Anticipated Applications Potential of RADARSAT-2 Data

J.J. van der Sanden
Natural Resources Canada, Canada Centre for Remote Sensing, Applications Division, 588 Booth Street, Ottawa, ON, K1A 0Y7. Tel: + 1-613-947-1324, Fax: + 1-613-947-1385, E-mail: sanden@ccrs.nrcan.gc.ca

Abstract. In this paper we assess how RADARSAT-2's technical enhancements in terms of polarization, spatial resolution, look direction and orbit control will impact the potential utility of its data products for 32 applications in the fields of agriculture, cartography, disaster management, forestry, geology, hydrology, oceans, and sea and land ice. Our assessment relies on bibliographic sources and, in particular, case studies drawn from ongoing applications development work at the Canada Centre for Remote Sensing and the Canadian Ice Service. The applications potential of RADARSAT-2 data, compared to that of RADARSAT-1 data, is anticipated to improve in a major, moderate, and minor fashion for 3, 18, and 10 of the identified applications, respectively. For one of the applications considered the increase in potential of RADARSAT-2 vis-à-vis RADARSAT-1 cannot be assessed because this application relies completely on RADARSAT-2's new full polarimetric capability.

Introduction

RADARSAT-2 will provide all imaging modes of the current RADARSAT-1 satellite, as well as some new modes that incorporate significant technical innovations and improvements (cf. Ali *et al.*, 2004a; Ali *et al.*, 2004b; Fox *et al.*, 2004; Morena *et al.*, 2004). Hence, the satellite will offer data continuity to RADARSAT-1 users and new data that support the development of new applications and the refinement of existing ones. From an applications perspective, the most prominent technical enhancements embodied by RADARSAT-2 are those relating to polarization, spatial resolution, look direction, and orbit control. In this paper, we assess how these enhancements will impact the potential of RADARSAT-2 data products for applications in the fields of agriculture, cartography, disaster management, forestry, geology, hydrology, oceans, and sea and land ice. Evidently, the utility of the RADARSAT-2 data products will govern the satellite's economic viability and as such its role in the operationalisation of space-borne radar remote sensing.

The presented assessment is primarily based on an evaluation of data information content and largely disregards other conditions that may affect the promise of particular applications, e.g. economic or legal circumstances. After all, such conditions may vary widely from one geographical application area to another. Our evaluation relies on bibliographic sources and, in particular, case studies drawn from ongoing applications development work at the Canada Centre for Remote Sensing and the Canadian Ice Service (van der Sanden and Ross, 2001; CCRS, 2004). Logically, the evaluation will focus on data products that are not currently available from RADARSAT-1. Even so, the applications potential as demonstrated vis-à-vis RADARSAT-1 data products will often provide the starting-point for our discussions concerning RADARSAT-2.

Anticipated Applications Potential

Table 1 summarises our assessment of the specific effect of the most important technical enhancements of RADARSAT-2 on the data information content and hence on the associated applications potential. Our evaluation of the combined effect of these technical enhancements on the anticipated overall applications potential of RADARSAT-2 data is summarised in Table 2. This table also lists our ratings for the overall applications potential of RADARSAT-1 data products. As such, Table 2 illustrates the degree in which progress in space-borne SAR technology is expected to enhance the overall applications potential of RADARSAT-2 data products. With regard to Table 2 it is important to mention that we assume application of single date SAR images. The use of images acquired on different dates is known to enhance the application potential in fields dealing with vegetation in particular. As an example, the application potential of RADARSAT-1 data for crop type mapping would rate as 'moderate' rather than 'limited' if the use of multi-temporal images had been considered. In addition – and perhaps unnecessarily – it is noted that the ratings in Table 2 are general in nature. In specific cases or under certain conditions the true application potential may therefore differ from the one shown. For instance, it is well-known that mountainous conditions have an overall adverse effect on the applications potential of any type of SAR data.

In the sections following we will motivate our ratings shown in Tables 1 and 2 for each application field identified.

Agriculture

Crop type and crop condition mapping are among the three applications that are expected to benefit the most from the technical enhancements embodied by RADARSAT-2. As shown in Table 2, the potential of RADARSAT-1 data for these applications is rated 'limited' while the applications potential for RADARSAT-2 data is anticipated to be 'strong'. Table 1 shows that the introduction of the Selective Dual Polarization (SDP) mode and – even more so – the Quad Polarization (QP) mode contribute to the increase in potential for both applications. In addition, the crop condition mapping application is anticipated to benefit from RADARSAT-2's enhancements in terms of spatial resolution and look direction.

