Mapping forest clearcuts using radar digital imagery: A review of the Canadian experience

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Annual clearcut mapping is currently done in Canada mainly from photo-interpretation of aerial photographs. An advantageous alternative would use digital imagery. Optical imagery acquisition depends on weather and illumination conditions, but not radar images. This paper documents the state of practice in Canada in the use of radar digital images for clearcut mapping, with regards to the type of images used, to the influence of environmental conditions, the band, polarization, time of the year, and incidence angles, as well as to the mapping accuracy. Synergism between optical and radar images is also discussed. Finally, a few experimental automated mapping systems using radar imageries are presented.

Key words: remote sensing, forest inventory updating, clearcut mapping, synthetic aperture radar, microwave, digital imagery

La cartographie annuelle des coupes à blanc est actuellement faite au Canada à partir d'interprétation de photographies aériennes. Une alternative avantageuse utilise l'imagerie numérique. L'imagerie optique est dépendante des conditions climatiques et d'éclaircissement, mais pas l'imagerie radar. Cet article décrit l'état de la pratique au Canada sur l'utilisation des images numériques radars pour la cartographie des coupes à blanc, notamment par rapport au type d'images utilisées, à l'influence des conditions environnementales, de la bande spectrale, de la polarisation, du moment de l'année et de l'angle d'incidence, ainsi qu'à la précision cartographique. La synergie entre images optiques et radars est aussi discutée. Finalement, quelques systèmes expérimentaux de cartographie automatique à partir d'images radars sont présentés.

Mots-clés : Télédétection numérique, mise à jour de l'inventaire forestier, cartographie des coupes à blanc, radar à ouverture synthétique, micro-ondes, image numérique

Introduction

Forest clearcut mapping is an important issue for Canadian forest partners (governments and industries). In 1995, clearcuts represented 85.7% of the total area harvested in Canada (Canadian Council of Forest Ministers 1996). Forest inventory updating is required by various forestry Acts of the different Canadian provinces (Hilton 1986, Gillis and Leckie 1996). This updating is mainly done using remote sensing tools. Up to now, forest clearcut mapping has been done mainly by photo-interpreting 9" x 9" aerial photographs acquired at the scale of the inventory maps, varying from 1:10 000 in Nova Scotia, Ontario and Prince Edward Island to 1:20 000 in Quebec, Ontario, British Columbia and Alberta (Gillis and Leckie 1996). A promising alternative to these conventional aerial photographs would be provided by spaceborne sensors for two reasons. First, they can routinely provide lower-cost images in digital format that are easier to process and that allow the possibility of automating the mapping procedure. Second, fewer data are required, since spaceborne sensors cover a larger area.

Satellite images used for clearcut mapping were first provided by optical sensors (Leblon *et al.* 1995), for which data acquisition is limited because it depends on weather and illumination conditions. More recently, imaging radar spaceborne sensors, using synthetic aperture radars (SAR), were developed (Table 1). They can acquire images, independent of these conditions, because they produce their own incident radiation that can penetrate clouds. In addition to the sensors on board of currently operated Earth's observation satellites (Table 1), there was an imaging radar sensor on board of *SEASAT*,

which was operational only from June to October 1978 (Buiten 1993). There were also radar sensors that were operated only during Shuttle missions, the last one (*SIR-C/X-SAR*) being able to acquire multi-frequency and multi-polarization images (Table 2). This paper will document the state of understanding in Canada on applications of digital radar images acquired by spaceborne sensors to map forest clearcuts. Studies using airborne data will also be considered in this review, because of the lack of studies using radar satellite images, which have been provided more recently than the optical ones. Other Canadian examples on the use of imaging radar for clearcut mapping are also given in the review of Leckie and Ranson (1998).

