Preprint/Prétirage

RADARSAT-2 stereoscopy and polarimetry for 3-D mapping♥

Thierry Toutin
Natural Resources Canada, Canada Centre for Remote Sensing
588, Booth Street, Ottawa, Ontario, K1A 0Y7

ABSTRACT

Based on research studies over the last 20 years with different satellite synthetic aperture radar (SAR) sensors, a short review of elevation modeling, digital terrain model (DTM) generation and three-dimensional (3D) cartographic feature extraction using stereoscopic and polarimetric methods is given. The results of these research studies were used to evaluate the potential of RADARSAT-2 and three of its new characteristics for mapping applications: ultra-fine mode, better orbit knowledge and polarimetry. Stereoscopy and polarimetry can be used to improve the DTM generation when compared with RADARSAT-1. In the best case, 5-m accuracy (68% confidence level) can be expected in moderate topography. 3D feature extraction using stereoscopic ultra-fine mode data could meet the National Topographic Database standard (better than 10-m positioning, 90% confidence level). Polarimetry with two images from crossing orbits (quasi-orthogonal in North) can also be used for DTM generation depending of the topographic and land-cover conditions. The major drawback is the complex scattering models over forest or agricultural lands with C-band SAR data. In short term, the method can be applied in bare surfaces. All these forecast improvements should be confirmed with real data.

RÉSUMÉ

A partir des recherches sur des capteurs radar à synthèse d'ouverture (RSO) de satellites obtenues ces vingt dernières années, un état de l'art sur la modélisation de l'altitude, la création de modèle numérique de terrain (MNT) et l'extraction 3D d'éléments cartographiques est présenté. Des résultats de ces recherches, on évalue le potentiel de RADARSAT-2 et de trois de ces nouvelles caractéristiques pour les applications cartographiques : le mode ultra-fin, la meilleure connaissance de l'orbite et la polarimétrie. La stéréoscopie et la polarimétrie peuvent être utilisées pour améliorer la création de MNT par rapport à RADARSAT-1. Dans le meilleur des cas, une précision de 5 m (niveau de confiance de 68%). pourrait être obtenue sur des reliefs modérés. L'extraction 3D d'éléments à partir de données stéréoscopiques du mode ultra-fin pourrait permettre de respecter les normes de la Base nationale de données topographiques (précision de positionnement meilleure que 10 m, niveau de confiance de 90%). La polarimétrie utilisant deux images d'orbites croisées (quasi orthogonales dans le Nord) pourrait aussi être utilisée pour créer des MNTs. L'inconvénient majeur est les modèles complexes de rétrodiffusion des données RSO en bande C dans les forêts et les champs agricoles. A court terme, la méthode pourrait être appliquée sur des sols nus. Toutes ces améliorations prévues devront être vérifiées avec des données réelles.

INTRODUCTION

With the advent of instruments that produce images from electromagnetic radiation beyond wavelengths to which the human eye and cameras are responsive, human "vision and perception" have been greatly extended. Remote sensing has evolved into an important supplement to ground observations and aerial images in the study of terrain features, such as ground elevation. Digital elevation models (DEMs) are currently one of the most important data used for geo-spatial analysis. Unfortunately, DEMs of sufficient point density are still not available for many parts of the earth, and when available they do not always have sufficient accuracy. Since a DEM enables easy derivation of subsequent information for various applications, elevation modelling has become an important part of the international research and development (R&D) programs related to geo-spatial data.

♥ Published in Canadian Journal for Remote Sensing, Vol. 30, No. 3, pp. 496-503, June 2004.

Owing to the high spatial resolution of civilian satellite synthetic aperture radar (SAR) sensors, since the 1980s with the shuttle imaging radar (SIR), a large number of researchers around the world have investigated elevation modelling and the production of DEMs (Toutin, 2000a). In addition, discussions on different aspects of radar for radargrammetry or for cartography can be found in Leberl (1990) and Polidori (1997), respectively. The recent research in computer vision to model human vision has led to the advent of new alternatives applied to satellite imagery, and elevation extraction is becoming a more active R&D topic since the launch of the Canadian RADARSAT-1 in 1995. Consequently, an update of the previous research studies for mapping (elevation and three-dimensional (3D) planimetric features) is then useful for predicting RADARSAT-2 potential in relation to three of its new capabilities (ultra-fine mode, better orbit-control and polarimetry). Since interferometric applications are addressed in other papers of this RADARSAT-2 Special Issue (Bamler and Holzner, 2004; Short and Gray, 2004), this paper will focus on stereoscopy and polarimetry.

STEREOSCOPY for DEM GENERATION

Since the launch of different satellite SAR sensors (Almaz, ERS, JERS, etc.) in the beginning of the 1990s, radargrammetry has re-emerged as a hot R&D topic. The Russian Almaz-1 SAR system acquired images with different angles to obtain stereo images in the latitude range from 0º to 72º. Yelizavetin (1993) digitally processed two images with 38º and 59º look-angles over a mountainous area of Nevada, USA. No quantitative results were given. Stereoscopy with ERS-SAR data has been done using an image with its normal look-angle (23º) and a second image with the roll-tilt mode (RTM) angle (35º) to generate a same-side stereo pair (Raggam *et al.*, 1993). However, this ERS stereo configuration is very rare due to the limited amount of SAR data acquired in RTM. Another ERS stereo configuration can also be used with two normal look-angle (23º) images from ascending and descending orbits to generate an opposite-side stereo pair (Toutin, 1996), but this ERS stereo configuration can only applied on rolling topography. Comparison of these two research results confirmed the superiority of the opposite-side stereo pair (20 m versus 40 m). With the JERS-SAR, stereoscopy can only be obtained with adjacent orbits generating a small overlap with a weak stereo configuration (ray intersection angle less than 4°) that could be not used in a low-to-moderate relief terrain (Raggam and Almer, 1996).