The improved applications potential of images acquired in the SDP and QP modes results from an increase in information content with respect to the structural characteristics of the crops observed. It is well known that the polarization of backscattered microwaves is a function of the polarization of the transmitted microwaves and the structural characteristics of the features observed. Moreover, the polarization of the transmitted microwaves dictates which components of the vegetation and soil contribute to the total amount of energy scattered back to the SAR sensor. Vertically-polarized microwaves (V) couple with the predominant vertical structure of most vegetation and as a result, penetration of the signal through the canopy is reduced. VV-polarized radar returns thus provide good contrast among crop types that have different vertical canopy structures. Differences in this vertical structure that result from changes in growth stage or health may also be detected in VV-polarized images. Horizontally-polarized microwaves (H) tend to penetrate the canopy to a greater extent than vertically-polarized waves. At steep incidence angles, HH images therefore tend to provide information about the underlying soil condition. Cross-polarized radar returns (HV or VH) result from multiple reflections within the vegetation volume. C-HV and C-VH images are sensitive to crop structure within the total canopy volume and thus provide information that is complementary to HH and VV imagery. RADARSAT-2's capability to acquire full polarimetric data in the QP mode can be expected to extend its sensitivity to crop structural characteristics and hence potential for crop type and condition mapping beyond that of the SDP mode. McNairn and Brisco (2004) present a detailed review of the utility of C-band polarimetric data for agriculture. Buckley (2004) discusses the potential of RADARSAT-2 type data for the characterization of prairie landscapes.

Whereas crop type mapping calls for information at the level of individual fields, crop condition mapping requires information at the level of specific zones within individual fields. RADARSAT-2 images acquired in the Ultra-Fine mode will contain more detailed spatial information than any other commercially available space-borne SAR data product and are therefore anticipated to advance the potential for crop condition mapping (cf. McNairn *et al.*, 2004). The capability to image to either the right or the left of the sub-satellite track potentially shortens - on average - RADARSAT-2's acquisition response time and increases its revisit frequency in all but the most northerly regions on Earth. In the context of crop condition mapping, this improves application potential because it enhances the likelihood of acquiring multiple images immediately following and during critical events such as infestations, hailstorms etc.

Table 1 shows that images acquired in the QP and Ultra-Fine resolution modes are expected to contain moderately improved information in support of crop yield mapping. Accordingly, the application potential of RADARSAT-2 is rated one level above that of RADARSAT-1, i.e. 'limited' instead of 'minimal' (see Table 2). As in the case of crop condition mapping, the improved potential of the QP and Ultra-Fine resolution data products for crop yield mapping can be explained from the increased sensitivity to crop structure and the capacity to obtain within-field zonal information, respectively. The anticipated potential of RADARSAT-2 for crop yield mapping does not exceed the 'limited' rating because the employed C-band radar signal is known to saturate for larger biomass crops.

Cartography

Digital Elevation Models (DEMs) are currently one of the most important data sources used in geo-spatial analysis. Like RADARSAT-1, RADARSAT-2 will have the capacity to support the generation of DEMs by means of repeat-pass interferometry and stereoscopy. In addition, RADARSAT-2 data acquired in the QP mode can be applied to the generation of DEMs from polarimetry. While the techniques for the production of DEMs from interferometric or stereoscopic SAR image pairs are operational, the technique for the generation of DEMs from polarimetric SAR data is experimental.

DEM polarimetry involves the direct measurement of terrain slopes and the inference of terrain elevations from known elevation points. The generation of a two-dimensional DEM requires two (quasi-)orthogonal SAR overpasses since the capability to measure slopes is restricted to the azimuth direction. In addition, slope measurement requires the availability of a scattering model for the target observed (cf. Toutin, 2004). The requirements for DEM polarimetry in terms of elevation points, overpasses and scattering models explain why the associated application potential has been rated as 'limited' in Table 2.

Both the repeat-pass DEM interferometry and DEM stereoscopy applications will benefit from RADARSAT-2's enhancements in terms of spatial resolution and orbit control. DEMs generated from data acquired in RADARSAT-2's Ultra-Fine resolution mode can be expected to comprise more spatial details and have higher spatial accuracies than DEMs generated from any other commercially available space-borne SAR data source. Improved knowledge about and control over the orbit will enhance the absolute positional accuracy of image products as well as the accuracy with which baselines between interferometric image pairs can be computed. The anticipated effect of improved orbit control for DEM stereoscopy and DEM interferometry is rated as 'moderate' and 'major', respectively. The effect on the former application is rated lower because, in many cases, the positional accuracy of image products can also be improved through the identification of ground control points. In contrast, an alternative for more accurate calculation of baselines between repeat-pass interferometric image pairs is lacking. Table 2 shows that, while beneficial, the technical enhancements embodied by RADARSAT-2 are not anticipated to improve its overall application potential for DEM interferometry and DEM stereoscopy to a level above that of RADARSAT-1. The potential associated with repeat-pass DEM interferometry is assessed to halt at 'moderate' for both satellites because of two well-known problems with this technique – that is - the loss of coherence and changes in atmospheric propagation between subsequent image acquisitions. As for RADARSAT-1, the overall application potential of RADARSAT-2 for DEM stereoscopy is rated at the highest level, i.e. 'strong'.

As shown in Table 2, the overall potential for cartographic feature extraction is rated 'moderate' for RADARSAT-1 and 'strong' for RADARSAT-2. The most important feature contributing to this increase in application potential is the Ultra-Fine spatial resolution mode. RADARSAT-2's Ultra-Fine resolution data products will comprise more detailed spatial information. These products can thus be expected to enable the mapping of cartographic features with reduced errors of omission and increased positional accuracies (cf. Toutin, 2004). The enhancement in terms of orbit control improves the application potential because it will facilitate more accurate absolute positioning of features extracted. RADARSAT-2's capability to acquire QP data products is anticipated to enhance its potential for cartographic feature extraction because the polarimetric information comprised in these data (e.g. information re scattering mechanisms) is likely to ease the detection and hence the subsequent extraction of features of interest. It should be noted that, due to technical limitations, the QP data products will have a lower spatial resolution than the Ultra-Fine data products.