Factors Affecting the Clearcut Mapping on Radar Images

Most of the experimental studies on the use of SAR images for clearcut mapping have used C-band airborne images in preparation to the *RADARSAT* mission. Some studies were carried out using airborne images acquired in X-, L- or P-band (Wedler *et al.* 1980; Rochon *et al.* 1986; Dams *et al.* 1990; Ranson and Sun 1994, 1997; Ahern *et al.* 1995; Landry *et al.* 1996; Saatchi and Rignot 1997). Few studies have used spaceborne SAR L-HH images, like *SEASAT* images (Werle *et al.* 1986, Rochon *et al.* 1986) and *SIR-B* images (Drieman 1987). More recent studies tested images acquired with other spaceborne SAR, like the C-VV sensor on board the European satellite *ERS-1* (Cavayas *et al.* 1995, Schaller *et al.* 1995, Yatabe and Leckie 1995), the L-HH sensor on board the Japanese satellite *JERS-1* (Schaller *et al.* 1995, Yatabe and Leckie 1995) as well as the S-HH sensor on board the Russian *ALMAZ* satellite (Yatabe and Leckie 1995). The most recent studies have used simulated (Rossignol and Ahern 1992; Banner and Ahern 1995a, 1996) or real (Ahern 1996, Ahern *et al.* 1997; Leckie 1997; Murtha 1997, 1998) images of the newest

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Table 1. Principal specifications of the main current Earth's observation radar satellites (after Buiten 1993, Sardar 1997)

Satellite	Spatial resolution	Time repetitivity	Band	Polarization	Incidence angle	Date of launch
<i>ERS-1</i>	12.5 – 30 m	35 days	C	VV	23°	1991
<i>ERS-2</i>						1995
<i>ALMAZ-1</i>	15 – 30 m	5–7 days	S	HH	30–60°	1991
<i>JERS-1</i>	18 m	± 1 month	L	HH	38°	1992
<i>RADARSAT</i>	9–100 m	1 week – 24 days	C	HH	10–59°	1995

Table 2. Temporary SAR satellites or missions (after Buiten 1993, Sardar 1997)

Sensor	Spatial resolution	Band	Polarization	Incidence angle	Operational period
SEASAT	25 m	L	HH	20°	June–Oct. 1978
SIR-A	40 m	L	HH	47°	Nov. 1981
SIR-B	17 – 58 m	L	HH	15–60°	Oct. 1984
<i>SIR-C/X-SAR</i> ⁽¹⁾	10 – 60 m	C	All four	15–60°	April 1994
		L	All four		Sept. 1994
		X	VV		

⁽¹⁾ Multi-polarization and multi-frequency SAR

Canadian radar satellite, *RADARSAT*. There are also some studies using the *SIR-C/X-SAR* prototype, which produces X-VV and multi-polarized C and L-band images (Ranson *et al.* 1995, Ranson and Sun 1997).

As in the case of optical sensors (Leblon *et al.* 1995), most clearcut mapping was done using summer images. However, clearcut mapping is more accurate when winter images are included together in the analysis (Drieman *et al.* 1989a; Ahern *et al.* 1993a, b; Drieman 1994; Yatabe and Leckie 1995). Indeed, snow cover and frozen soil have a dielectric constant which is low enough to reduce the backscatter of open areas (Ahern *et al.* 1993a), probably because of the low dielectric constants of frozen or near freezing targets (Way *et al.* 1990). Another important environmental factor is the moisture – either atmospheric (rainfall or snowfall), surface moisture on vegetation or ground moisture – conditions which tend to reduce the contrast between forest and clearcuts on a C-band airborne multi-temporal image (Drieman *et al.* 1989a) and on an August *ERS-1* image (Yatabe and Leckie 1995). For this reason, dry summer weather was shown to be one of the best environmental conditions to discriminate clearcuts from surrounding forests on *ERS-1* images (Yatabe and Leckie 1995) and on *RADARSAT* images (Leckie 1997). However, more recently, wet snow was shown to be a better environmental condition to increase the contrast between clearcuts and surrounding forests (Ahern *et al.* 1997, Leckie 1997). Also, when there is no snow on the ground, *RADARSAT* winter images acquired on Pacific rain forests are useful to map recent clearcuts (Murtha 1997, 1998a). On these images, contrast between clearcuts and forests decreases when clearcuts dried out (Murtha 1998). The influence of environmental conditions during acquisition is more important in the case of C-band than for L- or S-band (Schaller *et al.* 1995, Yatabe and Leckie 1995, Leckie 1997). This environmental influence explains why the use of multi-temporal images acquired during contrasting seasons improved the clearcut identification on SAR images (Fig. 1) (Drieman *et al.* 1989a, Ahern *et al.* 1993a, Ranson and Sun 1994, Schaller *et al.* 1995, Ranson and Sun 1997, Murtha 1998).