Consequently, evaluation of DEM generation results was limited due to the small amount of SAR stereo data at suitable configurations. The launch of RADARSAT-1, with various SAR operating modes has changed this limitation. In fact, it is the first commercial SAR system, which can generate various stereo configurations using images from a broad range of look directions, beam positions and modes at different resolutions (Parashar *et al.*, 1993). Under the Applications Development and Research Opportunity (ADRO) program sponsored by the Canadian Space Agency (CSA), researchers around the world have undertaken studies on RADARSAT-1 stereoscopic capabilities by varying the geometric parameters (look and intersection angles, resolution, etc.). Most of the results were presented at the final RADARSAT-1 ADRO Symposium *Bringing radar application down toeEarth*, which was held in Montreal, Canada in 1998 (Canadian Space Agency, 1998). There was a general consensus on the achieved DEM extraction accuracy (68% confidence level, LE68): a little more (10 m) for the Fine mode, and a little less (20 m) than the image resolution for the Standard mode, independently of the method used (visual or image matching). The impact of using different stereo configurations with various look angles and intersection angles on DEM accuracy were well addressed (Sylvander *et al.*, 1998; Toutin, 1999). Relative elevation extraction from a Fine mode RADARSAT-1 stereo pair for the measurement of canopy heights in the tropical forest of Brazil was also addressed (Toutin and Amaral, 2000). **Table 1** summarises the general results of DEM generation for different satellites and terrain relief (Toutin and Gray, 2000).

There were, however, no significant correlations between DEM accuracy and intersection angle in ADRO experiment results, except that a minimum of 8° intersection angle is required (Sylvander *et al.*, 1997). In fact, some results showed that the principal parameter that had a significant impact on the accuracy of the DEM was the type of the relief. The greater the difference between two look angles (large intersection angle), the more the quality of the stereoscopic fusion and the image matching deteriorated. This cancels out the advantage obtained from the stronger stereo geometry. It is also more pronounced over high relief areas owing to the increase of layover for steep look angles, which implies small intersection angles (Toutin, 2000b, 2002). Since the reduction of one advantage could cancel the other advantage, a trade-off (steep or shallow look angles, small or large intersection angle, fine or coarse resolution) has to be reached between better stereo viewing and matching (small radiometric differences) and stronger stereo geometry and plotting (large parallax) (Toutin, 1999). Since there is no universal stereo pair addressing all requirements of DEM generation (accuracy, terrain relief, applications, use of the DEM, etc.), a Web tool, The RADARSAT-1 Stereo Advisor (http://www.ccrs.nrcan.gc.ca/ccrs/data/advisor/advpg1_e.html), has been developed to address this trade-off (Cyr and Toutin, 2001). While this Stereo Advisor makes recommendations for selecting images by specifying beam modes of RADARSAT-1, it could be easily upgraded to RADARSAT-2 images by taking into consideration the new specificities (ultra-high resolution and polarimetry) as well as the new research and development.

Table 1. General results of radargrammetric-DEM accuracy.

Satellite	**SAR Band-Polarization**	**Resolution (m)**	**Relief Type**	**LE68 (m)**	
				Same-Side	**Opposite-Side**
SIR A	L-HH	25	High	100	
SIR B	L-HH	40	Medium	25	
			High	60	36
ERS 1/2	C-VV	24	Medium	20	20
			High	45	
JERS	L-VV	18	High	75	
Almaz	S-HH	15	High	30-50	
RADARSAT	C-HH	F 7-9	Low	8-10	20
		S 20-29	Medium	15-20	40
		W 20-40	High	25-30	

Note: LE68 is the elevation linear error with 68% confidence level. F, fine imaging mode; S, standard imaging mode; W, wide imaging mode.

On the other hand, although a higher resolution (fine mode) produced a better quality image, it does not change the stereo acuity for a given stereo configuration (e.g. intersection angle), and it does not improve significantly the DEM accuracy relative to the SAR resolution. In fact, "sub-pixel" accuracy is achieved with standard stereo-pair versus "pixel" accuracy for fine mode stereo-pair. Furthermore, although speckle creates some confusion in stereo plotting, it does not degrade the DEM accuracy because the matching methods or the human stereo viewing "behave like a filter". Preprocessing the images with adaptive speckle filtering does not improve the DEM accuracy with a multiscale matching method (Dowman *et al.*, 1997); it can slightly reduce the image contrast and smoothes the relief (Toutin, 1999). In fact, most of the experiments showed that the principal parameter that has a significant impact on the accuracy of the DEM is the type of the relief and its slope. **Figure 1** gives examples of DEM accuracy as a function of the terrain slopes achieved with different stereo pairs over three different relief areas (Toutin, 2002). Good results were still obtained with small intersection angles (F2-F4) in high relief area, (Toutin, 2000b) in contradiction with previous research studies recommending to not use stereo pairs with intersection angles lower than 8° (Sylvander *et al.*, 1997)