Disaster Management

The urgency associated with disaster management dictates that applications in this field require instantaneous and frequent image acquisition. RADARSAT-2's selective look direction capability will (on average) shorten the response time and increase the revisit frequency in all but the most northerly regions on Earth. Consequently the effect of selective look direction capability on the information content of RADARSAT-2 data products for all disaster management applications is rated as 'major'. With the exception of polar glaciology, no other application is anticipated to benefit from the selective look direction feature in such a paramount fashion (see Table 1). It should be noted that even though look direction switching will be an operational RADARSAT-2 feature, the right-looking configuration is regarded as the default mode of operation. The left-looking mode is expected to be deployed primarily to meet data requirements for disaster management and Antarctic mapping (see section on Sea and Land ice).

RADARSAT-2's enhancements in terms of polarization are anticipated to have a mostly 'moderate' effect on the information content of its data for all of the disaster management applications identified with the exception of flood mapping. When operating in the Selective Single Polarization (SSP) mode, RADARSAT-2 will be able to acquire a single image in either the HH-, VV-, VH- or HV-polarization (note; RADARSAT-1 operates in HH only). The capability to image in VV will benefit the hurricanes application because available wind retrieval models are best developed for this particular polarization. Moreover, the oil spills application will gain from the VV imaging capability since VV-polarized images provide better oil-water contrast than HH and HV (VH) images. The option to simultaneously acquire both a VV and VH image in the SDP mode is not considered beneficial for either the hurricanes or oil spills application since the extra cross-polarized band does not contain additional information. In fact, the extra image band would hamper these applications by adding to the data volume to be handled. Accordingly, the effect of the SSP feature for the hurricanes and oil spills applications has been rated higher than the effect of the SDP feature (Table 1). RADARSAT-2's QP feature has been given the 'moderate' rather than 'minor' rating in connection with hurricanes because there is evidence in the literature that co- and cross-polarized ratios at C-band provide a mechanism to estimate rain rates (Braun *et al.*, 2000). Rain rates would represent important additional quantitative information on the state and evolution of hurricanes. It is therefore unfortunate that, due to technical limitations, QP data cannot be acquired in ScanSAR imaging mode, that is, the preferred mode for hurricane studies. The use of the narrow swath QP mode (25 km nominally) will considerably reduce the probability of obtaining a hurricane image.

As shown in Table 1, RADARSAT-2's SDP and QP data products are anticipated to offer moderately improved information content for the mapping of geological hazards. This can be explained from the difference in the sensitivity of (linear) like- and cross-polarized data to surface roughness, i.e. an important variable in the mapping of landslides and volcanoes. Indeed, QP data have been shown to hold promise for the quantification of surface roughness in agricultural terrain (e.g. Mattia *et al.*, 1997; Schuler *et al.*, 2002). Introduction of the QP mode is also expected to benefit the application of space-borne SAR to the search and rescue of crashed airplanes (cf. Lukowski *et al.*, 2004). Unlike any other image types, QP images can be evaluated for the occurrence of dihedrals formed by parts of the airplane structure. This is a particularly effective detection approach given that these highly reflective dihedral structures have been found to often survive the crash and are unusual features in natural environments.

The enhanced spatial information that will be available in RADARSAT-2's Ultra-Fine mode images is anticipated to be of value for search and rescue as well as the mapping of geological hazards and oil spills. Improved orbit control will simplify the extraction of accurate geographic coordinates for (candidate) crash sites and hence be of benefit to the search and rescue application. Moreover, this feature will facilitate the computation of accurate baselines between satellite overpasses. Consequently, it is anticipated to represent a 'major' improvement for applications that are known to use repeat-pass SAR interferometry techniques, e.g. geological hazards mapping and search and rescue.

Like other disaster management applications, the flood mapping application is expected to benefit in a 'major' fashion from RADARSAT-2's selective look direction capability. In contrast, the effects of enhancements in terms of polarization, spatial resolution and orbit control are anticipated to be 'minor' (see Table 1). In fact, the technical capabilities of the current RADARSAT-1 satellite are very well suited to the mapping of floods. Hence, RADARSAT-2 data products are not anticipated to be able to advance the floods application. Accordingly, the overall potential of both RADARSAT-1 and RADARSAT-2 for flood mapping has been rated in Table 2 as 'strong'.