Determining the best band/polarization combination for clearcut mapping is highly important because, unlike spaceborne optical sensors (Leblon *et al.* 1995), current satellite SAR sen-

sors work only in a single waveband and in a single polarization (Ahern *et al.* 1993c), although planned SAR sensors like the *SIR-C/X-SAR* prototype will work in a multi-polarization and multi-band manner (Sardar 1997). For C-band images, cross-polarized data (HV, VH) are more suitable than like-polarized data (VV, HH) (Leckie 1984, Drieman *et al.* 1989b, Werle 1989, Leckie 1990, Ahern *et al.* 1995, Landry *et al.* 1996) (Fig. 2). Also, a better map is obtained using composites of images having different polarizations and/or different bands (Leckie 1990, Ranson and Sun 1994, Ahern *et al.* 1995, Ranson *et al.* 1995, Landry *et al.* 1996, Ranson and Sun 1997, Saatchi and Rignot 1997). Similar to other open areas like agricultural fields, clearcuts are better discriminated from the surrounding forests on images acquired in long wave bands (L- or P-band) (Fig. 3) (Drieman 1987, Werle 1989, Koch *et al.* 1992, Ahern *et al.* 1995, Schaller *et al.* 1995, Yatabe and Leckie 1995, Landry *et al.* 1996). However, P-band is too sensitive to small holes in the forest canopy, which can lead to highly fragmented images after classification (Ahern *et al.* 1995, Landry *et al.* 1996). The bad separability on C-band images between open and forested areas is due to the wide range and variability of radar backscatter from open areas (Ahern *et al.* 1993a, Mancilla *et al.* 1995), as well as to an overlap of radar backscatter with surrounding forests (Leckie 1984, Ahern and Drieman 1988, Ahern *et al.* 1993a, Yatabe and Leckie 1995). Also, short-wave bands are more strongly influenced by fine canopy elements such as leaves, needles and small branches as well as by grass and shrubs on the ground (Yatabe and Leckie 1995). For this reason, leafless hardwoods have a radar return similar to conifer stands on *ERS-1* C-VV images, and thus discrimination between leafless hardwoods and clearcuts is possible on such images (Cavayas *et al.* 1995).

Regeneration, which tends to mask clearcut boundaries (Drieman 1987, Mancilla *et al.* 1995), is better assessed using L-band images (Wedler *et al.* 1980, Ahern *et al.* 1995, Landry *et al.* 1996) rather than using shorter-wavelength images. For C-band images, HH polarization is more sensitive to regeneration than VV polarization (Mancilla *et al.* 1995). Multi-polarization images were shown to outperform single polarization images in distinguishing regeneration classes (Ahern *et al.* 1995, Landry *et al.* 1996). As for clearcuts, regeneration areas were better classified using multi-polarized, multi-frequency and/or multi-

Fig. 1. Single-date image acquired in August and colour composite made from February (red gun), August (blue gun) and October (green gun) images, in the case of *JERS-1* images acquired in 1993 and on the same harvested area near Whitecourt, Alberta.

temporal images (Ranson and Sun 1994, 1997). The better L-band performance for clearcut mapping and regeneration assessment is due to the higher penetration of the ground vegetation in the cuts, resulting in low backscatter for recent clearcuts and increasing backscatter with vegetation density and, therefore, high cut-background contrast (Yatabe and Leckie 1995). Also, longer-wavelength bands are less sensitive to the fine canopy elements than to the dominant branches, to the trunks

and to the double bounce interaction between trunk and soil (Richards *et al.* 1987, Yatabe and Leckie 1995, Landry *et al.* 1996).