The two main characteristics of RADARSAT-2, that distinguish it from RADARSAT-1, which could improve DEM generation, are the ultra-fine mode (3 m × 3 m; 1 look) and a better-orbit knowledge (5 m in each axis with 68% confidence level) (A.P. Luscombe, McDonald Dettwiler and Associates Ltd., personal communications, 2003) using global positioning system (GPS) receivers and star-trackers onboard. Ultra-fine Beam modes of 3-m resolution cover the incidence angle range from 30° to 40° (a 7° shift from the fine mode incidence angle range of 37° to 47°), and will be available in selective single polarization (HH or VV). The addition of GPS receivers onboard the satellite will greatly improve RADARSAT-2's known position, which will in turn permit more accurate analysis of the orbit and subsequently benefiting the applications. RADARSAT-2 satellite stability should be easy to maintain through the addition of star trackers, which provide reliable positioning information. RADARSAT-1 relied on several techniques such as sun-sensors, magnetometers, and horizon scanners that are deemed less accurate and subject to seasonal eclipse outages. More information on the RADARSAT-2 modes and characteristics can be found in Ali *et al.* (2004) or on the CSA web site (http://www.space.gc.ca/asc/index.html).

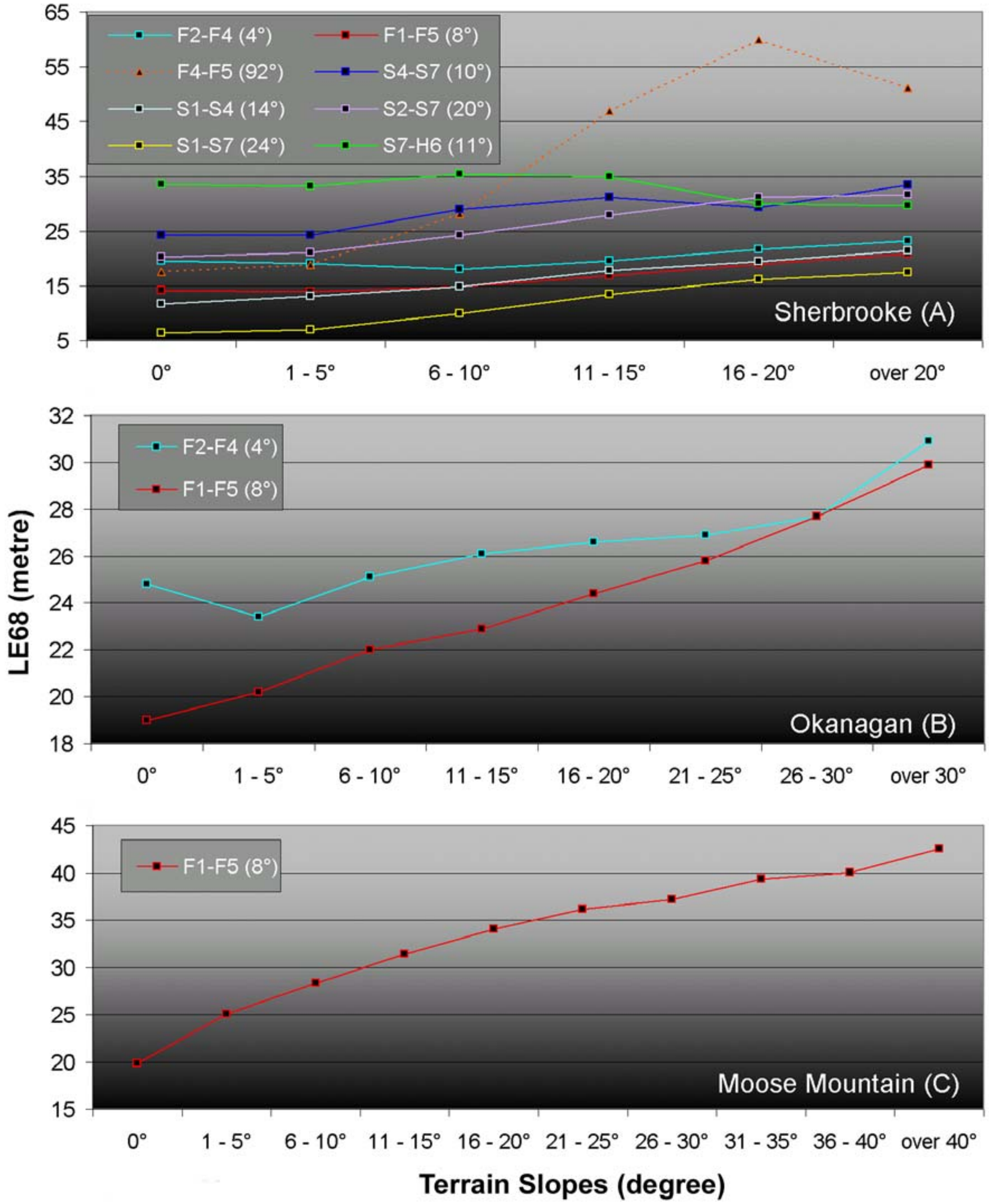

Figure 1. Results on the elevation errors with a confidence level of 68% (LE68) of radargrammetric DEMs generated from different stereo pairs as a function of the terrain slopes over three study sites and topography: (A) Sherbrooke, Quebec, with medium relief; (B) Okanagan, British Columbia, with high relief; (C) Moose Mountain, Alberta, with steep relief. All stereo pairs are same side except F4-F5 over Sherbrooke (A). The approximate intersection angles (in degrees) for each stereo pair are noted in parentheses in the figure legends (Toutin, 2002).