Forestry

Table 2 rates the respective overall potential of RADARSAT-1 and RADARSAT-2 for the mapping of clearcuts and fire-scars as 'limited' and 'moderate'. RADARSAT-2's moderately improved potential for these applications results primarily from its capability to acquire HV- (VH-) polarized images in SSP mode. Compared to HH- and VV-polarized images, HV- (VH-) polarized images offer improved information content in the sense that they show better contrast between the clearcuts or fire-scars and the surrounding forest cover (Ahern and Drieman, 1988; Kneppeck and Ahern, 1989). This superior contrast results from the scarcity of HV backscatter generating multiple reflections in the lightly vegetated clearcuts or fire-scars and the abundance of such reflections in the heavily vegetated forest. RADARSAT-2's capability to acquire images in the SDP or QP mode is not considered beneficial for either application since the extra image bands do not contain additional information but rather add to the volume of data to be handled. Accordingly, the ratings in Table 1 associated with clearcuts and fire-scars are higher for the SSP mode of operation than for either the SDP or QP mode of operation. Thanks to increased spatial information content, RADARSAT-2's images can be expected to facilitate clearcut and fire-scar mapping with reduced errors of omission and increased positional accuracies. However, the potential of Ultra-Fine resolution data for application to large-scale clearcut and fire-scar mapping is compromised by the associated limited coverage (20 km by 20 km nominally).

As shown in Table 2, RADARSAT-2 data are not expected to contain the information required to improve the application potential for forest type and forest biomass mapping to levels above that of RADARSAT-1 data. Forest type mapping is likely to benefit moderately from the introduction of the QP and Ultra-Fine spatial resolution modes but the resulting overall application potential is anticipated to be at the RADARSAT-1 level, i.e. 'limited'. The moderately increased information content of full polarimetric RADARSAT-2 data can be explained from the enhanced sensitivity of this data type to differences in forest canopy structure (cf. Touzi *et al.*, 2004b). Similarly, the improved spatial detail available in Ultra-Fine mode data will represent an enhanced source of information for forest type mapping by means of analysis of image texture. Like RADARSAT-1, RADARSAT-2 is anticipated to offer only 'minimal' potential for application to the mapping of forest biomass. The main impediment of both satellites for operational forest biomass mapping is the high frequency of operation, i.e. C-band. It is well known that the sensitivity of C-band radar signals to differences in aboveground biomass is restricted to a level below that of most forests, i.e. below ca. 50 t ha^{-1} in dry biomass (Dobson *et al.*, 1992; Le Toan *et al.*, 1992).

Geology

RADARSAT-2 is anticipated to offer a moderately improved potential for application to terrain mapping and structure mapping. The overall potential for these respective applications is rated as 'limited' and 'moderate' for RADARSAT-1 and as 'moderate' and 'strong' for RADARSAT-2 (see Table 2). This increase in potential for both applications results primarily from the introduction of the SDP, QP and Ultra-Fine spatial resolution modes. RADARSAT-2's capability to acquire dual-polarized or full polarimetric data increases its sensitivity to differences in vegetation structure and relief. Thanks to geobotanical relationships, differences in vegetation structure often reflect the properties and extent of underlying surficial deposits and rock units. Hence, more information concerning structural characteristics of vegetation translates in improved potential for terrain mapping (Singhroy, 1996). Greater sensitivity to relief can be observed in cross-polarized data in particular and explains the anticipated increase in application potential of RADARSAT-2 for the mapping of geological structures, including fracture zones and fault scarps (Huadong *et al.*, 1997; Schaber *et al.*, 1998). Like other applications that rely on repeat-pass SAR interferometry techniques, the mapping of terrain displacements can be expected to benefit in a major way from RADARSAT-2's enhancements in terms of orbit control.

The potential of both RADARSAT-1 and RADARSAT-2 for application to lithological (or rock type) mapping is rated as 'limited'. C-band SAR images have been reported to contain information in support of the mapping of lava flows and other rock types with distinct differences in surface roughness (Gaddis, 1992; MacKay and Mouginis-Mark, 1997). However, in most cases the lithological mapping application will be served much better with data acquired by optical sensor systems in general and hyperspectral sensor systems in particular.

Hydrology

Table 2 shows that the potential of RADARSAT-2 for application to the mapping of soil moisture, snow and wetlands is anticipated to be one level above that of RADARSAT-1, i.e. 'moderate' rather than 'limited'. The increased potential for the soil moisture and snow mapping applications results mainly from the introduction of the QP mode and the selective look direction capability. In turn, the wetland mapping application is expected to benefit from RADARSAT-2's SDP, QP and Ultra-Fine resolution mode (see Table 1). Sokol and Pultz (2004) present a detailed review of the utility of RADARSAT-2 type data for hydrology.

It is well known that the radar return signal of a soil surface is a function of both the soil's moisture content and effective surface roughness. Hence, reliable mapping of soil moisture with the help of SAR images requires information about the soil surface roughness and vice versa. SAR-assisted assessment of both soil moisture and soil surface roughness is feasible with systems that can provide a minimum of two independent observations, i.e. measure backscatter in two or more polarizations. A combination of HH- and VV-polarized signals constitutes the preferred polarization combination for soil moisture (and soil roughness) mapping. This results from the fact that HH-polarized radar signals and, to a lesser extent, VV-polarized radar signals have the best capacity to penetrate overlying vegetation cover. The foregoing explains the anticipated effect of the QP mode on the potential of RADARSAT-2 for application to soil moisture mapping. Given the narrow swath width of the QP mode (25 km nominally), it is unfortunate that RADARSAT-2 will not have the capability to acquire a combination of HH- and VV-polarized images in the SDP mode. The swath width of images that can be acquired in the SDP mode will range from about 50 km in the Fine spatial resolution mode to about 500 km in the ScanSAR Wide mode. RADARSAT-2's selective look direction feature potentially increases the revisit frequency in all but the most northerly regions on Earth. A capacity to map soil moisture more frequently should facilitate the work of water resource managers, for example, by providing more frequent and more up-to-date input for hydrological and crop-growth models. It must be noted that RADARSAT-2 data will support the mapping of moisture in the upper soil layers only. This is due to the limited penetration depth at C-band.