Similar to optical images (Leblon *et al.* 1995), clearcuts on radar images can be confused with open areas, like agricultural fields and wetlands. These open areas can be masked when using a geographical information system database. Another solution would be to try to discriminate them from the

(a) HH polarization

(b) VV polarization

(c) HV polarization

Fig. 2. Comparison between C-band SAR images acquired with the *JPL-AIRSAR* in three polarization modes (HH, VV and HV), on the same harvested area near Whitecourt, Alberta, in May 1991.

clearcuts. Yatabe and Leckie (1995) showed that grasslands are discriminated from clearcuts on *ERS-1* or *JERS-1* images acquired in July during dry conditions, because grasslands have a lower backscatter than clearcuts. Clearcut backscatter is increased with the ground vegetation density. Clearcuts and wetlands are better separated on L-band images than on shorter-wavelength images (Ahern *et al.* 1995, Yatabe and Leckie 1995, Landry *et al.* 1996), possibly because the higher vegetation density on wetlands than on clearcuts results in a greater penetration and a lower return of C-band waves from the clearcuts than from the wetlands.

Unlike optical sensors (except the *SPOT* satellite sensor), SAR sensors have the capability of acquiring data in different incidence angles (Ahern *et al.* 1993c). This factor has probably the most important influence on the contrast between clearcuts and surrounding forests. Contrast increases with the incidence angle (Fig. 4) (Banner and Ahern 1995b). The incidence angle must be at least 30° to allow clearcut identification on SAR images (Werle *et al.* 1986, Rossignol and Ahern 1992). Incidence angles of *ERS-1* (23°) and of *SEASAT* (20°–26°) are therefore insufficient for discriminating clearcuts (Werle *et al.* 1986, Rossignol and Ahern 1992, Ahern and Raney 1993, Schaller *et al.* 1995, Yatabe and Leckie 1995). By contrast, clearcuts were well identified on a *SIR-B* L-HH image acquired with an incidence angle of 59° (Drieman 1987). On C-HH airborne images, contrast between clearcut and surrounding mixed boreal forests is greater than 2:1 (3 dB) for incidence angles greater than 60° (Banner and Ahern

1995b). The better contrast between clearcut and surrounding forests on simulated (Rossignol and Ahern 1992, Banner and Ahern 1995a) or real (Ahern 1996) *RADARSAT* C-HH images is also explained by the higher incidence angle (47°) of the *RADARSAT* sensor compared to the *ERS-1* system.

The effect of incidence angle on clearcut visibility depends on the topography of the area, and local incidence angles as defined in Foody (1986) must be considered in the case of rugged terrain. Slope effects on radar backscatters are such that clearcut visibility can be greatly reduced on slopes facing towards the radar illumination (Drieman 1987, Ahern *et al.* 1997). These effects are stronger on images acquired using a steep incidence angle, like with the *ERS-1* satellite, and for the coherent component of the scattering than for its diffuse component (Ahern and Raney 1993). They are also more important on images acquired in short-wave bands, like the X-band (Werle *et al.* 1986) or the C-band of *ERS-1* (Cavayas *et al.* 1995, Schaller *et al.* 1995, Yatabe and Leckie 1995). The relationship between backscatter and local incidence angle does not depend only on the topography, but also on the cover type (Hinse *et al.* 1988, Warner *et al.* 1996).

Another factor of variability on SAR images is the speckle, which gives the typical grainy appearance of SAR images. The speckle effect can be reduced by different image pre-processing techniques, for example principal component analysis (Ahern *et al.* 1993b) or spatial filtering (Koch *et al.* 1992, Yatabe and Leckie 1995), although Banner and Ahern (1996) showed that spatial filtering does not improve the clearcut bound-

Fig. 3. Comparison between HH-polarized SAR images acquired with the JPL-AIRSAR in three bands (C, L and P), on the same harvested area near Whitecourt, Alberta, in May 1991.

ary mapping accuracy when visual interpretation is used to delineate boundaries.