According to theoretical error propagation modelling, an estimation of error in the elevation coordinate, E_h, due to an error in range considered equivalent for the left and right images, E_r, for the measurement of a target in the stereo image can be computed (Leberl, 1990):

$$E_h = [(\sin^2\theta_L + \sin^2\theta_R)^{1/2} / \sin\Delta\theta]\ E_r \qquad (1)$$

where θ_L and θ_R are the look angle of the left and right images, respectively, and $\Delta\theta$ is the intersection angle, approximately the difference between the two look angles.

Based on this modelling, an theoretical accuracy (LE68) of 5-7 m, using accurate ground control points for the stereo-model parameter computation, could be achieved for DEM generated from a stereo ultra-fine mode stereo-pair ($\theta_L = 30°$; $\theta_R = 40°$; $\Delta\theta = 10°$; 1.5-m pixel spacing), assuming an error in range, E_r, to be in the order of one pixel or less for the image matching (Gülch, 1991; Leberl *et al.*, 1994). This estimation will be a good approximation only in moderate relief because this theoretical modelling takes into account only the geometric disparities and not the radiometry-induced disparities due to SAR and surface interaction (Toutin, 1999). In higher relief, the accuracy should be worse as a function of the almost linear correlation between DEM accuracy and terrain slopes (**Figure 1**). The previous experiments and results (**Table 1**) with RADARSAT-1 standard and fine modes also demonstrated a degradation of the DEM accuracy (LE68) relative to the SAR resolution: a little more (10 m) for the Fine mode, and a little less (20 m) than the image resolution for the Standard mode. Consequently, it is more conservative to expect accuracy (LE68) between 5 and 10 m in operational environment with the ultra-fine mode of RADARSAT-2.

In areas without control data, the better-orbit knowledge of RADARSAT-2 will be a key point to achieve better results than those achieved with RADARSAT-1. Even if RADARSAT-2 should be theoretically able to provide sub-metre location accuracy (with GPS data correction using externally supplied data service), a 5-m accuracy (with 68% level of confidence) in the three axes is targeted as a routine delivered performance (A.P. Luscombe, McDonald Dettwiler and Associates Ltd., personal communications, 2003). The 5-m accuracy impact in computing the stereo model will be thus highly dependent on the stereo geometry: from ~10 m for stereo pairs equivalent to S1-S7 to tens metres (20-30 m) for stereo pairs equivalent to S5-S7 or F1-F5. These stereo-model errors will be thus the major errors in DEM error budget when compared to the image matching accuracy theoretically computed from Equation 1. However, the type of relief will still be the most important parameter influencing the DEM accuracy.

Since the same RADARSAT images can be obtained with different pixel spacing (SGX or SGF formats) it is also important to evaluate the impact of image pixel spacing in the DEM generation. Radargrammetric DEM extracted on a very steep relief study site were then evaluated using two fine mode stereo pairs: the SGF format was undersampled (6.25-m pixel spacing) and the SGX format was oversampled (3.125-m pixel spacing) versus the SAR resolution (7-9-m) according to the Nyquist law (Toutin, 2000c). Too much image oversampling generates a repetitive pattern, a "worms effect", which is the major source of error in the matching process. This "worms effect" thus reduces the accuracy of the extracted DEM. Furthermore, this accuracy reduction is independent of geometric parameters related to the relief (elevation, slope and aspect). Using an adaptive filter does not overcome either the speckle effect or this worms effect to improve the DEM accuracy. On the other hand, too much undersampling reduces the image content, the stereo-model accuracy and then DEM accuracy. Consequently, for all RADARSAT-2 image modes, an exact image sampling according to Nyquist law should be preferred, as was done with the standard mode RADARSAT-1 images in SGF format.

POLARIMETRY for DEM GENERATION

SAR polarimetry has been used with success for thematic classification studies involving natural scenes and man-made targets. A recently developed application of SAR polarimetry involves both a direct measure of terrain azimuthal slopes and a derived estimate of the terrain elevations (Schuler *et al.*, 1996). The method is mainly based on empirical comparisons, supported by preliminary theoretical analysis between the terrain local slope and the copolarized signature maximum shift. This has been validated over different geographical areas and different types of natural targets using different DEMs as reference. Although it was only tested with airborne P- and L-band SAR platforms, it is worth mentioning since RADARSAT-2 will generate full polarimetric SAR data.

Polarimetric SAR measures the amplitude and phase terms of the complex scattering matrix. Based on a theoretical scattering model for tilted, slightly rough dielectric surfaces (Valenzuela, 1968), azimuthal surface slope angles and signature-peak orientation displacements produced by such slopes are proportional over a range of azimuthal slopes. Schuler *et al.* (1993) first demonstrated that the resolved azimuthal wave tilts produced significant and predictable displacements in the location of the maxima of the copolarized signature of ocean backscatter. They then hypothesised that an azimuthal angle of an open-field terrain caused a proportional shift of the copolarized polarimetric signature maximum from its flat position by an angle almost equal to the terrain slope. Azimuthal direction slopes can then be computed from the polarimetric SAR data without any prior knowledge of the terrain. By integrating the slope profiles in the azimuthal direction relative terrain elevation can be derived. To obtain absolute elevation, one elevation point must be known along each slope profile.

Since one elevation point along each slope profile is not normally available in an operational environment, sets of elevation profiles spaced throughout the range direction had to be available to obtain two-dimensional (2D) topographic elevations maps. Two orthogonal-pass SAR data are thus a solution to generate an elevation surface with only one elevation point (Schuler *et al.*, 1998). The elevation surface may be generated as an iterative solution of a Poisson-type differential equation, which uses the 2D slope data obtained from the orthogonal-pass pair.

