and polarization. This analysis indicates the overall usefulness of bands and the discrimination expected in mapping forest types.

Best bands. For discriminating composition of forest stands, the near-infrared (835-nm, 955-nm, and 730-nm) and mid-infrared (2150-nm) bands were best, followed by the X parallel polarized bands (single band B-distance for general forest species of Table 3). The infrared bands were particularly good at separating softwood from hardwood species. The parallel polarized bands were the best radar bands for overall species discrimination (Table 3). The X parallel polarized bands were especially useful for discriminating the mixed pine (red and white pine) class from other species, particularly the aspen classes. The best combination of five bands for general species discrimination was a combination of a near-infrared band (835 nm), a green band (575 nm), a mid-infrared band (2150 nm), X_{VV}, and C_{HH} (Table 4). Band correlation analysis indicated that the three near-infrared bands were highly correlated. A second near-infrared band (i.e., 730 nm) was, therefore, less important in the sequence of bands after the 835-nm band was included in the sequence. Classification accuracy for the seven general species classes increased steadily with the number of bands up to five or six bands (Figure 2). Accuracies were 67 percent to 70 percent for five or six bands and maximum accuracy was 74 percent. In contrast, classification accuracy for the eight visible/infrared bands was 62 percent and, for all eight radar bands, 49 percent.

Confusion of forest stands with other surface types and image features. Confusion of forest stands with other surface types and image features can be important obstacles to forest type mapping and species discrimination. Stands of mixed species composition and varying density can also cause confusion. Confusion of the open areas defined in this study with forest stands has been detailed earlier. In addition to the open areas classified in this study, there are many other varieties of ground vegetation in open areas. For example, areas of low and moderate density hardwood and/or softwood regeneration caused difficulties in classification, because these areas were usually placed in the mixed hardwood and young aspen classes. The wetland shrub class was easily discriminated from forest species. There are additional confusing factors such as radar shadow areas and high backscatter areas at the boundaries of forest stands with open areas. It was necessary to include these classes in the maximum likelihood classification of the imagery; otherwise, some areas of these classes would be erroneously classified.

Relative importance of visible/infrared and radar data, multiple radar frequencies, multiple transmit polarizations, and an ability to receive cross polarized data. The importance of a combination of visible/infrared and radar bands was demonstrated by the presence of a near-infrared, visible, mid-infrared, and two radar bands in the best combination of five bands for both general and softwood species discrimination (Table 4). The better classification accuracy of combined visible/infrared and radar bands versus that of only visible/infrared or radar bands (Figure 2) also indicated the benefit of combined visible/infrared and radar data. As well, there is improvement in accuracy of classifying open areas versus forest species with combined visible/infrared and radar bands.

Use of multifrequency radar was important. X and C parallel polarized bands were among the most effective bands for both general species and softwood species discrimination (Table 4). Classification of forest species using only the four X bands was 39 percent and 22 percent with only the four C bands whereas, with the best four radar bands for general species differentiation, classification accuracy was 45 percent. The best four combined visible/infrared and radar bands gave 64 percent accuracy.

Dual transmit polarization has some advantages. However, in situations of limited band availability, dual transmit polarization is perhaps not a critical factor. B-distance analyses of Tables 3 and 4 indicate that corresponding bands of opposite transmit polarization (e.g., X_{HH} and X_{VV} or C_{HH} and C_{VV}) may be useful for discriminating forest types. This data set does not clearly indicate that there is one transmit polarization better than the other (e.g., Table 3 and 4).

Long (1975) states that the difference between parallel and cross polarized bands should not be large for forest areas. Drake and Shuchman (1974) using X band and Leckie (1983) with C band observed little difference between parallel and cross polarized bands in their response to stand differences. The cross polarized bands of this study were of lower value for differentiating forest types than parallel polarized bands (e.g., Table 3 and 4).