Compared to optical images, less elaborate analysis methods have been used on radar images, because of the general poorer clearcut visibility on radar images (Leblon *et al.* 1995). Most clearcut mapping was performed by visual interpretation of raw or digitally enhanced images. Enhancements significantly improved mapping results. Some statistical parameters were also employed to assess clearcut separability from other forest cover type classes, such as the Jeffreys-Matusita distance (Ahern *et al.* 1993a, Yatabe and Leckie 1995). Rochon *et al.* (1986) applied the maximum-likelihood classifier on a pixel-by-pixel basis to classify forest cover types (including clearcuts) on an airborne SAR X-HH and on a SEASAT L-HH image, both being acquired over temperate conifer rain forests. In both cases, the percentage of correctly classified pixels was low. Indeed, good classification accuracy supposes a unique radar return from the class, which must, in addition, be distinct from the radar return of the other classes (Leckie 1984). Both criteria are not met in most of cases. For example, at least on C-band images, clearcuts have been shown to have variable radar return (Drieman 1987, Ahern *et al.* 1993a, Mancilla *et al.* 1995, Yatabe and Leckie 1995), because of the variability effects of moisture and temperature conditions (Drieman *et al.* 1989a, Way *et al.* 1990, Yatabe and Leckie 1995, Ahern *et al.* 1997, Leckie 1997), ground vegetation density (Drieman 1987, Yatabe and Leckie 1995), surface material (Yatabe and Leckie 1995, Murtha 1998) or incidence angle

(Wedler *et al.* 1980). All these factors can also lead to radar backscatter overlapping between clearcuts and surrounding forests (Leckie 1984, Drieman 1987, Ahern and Drieman 1988, Ahern *et al.* 1993a, Yatabe and Leckie 1995, Murtha 1998).

Synergism Between Optical and Radar Images

Advantages of combining optical and radar data were investigated in few studies. Indeed, optical imagery provided excellent spectral and interpretative information (including vegetation competition in plantations), while radar imagery provided good edge definition of delineating boundaries and good portrayal of relief (Baker 1992). Drieman (1987) combined a SIR-B L-HH image with a LANDSAT-TM image (all optical bands). The first image was acquired in October and the second, in the summer following the SIR-B overpass. He concluded that the addition of SIR-B to the TM data set did little to improve class separabilities as calculated using TM alone. Leckie (1990) combined airborne multi-polarization X- and C-band SAR images with visible/infrared airborne MSS data acquired in the same time. Open areas best differentiated from forest classes in the visible and in the mid-infrared. The near-infrared bands were best for discriminating open areas of different vegetation densities. Adding X-VV and C-HH data little improved class separabilities, both bands, however, being highly useful for forest species discrimination. For mapping forest clearcuts on 1:50 000 maps of woodlots, Baker (1992) used two methods to combine one 30m-resolution

(a) Incidence angle of 20 - 27°

(b) Incidence angle of 45-49°

Fig. 4. RADARSAT (C-HH band) images acquired in winter 1996 on the same harvested area near Whitecourt, Alberta, with two incidence angles.

LANDSAT-TM (band 4, 5, and 7) image acquired in June with one airborne 15 m-resolution radar image acquired in April. The first method is an intensity, hue and saturation (IHS) method that produces images with good colour quality. The second one is an arithmetic procedure in which each red, green, blue (RGB) channel results from an arithmetic combination on TM and radar bands. The IHS method produced images, where a part of the clearcut area was obscured by radar shadow. However, in both cases, clearcuts cannot be automatically mapped from the digital image and on-screen visual digitizing of the image put as backdrop is required. Finally, Rossignol and Ahern (1992) showed that a simulated RADARSAT image can be used as complementary to a *LANDSAT-TM* image to monitor forest changes, once the *LANDSAT-TM* image is registered to the SAR image to permit the overlay of both scenes.