Furthermore, attempts to use shorter wavelength radars (C- or L-band) yielded larger errors for forested terrain, mainly for the C-band (Schuler *et al.*, 1996). The larger slope errors indicated that canopy and (or) branch scattering is then dominant over the terrain relief scattering. **Table 2** summarises the general results of elevation extraction or DEM generation with polarimetry from airborne SAR data (Toutin and Gray, 2000). There was no test realised with two passes over forested area. There was no accuracy evaluation for the whole desert area with one pass technique (Schuler *et al.*, 1996). There was also no explanation why the two-pass technique over the desert area achieved a worse accuracy (LE68) for the whole area (29 m) than for the other relief classes (6 m and 18 m) (Schuler *et al.*, 1998).

Table 2. Results of polarimetric-DEM accuracy with NASA/JPL's AIRSAR data.

Study Site	**SAR Band**	**Resolution (m)**	**Relief**	**LE68 (m)**	
				One Pass	**Two Passes**
Forested area	P	6.6 x 12.1	Low-Medium	10-20	
			High	30-40	
			Whole area	20-30	
Desert area	L (1 pass) P (2 passes)	6.6 x 12.1	Low-Medium	6	6
			High	24	18
			Whole area		29

Note: LE68 is the elevation linear error with 68% confidence level.

Orthogonal flights with spaceborne platforms, however, are very rare, and therefore crossing orbits or convergent configurations must be considered. The left- and right-looking capabilities of RADARSAT-2 combined with ascending and descending orbits can give quasi-orthogonal pass SAR data in higher latitudes to apply the two-pass method. The main difficulty to apply this technique (one pass or two quasi-orthogonal passes) with RADARSAT-2 SAR C-band data is the more complex radiative transfer models or discrete scatter formulations (Durden *et al.*, 1989) of forest backscatter from a sloping terrain than with the open-terrain algorithm using P-band data. Future work should be directed towards an analysis based on a volume scattering to take into account the more complicated situation of the SAR backscattering in forested or agricultural areas. With such scattering models, quantitative slope and elevation values can be derived from the relationship between radiation frequency, incidence angle, and type of scatterer. However, the main drawbacks of this emergent technique are the volume scattering models, and also the limited availability of polarimetric data to evaluate the robustness of the technique with different topographic and land-cover situations. In the short term, the two-pass method can be applied with RADARSAT-2 on bare surfaces, mainly in the north where the two orbits (left- and right-looking or ascending and descending) are quasi-orthogonal, and in the medium term, RADARSAT-2 can be a good candidate to address some of these drawbacks.

3D CARTOGRAPHIC FEATURE EXTRACTION

Few qualitative and quantitative results have been published on cartographic feature extraction (such as transportation networks and hydrography) from RADARSAT-1 images. Sempere (1998) made a quantitative evaluation of the image content of ortho-rectified RADARSAT-1 images in a French operational context for topographic mapping and digital data base updating. Sempere (1998) noticed a small potential for mapping some cartographic features (roads, railroads) at 1 : 100 000 scale because of the high density of communications network in developed countries. Although the ortho-rectified RADARSAT-1 images are compatible with the planimetric precision at this scale, important fieldwork should be required to resolve the omission and commission errors. Nevertheless, such mapping applications remain possible for developing countries, which are often difficult to survey with optical sensors due to perennial cloud cover. Consequently, the ultra-fine mode will have two positive impacts in the applicability of the method: the increase in positioning accuracy to potentially meet 1 : 50 000 scale maps and the reduction of omission and commission errors. However, the SAR ortho-rectification process requires precise DEMs, which are rarely available in these countries. **Figure 2** shows the relationship between the DEM accuracy, the viewing angle of the SAR image, and the resulting error generated on the ortho-image (Toutin and Rivard, 1997). As an example, a 20-m elevation error due to the DEM accuracy and the interpolation into the DEM generates a positioning error of 60 m and 20 m on the standard-1 (S1) and fine-5 (F5) ortho-images, respectively. Consequently, the limitation of the cartographic feature extraction will still be the availability of accurate DEMs: to meet 10-m accuracy with 90% level of confidence (LE90) compliant with 1 : 50 000 scale maps, a 6-8 m accurate DEM (LE90) will be required for the ortho-rectification of the ultra-fine mode images (40°-30° incidence angle), respectively (**Figure 2**).

Some studies related to the detectability of trails and roads in rainforests with no significant topographic relief, as a function of the SAR parameters and trail (or road) shapes, were also addressed (Touzi and Sasitiwarih, 2001). It is shown that the visibility of these features on SAR images depend mainly on the SAR resolution, trail (or road) widths and their orientation relative to the SAR viewing direction. The results are confirmed experimentally on the dense forest site in the south of Sumatra, Indonesia, using the multi-resolution capability of RADARSAT-1. The best trail detectability was obtained with the RADARSAT modes of finest azimuth and ground range resolution – 9-m azimuth resolution and a ground range resolution ranging from 8.27 m for F1 to 7.17 m for F5. This permits even the detection of 7- to 8-m width trails under particular conditions. The use of the ascending and descending modes is also ideal because it permits trail imaging with different orientation, and as such increases trail detectability: a 5-m width trail was detected in a rubber tree plantation (Touzi and Sasitiwarih, 2001). Finally, the effect of speckle on trail and road visibility is discussed, as well as the speckle reduction of SAR images for trail and road enhancement. These results, therefore, can be extrapolated to RADADARSAT-2, mainly with the ultra-fine mode, which should permit the detection of 3-m width trails with similar experimental conditions. The 7°-shift in the incidence angle range between the fine mode and the ultra-fine mode would not have any impact because the relate ed variation in the ground range resolution will not be significant for the width of detected trails.