The positive effect of RADARSAT-2's QP mode on its potential for application to the mapping of snow can be explained from the greater information content of full polarimetric radar data concerning the snow pack. Sokol *et al.* (2004) report that parameters derived from polarimetric radar data can provide information on snow state (wet/dry) and complexities (e.g. ice layers) in the snow pack structure. Knowledge of these conditions can be used to improve the mapping of an important snow parameter, i.e. snow water equivalent (SWE). Typically, SWE is mapped on the basis of brightness temperature recorded by microwave radiometers. Temporal information on snow state can also be used as an indicator of the onset of snowmelt. Onset of snowmelt and SWE are important variables for activities such as flood forecasting and reservoir management. Once again, the selective look direction feature has the potential to improve the quality of the information on snow cover by providing more frequent imaging and thus mapping opportunities.

The wetland mapping application is anticipated to benefit from RADARSAT-2's SDP and QP modes because of the enhanced sensitivity of dual-polarized and full polarimetric radar data to the structural characteristics of the target observed. The structural characteristics of wetlands are governed by the structure of the vegetation and the presence/absence of water. Please refer to the section on agriculture for a discussion concerning the relationship between microwave polarization and vegetation structure. The presence of water leads to the dominance of the double-bounce scattering mechanism. Full polarimetric radar data facilitate the classification of scattering mechanisms and as such provide increased information content in support of wetland mapping. RADARSAT-2's Ultra-Fine resolution data can be expected to facilitate the mapping of smaller wetland units. In addition, the greater spatial information content in these data will enhance the potential of wetland mapping on the basis of image texture.

Oceans

With the exception of the waves application, all oceans applications identified are anticipated to moderately benefit from the introduction of RADARSAT-2. The potential of both RADARSAT-1 and RADARSAT-2 for the waves application can be seen to halt at the 'limited' rating. This can be explained from the satellites' polar orbit, which restricts the information content of the images acquired to specific ranges of the total available ocean wave spectrum (e.g. Vachon *et al.*, 1997; Dowd *et al.*, 2000). Even so, the capability of RADARSAT-2 to simultaneously acquire HH- and VV-polarized data in the QP mode can be considered a technical enhancement that benefits the wave application. As reported by Engen *et al.* (2000), the combination of HH- and VV-polarized images permits more accurate and more complete retrieval of ocean wave spectra.

The added capability to acquire VV-polarized images explains the increase in application potential for wind speed retrieval from 'moderate' for RADARSAT-1 to 'strong' for RADARSAT-2. Compared to HH-polarized data, VV-polarized data offer a better signal-to-noise ratio for higher incidence angles in particular. This will be especially beneficial for the extraction of lower wind speeds. In addition, existing models for wind speed retrieval from VV-polarized data are more mature than those developed for HH-polarized data (cf. Vachon *et al*., 2004). The benefit of the VV imaging capability for wind speed retrieval is acknowledged in the rating for RADARSAT-2's SSP mode only. Indeed, the SDP and QP mode can be used to acquire VV-polarized images but the data volume of the associated images needlessly complicates image handling and thus hinders the application.

Like wind speed retrieval, the mapping of ocean currents is anticipated to benefit from the introduction of the SSP mode. Ocean currents may appear in SAR images through several mechanisms (Johannessen *et al*., 1996). Natural surfactants are known to express spiral eddies and to concentrate in zones parallel to the mean flow direction. VV-polarized images will provide a better contrast between natural surfactants and water and can therefore be expected to provide better potential for this indirect approach to current mapping. On the other hand, meandering fronts may appear in SAR images due to short wave-current interactions that locally modify the surface roughness. According to Ufermann and Romeiser (1999), the effect of this type of interaction is more apparent in HH-polarized images than in VV-polarized images. It follows, that the polarization diversity offered in the RADARSAT-2 SSP mode will benefit the ocean current mapping application. The applications potential associated with full polarimetric data is largely unknown but it is likely that this data type will be beneficial to improving the understanding of the imaging of ocean currents.

The potential for ship detection and tracking increases from 'moderate' for RADARSAT-1 to 'strong' for RADARSAT-2. As shown in Table 1, all new RADARSAT-2 features are expected to contribute to this increase in applications potential. The most important technical enhancement for the tracking of previously detected ships is the Ultra-Fine resolution mode (nominal resolution 3 m by 3 m). Imagery from this mode will allow a more detailed analysis of ship structures and should facilitate the estimation of ship type, size and orientation. However, the high spatial resolution comes at the expense of spatial coverage. The limited swath width (20 km nominally) of the Ultra-Fine resolution data precludes its operational use for the detection of ships over extensive areas.