Therefore, of the three radar parameters—frequency, transmit polarization (H or V), and transmit/receive polarization combination (parallel or cross)—frequency appears to be the most important for forest species discrimination. The ability to transmit in different polarizations was next most important, followed by the ability to receive cross polarized data. This was further supported by a B-distance analysis using classification training areas and test areas for two cases, general species and softwood species. The average B-distances for these cases were determined for band pairs of radar data. Pairs of radar bands with similar parallel polarization but different frequencies (X and C) generally had higher B-distances than band pairs with the same frequency. Of the pairs with the same frequency, those with parallel polarization and opposite transmit polarization (X_{VV} and X_{HH}, and C_{VV} and C_{HH}) generally had higher B-distances than pairs of the same frequency with corresponding parallel and cross polarization (X_{VV} and X_{VH}, X_{HH} and X_{HV}, C_{VV} and C_{VH}, and C_{HH} and C_{HV}). These results were also true for B-distances derived from four bands including visible/infrared bands 835 nm and 575 nm combined with the two paired radar bands. It was also observed that accuracy for both general species (Figure 2) and the four softwood species did not increase with the use

of more than the four best radar bands for general species discrimination (Table 4) (i.e., X_{VV}, C_{HH}, and X_{HH}, C_{VV}).

Ratio or difference features. There may be relationships between pairs of radar bands useful for discriminating forest types. B-distance analysis for general species discrimination and softwood species discrimination indicated that there was no advantage in using ratio or difference features. B-distances for ratio and difference features were much lower than for the single bands. Separation of individual species pairs was also generally less than or similar to individual bands. As well, there was no benefit in using the ratio or difference features for differentiating hardwoods from softwoods, open from forested areas, or age classes. Of the ratio features tested, the ratio or difference between C and X like-polarized bands (i.e., C_{HH} and X_{HH}, and C_{VV} and X_{VV}) were best for both softwood and general species discrimination. The average B-distances for general species discrimination were 0.314 and 0.263 for the features representing the ratio of C_{HH} and X_{HH}, and C_{VV} and X_{VV}, respectively, and 0.297 and 0.227, respectively, for the difference features. Ratio and differences of parallel polarized bands of the same frequency (i.e., C_{VV} and C_{HH}, and X_{VV} and X_{HH}) were particularly poor for forest species discrimination.

Conclusions. The best single bands for general forest species discrimination were the near-infrared bands, the mid-infrared band, and the two X parallel polarized bands. The best combination of five bands was a near-infrared (835 nm), a green (575 nm), a mid-infrared (2150 nm), X_{VV}, and C_{HH}. Parallel polarized radar bands were more important than cross polarized bands. There were no advantages to using ratio or difference features derived from the radar bands for forest type mapping.

Maximum classification accuracy of seven forest species classes was 74 percent. Classification accuracy using eight visible/infrared bands was 62 percent and using all eight radar bands 49 percent. Good classifications (approximately 69 percent) were achieved with the best five or six combined visible/infrared and radar bands (Figure 2). A combination of visible/infrared and radar bands is important. It was also important to include classes of various types of open areas plus radar shadow and radar high backscattering at forest edges so that these areas would not be erroneously classified as forest types.

SUMMARY

Airborne MSS and airborne X and C band SAR data over a forest test area were registered at a 10-m pixel resolution. Signatures, B-distance between classes, classification results, and the literature were examined in order to assess the usefulness of each band and combinations of bands for discriminating forest types.

Combining visible/infrared and X and C band radar data improved forest type discrimination. Five or six bands including a near-infrared, a visible, a mid-infrared, and an X and C parallel polarized band provided close to the maximum classification accuracy obtainable using all bands. Radar bands were the most useful for discriminating both among the softwood species and the hardwood species of this study. Visible/infrared data were important for good differentiation of softwoods from hardwoods and open from forested areas, as well as for improving species discrimination. There is a definite synergistic relationship between visible/infrared data and radar data that provides significant benefits to forest mapping.

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