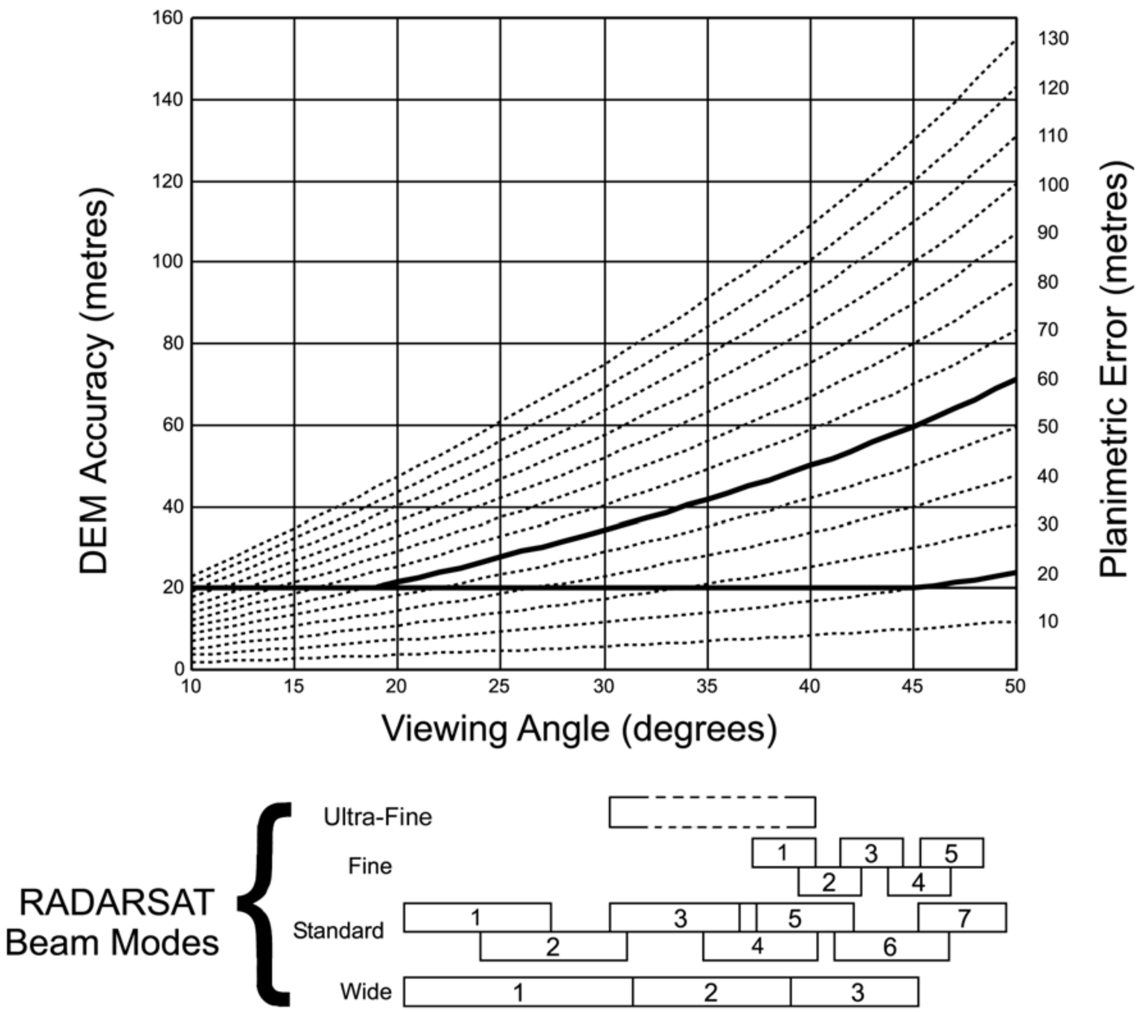

Figure 2. Relationship between the DEM accuracy, the viewing angle of the SAR image, and the resulting error generated on the ortho-image (Toutin and Rivard, 1997). The main modes and beams of RADARSAT are also indicated with their viewing angle range. As an example of error evaluation (bold lines and curves), a 20-m elevation error due to the DEM accuracy and the interpolation into the DEM grid spacing generates a planimetric positioning error of 60 m and 20 m on the standard-1 (S1) and fine-5 (F5) ortho-images, respectively.

Even though stereo-radargrammetry is generally used for DEM extraction in the international research communities, it can also be used by analogy with photogrammetric stereoscopic methods to extract cartographic features from a digital stereo workstation without *a priori* existing elevation information. The "naturalness" of a 3D representation of reality enhances our ability to interpret 2D imagery. Cartographers, engineers, geologists, hydrologists, and other geo-scientists, use different 3D viewing methods to perceive the ground elevation and better understand the earth's surface. Representation of the third dimension of the terrain relief supplies important information about the relationship between land shape and structure, slopes and waterways, and surface material and vegetative growth. Consequently, subtle features not discernible in a single SAR image are often recognized in stereo images combining the radiometry of the two images and the relief perception.