Full polarimetric images acquired in the QP mode have similar limitations in terms of coverage (nominal swath width 25 km) and are therefore also better suited for operational application to the tracking of known ships than to ship detection over large areas. On the other hand, full polarimetric data have been shown to facilitate the enhancement of ship-sea contrast. A better ship-sea contrast will improve results of ship detection by reducing errors of omission (cf. Touzi *et al*., 2004a). The information in full polarimetric data pertaining to microwave scattering mechanisms has the potential to improve ship detection results because it can be used to facilitate discrimination between ships and ship look-alikes (e.g. protruding rocks or icebergs). In addition, this type of scattering information is expected to be of value for ship classification.

With the introduction of the SSP and SDP modes, RADARSAT-2 will be in a better position to support the two basic approaches to ship detection using SAR, that is, detection of the ship wake signature and detection of the ship target itself. Thanks to a greater sensitivity to sea state, VV-polarized images offer better potential for ship wake detection than either HH- or HV-polarized images. At the same time, this sensitivity to sea state decreases the ship-sea contrast in VV-polarized images as compared to the contrast in HH- and HV-polarized images. Hence, HH- and HV-polarized images are the better choice for the detection of ship targets. HH-polarized images will show the best ship-sea contrast at large incidence angles (> ca. 35°), while HV-polarized images will do so at small angles of incidence. It follows that a combination of VV and VH-polarized images can be expected to offer good potential for ship detection because these data support both ship detection approaches. This combination of images can be acquired in the RADARSAT-2 SDP mode.

The benefits of the selective look direction and improved orbit control features for ship detection are easily explained. The selective look direction potentially facilitates more continuous ship detection by increasing the number of imaging opportunities, while the improved orbit control will simplify the extraction of accurate geographic coordinates for ships detected.

The moderate increase in the overall applications potential of RADARSAT-2 vis-à-vis RADARSAT-1 for coastal zone mapping results from the enhancements in terms of polarization diversity and spatial resolution. The capacity to acquire HV-polarized data in the SSP mode is anticipated to improve the potential for the mapping of the high water shoreline. Unlike in HH and VV images, the land-water contrast in HV images will be largely unaffected by the angle of incidence and high wind conditions. The SDP and QP modes of operation will enable RADARSAT-2 to detect structural differences in the features observed, e.g. differences in vegetation cover/type and soil surface roughness. As such, these modes facilitate the mapping of land cover in coastal zones. Please refer to the preceding sections on agriculture, geology and hydrology (wetlands) for discussions regarding the relationships between microwave polarization and the structure of natural targets. The potential of the SSP, SDP and QP modes for the mapping of near-shore bathymetry is largely unknown. However, results reported by Ufermann and Romeiser (1999) indicate that HH- and HV-polarized images are more suited for application to bathymetric mapping than VV-polarized images. The Ultra-Fine spatial resolution images can be expected to enable more detailed shoreline and land cover mapping. Moreover, these images will make a better source of information for coastal mapping by means of textural analysis.

Sea and Land Ice

Table 2 shows that the introduction of RADARSAT-2 is anticipated to increase the overall potential for all applications identified with the exception of the mapping of sea ice types. Indeed, sea ice topography and structure mapping is among the three applications that are expected to benefit the most from the technical enhancements embodied by RADARSAT-2. The (anticipated) potential for this application increases from 'limited' for RADARSAT-1 to 'strong' for RADARSAT-2. This increase in applications potential results primarily from RADARSAT-2's capability to acquire HV-polarized images in the SSP mode. Compared to HH- and VV-polarized images, HV-polarized images are more suited to the mapping of ice surface topography and structural features resulting from ridging or other types of deformation. Consequently, HV-polarized images offer better potential for the routing of ships around hazardous sea ice areas. RADARSAT-2 QP mode data products are likely to display even more sensitivity to ice topography and structure. However, the value of this data type for operational sea ice mapping is limited by its narrow swath width (nominally 25 km). The difference in the information content between images acquired in the SSP and SDP modes is not expected to be significant. The lower rating for the SDP mode can be explained from the redundancy in data volume. The potential increase in revisit frequency resulting from the capability to switch from left- and right-looking would be of benefit to sea ice mapping/monitoring at mid-latitudes where the current revisit with RADARSAT-1 is every 2 to 3 days.

Like in the case of sea ice topography and structure mapping, the increase in application potential for sea ice edge and ice concentration mapping results mostly from the HV imaging capability in the SSP mode. Unlike in HH and VV images, the ice-water contrast in HV images will be largely unaffected by the angle of incidence and high wind conditions. Consequently, HV images can be expected to offer improved potential for sea ice edge and ice concentration mapping (cf. Flett *et al.*, 2004). Full polarimetric data products as acquired in the QP mode of operation can likely be manipulated to enhance the ice-water contrast to a level above that of HV data. However, as mentioned before, the value of this data type for operational application to sea ice is limited by the swath width. The promise of the selective look direction feature for applications potential was discussed above.

Data from single frequency and single polarization SAR systems like RADARSAT-1 are known to offer moderate potential for the mapping of multi-year and first-year ice types. On the other hand, this type of data has shown little promise as a source of information for discrimination of thin/new ice and open water. According to Drinkwater *et al*. (1991) and Thomsen *et al*. (1998), C-band full polarimetric data, that is, the type of data acquired in RADARSAT-2's QP mode, offer considerably more potential for sea ice type mapping. For example, a polarimetric parameter known as the co-polarization phase difference is reported to allow for separating water from a range of thin ice types. As mentioned before, the value of the QP data products for operational mapping of ice types is limited by the narrow swath width.