Accuracy Considerations

Table 3 compares literature results for clearcut mapping accuracies. All the reported studies refer to the same logging area in Alberta, except Drieman (1994), who studied logging areas in Newfoundland. Also, all of them refer to C-HH images, except Dams *et al.* (1990), who used X-HH images. Clearcut mapping accuracies in Table 3 were assessed using the following criteria:

(i) the areal percentage accuracy, calculated as:

$$\% \text{ accuracy} = 100 \% - \frac{(\text{Image-derived area} - \text{Actual area})}{\text{Actual area}} \quad (1)$$

(Hall *et al.* 1989)

(ii) the boundary mapping error, calculated following the method of Archibald and Ahern (1985). This method uses twelve vectors about the mean centroid, vectors pointing towards (away from) the centre having a negative (positive) direction. For the

j^{th} clearcut polygon, two variables can be estimated from its arbitrary centroid, as measure of the boundary mapping error: a) D_j , which is the average of the absolute values of the 12 vector lengths D_i :

$$D_j = \frac{1}{12} \sum_{i=1}^{12} |D_i|_0 \quad (2)$$

where $D_i = \sqrt{(x_{i2} - x_{i1})^2 + (y_{i2} - y_{i1})^2}_0$ = length of the vector in the i^{th} direction

(x_{i1}, y_{i1}) = coordinates of the intersection between the i^{th} direction and the actual boundary

(x_{i2}, y_{i2}) = coordinates of the intersection between the i^{th} direction and the image-derived boundary.

b) RMS_d , which is the standard deviation of the 12 vector lengths:

$$\text{RMS}_d = \sqrt{\frac{1}{12} \sum_{i=1}^{12} D_i^2}_0 \quad (3)$$

Values reported in Table 3 as boundary-mapping errors are the mean value for all the clearcut polygons considered of either D_j (Ahern and Drieman 1988, Dams *et al.* 1990) or RMS_d (Ahern and Drieman 1988, Banner and Ahern 1995a, Ahern *et al.* 1997). Archibald and Ahern (1985)'s method can be used only in the case of regular-shaped clearcuts with relatively small differences between actual and image-derived boundaries. In the case of irregular-shaped clearcuts with large differences between actual and image-derived boundaries, it is preferable to use a generalization of the method of Archibald and Ahern (1985), developed by Edwards and Rioux (1995), because under this method, all directions are considered instead of only the twelve directions.

Table 3. Comparison between literature results for clearcut mapping accuracy on SAR images

Sensor	Spatial resolution	Minimum clearcut size (in ha)	Areal accuracy (in %)	Boundary mapping error (in m) ⁽¹⁾	Authors
Airborne (X-HH band)	6 – 12 m	0.7	89.8	29.4 ^(*)	Dams <i>et al.</i> (1990)
Airborne (C-HH band)	6 – 12 m	5.0	89.0	30.0 ^(*)	43.0 Ahern and Drieman (1988)
Airborne (C-HH band)	6 – 12m	1.3	89.3	n/a	Drieman (1994)
Airborne (C-HH band)	6 – 12 m	n/a	92.0	24.6	Banner and Ahern (1995a)
Simulated RADARSAT (C-HH band, fine-mode)	10 m	n/a	84.0	44.9	Banner and Ahern (1995a)
Simulated RADARSAT (C-HH band, standard-mode)	25 m	n/a	71.0	72.7	Banner and Ahern (1995a)
RADARSAT (C-HH band, fine-mode)	9 – 10m	Contrast: - high - medium - low	n/a n/a n/a	21.6 40.6 69.6	Ahern <i>et al.</i> (1997)

⁽¹⁾ The boundary mapping error is calculated according to Eq. 2, for the studies with asterisks and according to Eq. 3, for the other studies.