Stereoscopy is thus an important issue in countries where precise DEM and maps are not available. Stereo-radargrammetry has been proven to be more accurate for planimetric feature extraction because the feature positioning is not affected by any elevation error in the stereo-restitution (the operator views and compiles at the vertical of the point) (Toutin, 2001). Furthermore, since the stereo restitution is directly done on the raw images, no resampling, such as in the ortho-rectification process degrades the image radiometry, geometry and interpretability. Few researchers have addressed these stereo-radargrammetry capabilities and results are unfortunately limited to those performed at the Canada Centre for Remote Sensing (Toutin, 2001) to evaluate the potential of RADARSAT-2 for cartographic feature extraction.

Planimetric features such as roads were interactively stereo extracted by an operator on a PC-based stereo workstation from stereo pairs generated with standard mode images (S1-S7 and S4-S7) and fine mode images (F1-F5). The omission errors and positioning accuracy depend mainly on the definition, the visibility of each road category by itself and with its surrounding element (forest, bare soil, agricultural fields, houses, etc.), and the backscatter related to SAR and surface interaction. The omission errors vary from 0% for the highways extracted from F1-F5 stereo pair to 73% for the city streets extracted from S1-S7 or S4-S7 stereo pairs. Completeness needs to be assessed based on density of the communication network and the map scale. Positioning accuracies, LE68 and LE90, of about one resolution cell and two to three resolution cells respectively, were obtained. The stereo configurations (e.g., the intersection angles) do not have an impact on this accuracy.

Even if the omission errors are presently not acceptable for the mapping community, the road accuracy results obtained from the stereo compilation of fine and standard mode RADARSAT-1 images are encouraging since they correspond to the positional accuracy standard of 1 : 50 000 scale and 1 : 100 000 scale paper maps, respectively. The ultra-fine mode of RADARSAT-2 can thus reduce the omission error, mainly in the dense communication network, to better fulfil the mapping requirements. If the two to three resolution cell accuracy with 90% confidence level obtained with RADARSAT-1 fine mode images can be extrapolated to RADARSAT-2 ultra-fine mode images (6-9 m), it should then meet the accuracy for the 1 : 50 000 scale paper maps and also for the digital maps and cartographic data bases, such as the Canadian National Topographic Data Base (NTDB), which has higher standards (about 10-m LE90). In addition, a better detection ability of roads can reduce the omission and commission errors.

CONCLUSION

The results of previous research studies on DEM generation and 3D feature extraction from stereoscopic or polarimetric SAR data were used to evaluate the potential of RADARSAT-2 in relation to three of its new characteristics: ultra-fine mode, better orbit knowledge, and polarimetry. The two first characteristics should enable RADARSAT-2 to generate DEMs by stereoscopy with 5-10 m accuracy (LE68) in moderate relief with ground control and 10-30 m accuracy (LE68) depending on the stereo-pair, without ground control. Results in operational environments should be more conservative, mainly in high reliefs. Polarimetry with two-passes should be investigated to evaluate the different topographic and land-cover situations (bare surfaces in the north) where this method using C-band radar could work for generating DEMs. The ultra-fine mode should also enable RADARSAT-2 to meet NTDB standard for 3D planimetric feature extraction (e.g., transportation networks) as well as to reduce the omission and commission errors. Stereo-radargrammetry should be favoured for the planimetric feature extraction when no accurate DEM is available. However, these forecast improvements should be confirmed with real data, first in a research environment and then in operational environments.

REFERENCES

Ali, Z., Barnard I., Fox P., Duggan P., Gray R., Allan P., Brand A., and Ste-Marie, R. 2004. The RADARSAT-2 Synthetic Aperture Radar Design Description, *Canadian Journal for Remote Sensing*, Vol. 30, No. 3, pp.??.

Bamler, R., and Holzner, J. 2004. ScanSAR Interferometry for RADARSAT-2 and –3, *Canadian Journal for Remote Sensing*, Vol. 30, No. 3, pp.??.

Canadian Space Agency. 1998. Bringing Radar Application Down to Earth, in *Proceedings of the RADARSAT ADRO Symposium*, 13-15 October 1998, Montreal, Que. Canadian Space Agency, Ottawa, Ont. [CD-ROM].

Cyr, I., and Toutin, Th. 2001. RADARSAT-1 Stereo Advisor on CCRS Web, *Canadian Journal of Remote Sensing*, Vol. 27, No. 1, pp. 62-66.

Dowman, I.J., Twu, Z.-G., and Chen, P.H. 1997. DEM generation from stereoscopic SAR data, in *Proceedings of the ISPRS Joint Workshop on Sensors and Mapping from Space,* 29 September – 2 October 1997, Hannover, Germany, Institute of Photogrammetry and Engineering Surveuys (IPI), University of Hannover, Hannover, Germany, pp. 113-122.

Durden, S.L., van Zyl J.J., and Zebker, H.A. 1989. Modeling and observation of radar polarization signature of forested areas, *IEEE Transactions on Geoscience and Remote Sensing,* Vol. 27, No. 3, pp. 290-301.

Gülch, E. 1991. Results of Test on Image Matching of ISPRS WG III/4, *ISPRS Journal of Photogrammetry and Remote Sensing*, Vol. 46, No. 1, pp. 1-8.

Leberl, F. 1990. Radargrammetric image processing, Artech House, Norwood, Mass. 595 pp.

Leberl, F., Maurice K., Thomas J.K., and Millot M., 1994. Automated Radar Image Matching Experiment, *ISPRS Journal of Photogrammetry and Remote Sensing*, Vol. 49, No 3, 19-33.