Icebergs, like ships, manifest themselves in radar images as bright point targets against a dark background of ocean clutter. Consequently, much of the ratings in Table 1, and justifications thereof, for icebergs and ships are identical. Only the effect of SDP feature rates differently, i.e. 'minor' for icebergs and 'moderate' for ship detection. In the case of iceberg detection, a dual-polarization image pair (e.g. VV and VH) is not expected to contain any more relevant information than a single VH-polarized image. Ship detection, on the other hand, will benefit from the capability to acquire images in the SDP mode since ship targets often have higher contrast in VH-polarization while ship wakes are most evident in VV-polarization. Generally speaking, iceberg detection by means of SAR creates a bigger challenge than ship detection. This is reflected in the applications potential ratings for both RADARSAT-1 and RADARSAT-2 in Table 2. Differences in material, shape, and size as well as the effects of environmental conditions on the radar signature of icebergs contribute to this discrepancy in applications potential.

By far the most beneficial feature of RADARSAT-2 for the polar glaciology application is its selective look direction. The ability to easily change from right- to left-looking will enable RADARSAT-2 to image parts of Antarctica not accessible by other high-resolution remote sensing satellites. As such, RADARSAT-2 will facilitate the study of Antarctic ice flows and floating ice shelves in a way and at a scale not previously possible. The capability to acquire cross-polarized data in the SSP mode and full polarimetric data in the QP mode is likely to benefit the application since these data types are more sensitive to differences in both surficial and internal ice structure. However, more research is required to assess the potential for application to polar glaciology of full polarimetric C-band data in particular. Repeat-pass SAR interferometry techniques have been shown to yield information on ice motion (e.g. Gray *et al.*, 2001; Short and Gray, 2004). Thanks to improved orbit control RADARSAT-2 can be expected to offer better interferometric capabilities than RADARSAT-1.

Summary

RADARSAT-2's Selective Single Polarization (SSP) mode is shown to moderately advance the potential for applications for which information needs can generally be met by single channel C-band data, but for which the HH-polarization as offered by RADARSAT-1 is not the most favourable. As a rule, the information needs associated with hurricanes, oil spills, and winds are better met through application of VV-polarized images. Similarly, the requirements pertaining to clearcuts, fire-scars, ships, and selected sea and land ice applications are more easily satisfied when HV or VH images can be applied. On the other hand, the current application can benefit from information contained in both HH- and VV-polarized images.

The capability to operate in the Selective Dual Polarization (SDP) mode is projected to moderately improve the potential of RADARSAT-2 to provide information in support of applications dealing with targets that include transparent (at C-band) vegetation volumes with varying structural properties or land surfaces with varying degrees of roughness. The hurricanes, oil spills, clearcuts, fire-scars, winds, current and sea and land ice applications are expected to gain little information from SDP image acquisitions. In fact, the larger data volume of SDP products is anticipated to burden these applications in terms of data handling.

Data acquired in the Quad Polarization (QP) mode will facilitate the computation of a wide variety of variables that relate to the strength, polarization or phase of the received backscatter signal. Introduction of this imaging mode is expected to moderately advance the potential of RADARSAT-2 for most of the applications identified. The QP mode data are anticipated to be particularly valuable or essential for the crop type, crop condition, DEM polarimetry, and search & rescue applications. On the other hand, the oil spills, clearcuts, fire-scars, winds and currents applications are not expected to benefit from the QP mode imaging capability. Due to technical limitations, the swath width of the images acquired in the QP mode is restricted to 25 km (nominally). This will definitely constrain the operational use of QP mode data in support of applications that require information over large areas, e.g. forestry, oceans and sea ice applications.

RADARSAT-2's capacity to acquire images with Ultra-Fine spatial resolutions is restricted to the SSP imaging mode. The expectation is that this capability will be most beneficial to cartographic applications and applications dealing with point targets, that is, ship and iceberg detection. In addition, a considerable number of applications are foreseen to moderately benefit from Ultra-Fine resolution space-borne SAR data. Like QP data products, Ultra-Fine resolution data products will have a limited swath width (20 km nominally). Again, this can be expected to obstruct the operational use of this data type in certain applications.

The selective look direction feature of RADARSAT-2 is anticipated to have a major effect on its potential for applications in the fields of disaster management and polar glaciology. Disaster management applications will benefit form the reduced average response time and the generally increased revisit frequency. On the other hand, the polar glaciology application will gain from the fact that the left-looking configuration will enable routine imaging of the most southerly regions on Earth including Antarctica. Applications concerned with crop condition, soil moisture, snow, ships, icebergs and sea ice are expected to benefit from the selective look direction capability in a more moderate fashion.

Improved knowledge about and control over the RADARSAT-2 orbit will lead to enhanced potential of its images for applications that make use of interferometric processing techniques in particular. This includes applications dealing with DEM interferometry, geological hazards, search and rescue, terrain mapping and polar glaciology. Applications such as DEM stereoscopy, DEM polarimetric, cartographic feature extraction, search and rescue, and ship and iceberg detection will moderately benefit from the associated improved image georeferencing accuracy.