Table 3 shows that fine mode RADARSAT images gave a better mapping accuracy than standard mode images, thanks to the higher spatial resolution of the first type of images. In the case of optical images, Leblon *et al.* (1995) already showed that the spatial resolution of optical sensors is a key parameter for clearcut-mapping accuracy. Also, as reported above, clearcut-mapping accuracy is affected by the contrast between clearcuts and surrounding forests. For example, the boundary-mapping error decreases when this contrast increases in the case of fine-mode RADARSAT images like those used in Ahern *et al.* (1997) (Table 3). This contrast depends on the environmental conditions at the time of image acquisition. For example, in Ahern *et al.* (1997), high-contrast images were acquired under wet snow conditions. For the studies using airborne images, the best mapping accuracy, which was achieved in Banner and Ahern (1995a), was also obtained on winter images with snow, whereas the worst mapping accuracy was obtained by Ahern and Drieman (1988), who used fall images. Leckie (1997), Ahern *et al.* (1997) and Murtha (1998) already concluded that clearcut visibility on RADARSAT images depends primarily on surface moisture conditions.

Clearcut boundaries are more complex to define on radar images than on optical images, because they differ as a function of the radar illumination direction. According to Murtha (1997), four kinds of boundaries can be defined: bright boundary when at right or oblique angles (facing) to radar illumination, shadowed boundary facing away from the illumination, and two boundaries parallel to the illumination. The two last boundaries were found to be difficult to see on a fall airborne C-HH image acquired on Alberta boreal forests (Ahern and Drieman 1988) as well as on a winter wet evening fine-mode RADARSAT image acquired on British Columbia rain forests (Murtha 1997). In this case, these boundaries must be located by comparison to adjacent uncut forests (Murtha 1997). The boundary facing the illumination can be very bright, because of the corner reflection effect made by straight edges (Ahern and Drieman 1988, Murtha²). As for the shadowed boundary,

for such a bright boundary, the true cut edge is difficult to estimate on the airborne C-HH image used by Ahern and Drieman (1988), but not on a fall SIR-B L-HH image acquired on Alberta boreal forests (Drieman 1987) nor, according to Murtha², on the fine-mode RADARSAT image used by Murtha (1997). Shadowed and bright boundaries also allowed older clearcuts to be distinguished on a RADARSAT image simulated with airborne data acquired in March (Rossignol and Ahern 1992).

Apart from the mapping error related to the radar imagery itself, another possible source of boundary mapping errors is related to the accuracy of the reference map. For example, the required minimal boundary mapping error of 20 m (Gillis and Leckie 1996) represents 1 mm on a 1:20 000 scale map. Such a scale is small enough to contribute to mapping errors through plotting errors and pen line widths (Hall *et al.* 1989). Furthermore, in most of mapping accuracy analysis, maps derived from ground-truth are compared within a geographic information system to maps derived from satellite images. However, Edwards (1993) pointed out that the main problem in this procedure is the different nature of the compared maps: the satellite-derived map is a thematic map, that results from physical (electromagnetic radiation) measurements of the reality, whereas the ground truth-derived map is a representation and a simplification of the reality. The problem could be more significant, if both maps have a different scale (Lee *et al.* 1993).

Automated Processing of Radar Digital Imagery

Because the visibility of clearcuts on SAR imagery is poorer than on optical imagery, only a small number of automated systems to process such images has been developed. For example, Edwards and Beaulieu (1989) applied, on SAR imagery containing forest clearcuts, a segmentation algorithm called the Hierarchical Step-Wise Optimization (HSWO) algorithm (Beaulieu and Goldberg 1989). The method requires this algorithm be applied twice: first, on the original unfiltered image resulting in very large segments that are actually networks of smaller segments joined by "noise bridges" and second, on the heavily filtered image, on which compact regions

²Personal communication. E-mail 23/06/98.