Parashar, S. and Langham, E. McNally, J., and Ahmed, S. 1993. RADARSAT mission requirements and concepts, *Canadian Journal of Remote Sensing*, Vol. 18, No. 4, pp. 280-288.

Polidori, L. 1997. Cartographie radar. Gordon and Breach Science Publishers, Amsterdam. 287 pp.

Raggam J., and Almer, A. 1996. Assessment of the Potential of JERS-1 for Relief Mapping Using Optical and SAR Data, In *Proceedings of the International Archives of Photogrammetry and Remote Sensing*, Vol. 31, No. 4, pp. 671-676.

Raggam, J., Almer, A. Hummelbrunner, W., and Strobl, D. 1993. Investigation of the stereoscopic potential of ERS-1 SAR data, in *Proceedings of the 4th International Workshop on Image Rectification of Spaceborne Synthetic Aperture Radar*, 26-28 May 1993, Loipesdorf, Austria, pp. 81-87.

Schuler, D.L., Lee J.S., and Hoppel, K.W. 1993. Polarimetric SAR image signatures of the ocean and Gulf Stream features, *IEEE Transactions on Geoscience and Remote Sensing*, Vol. 31, No. 5, pp. 1210-1221.

Schuler, D.L., Lee J.S., and De Grandi, G. 1996. Measurement of topography using polarimetric SAR images, *IEEE Transactions on Geoscience and Remote Sensing*, Vol. 34, No. 5, pp. 1266-1277.

Schuler, D.L., Ainsworth, T.L., Lee J.S., and De Grandi, G.F. 1998. Topography mapping using polarimetric SAR data, *International Journal of Remote Sensing*, Vol. 19, No. 1, pp. 141-160.

Sempere, J.-P. 1998. Quantitative evaluation of the planimetric potential of RADARSAT images, In *Proceedings of the ADRO Symposium "Bringing radar applications down to Earth"*, 13-15 October 1998, Montreal, Que. Canadian Space Agency, Ottawa, Ont. [CD-ROM].

Short, N., and Gray, L. 2004. Potential for RADARSAT-2 Interferometry: Glacier Monitoring using Speckle Tracking, *Canadian Journal for Remote Sensing*, Vol. 30, No. 3, pp.??.

Sylvander, S., Cousson D., et Gigord, P. 1997. Étude des performances géométriques des images RADARSAT, *Bulletin de la Société Française de Photogrammétrie et de Télédétection*, Vol. 148, pp. 57-65.

Toutin, Th. 1996. Opposite-side ERS-1 SAR stereo mapping over rolling topography, *IEEE Transactions on Geoscience and Remote Sensing*, Vol. 34, No. 2, pp. 543-549.

Toutin, Th. 1999. Error tracking of radargrammetric DEM from RADARSAT images, *IEEE Transactions on Geoscience and Remote Sensing*, Vol. 37, No. 5, pp. 2227-2238.

Toutin, Th. 2000a. Elevation Modeling from Satellite Data, in *Encyclopædia of Analytical Chemistry*, Vol. 10, Edited by R.A. Meyers. John Wiley & Sons Ltd., Chichester, UK, pp. 8543-8572.

Toutin, Th. 2000b. Evaluation of radargrammetric DEM from RADARSAT images in high relief areas, *IEEE Transactions on Geoscience and Remote Sensing*, Vol. 38, No. 2, pp. 782-789.

Toutin, Th. 2000c. SAR Image Sampling on DEM Generation, In *Proceedings of the IEEE International Geoscience and Remote Sensing Symposium, IGARSS'00*, 24-28 July 2000, Honolulu, Hawaii, IEEE, Piscataway, N.J. Vol. 2, pp. 794-796.

Toutin, Th. 2001. Potential of Road Stereo Mapping with RADARSAT Images, *Photogrammetric Engineering and Remote Sensing*, Vol. 67, No. 9, pp. 1077-1084.

Toutin, Th. 2002. Impact of terrain slope and aspect on radargrammetric DEM accuracy, *ISPRS Journal of Photogrammetry and Remote Sensing*, Vol. 57, No. 3, pp. 228-240.

Toutin, Th., and Rivard, B. 1997. Value-added RADARSAT Products for Geoscientific Applications, *Canadian Journal for Remote Sensing*, Vol. 23, No. 1, pp. 63-70.

Toutin, Th., and Amaral, S. 2000. Stereo RADARSAT data for canopy height in Brazilian forest, *Canadian Journal for Remote Sensing*, Vol. 26, No. 3, pp. 189-199.

Toutin, Th., and Gray, A. L. 2000. State-of-the-art of extraction of elevation data using satellite SAR data, *ISPRS Journal of Photogrammetry and Remote Sensing*, Vol. 55, No. 1, pp. 13-33.

Touzi, R., and Sasitiwarih, A. 2001. Radarsat Optimum Configuration for Trail and Road Detection in Indonesian Rainforests, *Canadian Journal for Remote Sensing*, Vol. 27, No. 5, pp. 555-567.

Valenzuela, G.R. 1968. Scattering of Electromagnetic Waves From a Tilted Slightly-Rough Surface, *Radio Science*, Vol. 11, No. 3, pp. 1057-1066.

Yelizavetin, I.V. 1993. Digital terrain modeling from radar image stereopairs, *Mapping Sciences and Remote Sensing*, Vol. 30, No. 2, pp. 151-160.