are identified as clearcut cores, but giving a very poor estimate of the clearcut boundary. By overlaying the two segmented images, segments can be regrouped into distinct clearcuts with relatively precise boundaries. However, this method requires a large processing time and often a semi-automated procedure is applied using visual correction of the image resulting from the overlaying of the two segmented images (Edwards and Rioux 1995). More recently, for detecting clearcuts on a *ERS-1* image acquired during leafless conditions (beginning of May) on typical mixed boreal forests in Quebec, Cavayas *et al.* (1995) proposed an automated system which classifies the polygon as clearcut, if for the corresponding polygon, the histogram describing the distribution of digital numbers (translated into an 8-bit grey level scale) is unimodal and has its mode being less than 6 and its entropy being less than 3. The polygon corresponding to a partial cut has a bimodal distribution with a mode of less than 6. This system gave a better classification accuracy for clearcut polygons than for partial cut polygons. However, as for the previous automated systems using optical images (see the review in Leblon *et al.* 1995), the empirical definition of threshold values limits the operational use of the system.

Conclusions

The literature review presented here has shown that the use of radar images for clearcut mapping is still under experimental study, although radar sensors have the advantage of being independent of weather and illumination conditions. Our review has shown that clearcut mapping is more accurate using multi-date images acquired during contrasting seasons of the year. This mapping was also shown to be more accurate on images acquired in longer wavelengths and in cross-polarized mode as well as in multi-frequency and multi-polarization images. Thus, the planned spaceborne SAR sensors, like the SAR sensor on the Earth Observing System (*EOS*) and the Advanced SAR (*ASAR*) on *ENVISAT* (Sardar 1997) as well as, later on, *RADARSAT-2* (CCRS 1998), will have the possibility of simultaneously acquiring data in different polarizations, including the cross-polarization. The latter two will acquire data only in the C-band, but the first one will have the additional advantage of simultaneously acquiring data in different frequencies (Sardar 1997). A key parameter of clearcut visibility on SAR images is the contrast between clearcuts and surrounding forests. This contrast is highly dependent on environmental conditions, particularly for C-band images, as well as on incidence angle. As with the most recent spaceborne SAR, *RADARSAT* (Table 1), future SAR will acquire data in a variety of incidence angles, from 15° to 45° in the case of *EOS-SAR* and *ENVISAT-ASAR*, (Sardar 1997).

Clearcut mapping accuracy is highly dependent on the spatial resolution of the image. Currently, *RADARSAT* has the capability of producing images with the highest spatial resolution (9–10 m) (Table 1). Among all the planned SAR sensors, *RADARSAT-2* is the one that will acquire images having a significantly higher spatial resolution (3 m). As for the current SAR images, there will be an increasing interest in using not only the spectral dynamic of the image, but also its spatial dynamic through so-called texture analysis, which is more suitable on high spatial resolution images. However, further research is required to evaluate the usefulness of textural analysis for clearcut mapping.

Despite the potential value of current spaceborne radar images, its operational use for clearcut mapping is limited by the poor visibility of clearcuts on the image. Operational use of radar images must also be assessed in terms of cost-effectiveness. In this assessment, one may not only consider the cost per hectare of image acquisition, but also other cost-related factors. Indeed, the use of digital imagery could be expensive, if clearcuts are not spatially concentrated on a single digital image. In addition, harvest operation methods are now changing, from total to partial harvest. Partial cuts will then be more difficult to map because of the remaining vegetation (trees, shrubs, etc.), which can lead to confusion with surrounding forests. However, uncut forest strips within clearcuts, like riparian zone leave strips, are detectable on fine-mode *RADARSAT* images acquired during wet conditions, particularly if they are undamaged and newly created (Murtha 1997, Murtha and Mitchell 1998). On such images, stumps and logging debris within the cuts makes clearcuts brighter than surrounding forests (Murtha 1997, 1998). Also, alternating strips of cuts and forests are visible on a fall *SIR-B* L-HH image (Drieman 1987) and on *JERS* L-HH images (Fig. 1). Finally, forest inventory updating from radar images is a challenge, not only for Canadian forests, but also for tropical forests, where forest depletions have dramatically increased in the past few years (Lee *et al.* 1993) and where clear days are more rare than at Canadian latitudes.

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