Comparison of ratings for the overall applications potential of RADARSAT-1 and RADARSAT-2 (anticipated) shows that the technical enhancements of RADARSAT-2 will be most beneficial to applications concerned with crop type, crop condition, and sea ice topography / structure. The improvement in overall potential for these three applications, from 'limited' for RADARSAT-1 to 'strong' for RADARSAT-2, results primarily from the enhancements in terms of polarization. For 18 out of the 32 applications identified, the introduction of RADARSAT-2 is anticipated to result in a moderate increase in applications potential, i.e. an increase in potential vis-à-vis RADARSAT-1 by one level. The technical enhancements that lead to these improvements in potential may differ depending on the application. The number of applications for which no increase in applications potential is foreseen amounts to ten. This 'no increase' group of applications includes the DEM stereoscopy and flood mapping, that is, applications for which the potential of RADARSAT-1 is already ranked at the highest level. The application potential for DEM interferometry and hurricanes stalls at the 'moderate' rating because of restraints imposed by atmospheric conditions and swath width, respectively. Orbital characteristics of RADARSAT-1 and RADARSAT-2 restrict the potential for the waves application to a 'limited' rating. Generally speaking, the information requirements of other applications in the 'no increase' group are better met by low- or multi-frequency SAR systems (e.g. forest type, forest biomass, sea ice type) or by optical remote sensing systems (e.g. oil spills, lithology). The potential of RADARSAT-2 for the one remaining application, that is, DEM polarimetry is rated as ‘limited’. DEMs produced from full polarimetric RADARSAT-2 data will not be complete since the elevation information will only be available in two specific directions, i.e. the azimuth directions of ascending and descending overpasses.

Acknowledgements

The author wishes to acknowledge the contributions of the following colleagues to the report that provided the basis for this paper (van der Sanden and Ross, 2001): Paul Budkewitsch, Dean Flett, Laurence Gray, Robert Hawkins, Shannon Kaya, Robert Landry, Tom Lukowski, Heather McNairn, Terry Pultz, Vern Singhroy, Jennifer Sokol, Thierry Toutin, Ridha Touzi, and Paris Vachon. In addition, he would like to thank Sylvia Thomas as the internal reviewer and the two anonymous external reviewers for their advice and comments on the manuscript.

References

Ahern, F.J. and J.A. Drieman. (1988). "Assessment of clearcut mapping accuracy with C-band SAR", In: *Proceedings of the IGARSS 1988 Symposium; Remote Sensing: Moving Towards the 21st Century*, Edinburgh, 12-16 September 1988, Vol. III, pp. 1335-1338.

Ali, Z., I. Barnard, P. Fox, P. Duggan, R. Gray, P. Allan, A. Brand, and R. Ste-Mari. (2004a). "The RADARSAT-2 Synthetic Aperture Radar design description", *Canadian Journal of Remote Sensing*, this issue.

Ali, Z., G. Kroupnik, G. Matharu, J. Graham, I. Barnard, P. Fox, and G. Raimondo. (2004b). "RADARSAT-2 space segment design and enhanced capabilities from RADARSAT-1", *Canadian Journal of Remote Sensing*, this issue.

Braun, N., M. Gade, and G. Schymura. (2000). "Multi-frequency/multi-polarization measurements of radar backscatter under different rain and wind conditions", In: *Proceedings of the IGARSS 2000 Symposium; Taking the Pulse of the Planet: The Role of Remote Sensing in Managing the Environment*, Honolulu, 24-28 July 2000, Vol. 1, pp. 123-125.

Buckley, J. (2004). "Enhanced classification of prairie landscapes using simulated RADARSAT-2 imagery", *Canadian Journal of Remote Sensing*, this issue.

CCRS. (2004). RADARSAT-2 Demonstration Website, http://www.ccrs.nrcan.gc.ca/ccrs/data/satsens/radarsat/r2demo/r2demo_e.html.

Dobson, M.C., F.T. Ulaby, T. Le Toan, A. Beaudoin, E.S. Kasischke, and N.L. Christensen. (1992). "Dependence of radar backscatter on coniferous forest biomass", *IEEE Transactions on Geoscience and Remote Sensing*, Vol. 30, No. 2, pp. 412-415.

Dowd, M., P.W. Vachon, F.W. Dobson, and R.B. Olsen. (2001). "Ocean wave extraction from RADARSAT synthetic aperture radar inter-look image cross-spectra", *IEEE Transactions on Geoscience and Remote Sensing*, Vol. 39, No. 1, pp. 21-37.

Drinkwater, M.R., R. Kwok, D.P. Winebrenner, and E. Rignot. (1991). "Multifrequency polarimetric synthetic aperture radar observations of sea ice", *Journal of Geophysical Research*, Vol. 96, No. C11, pp. 20,679-20,698.

Engen, G., P.W. Vachon, H. Johnson, and F.W. Dobson. (2000). "Retrieval of ocean wave spectra and RAR MTFs from dual-polarization SAR data", *IEEE Transactions on Geoscience and Remote Sensing*, Vol. 38, No. 1, pp. 391-403.

Flett, D., B. Scheuchl, and R. Caves. (2004). "Potential of RADARSAT-2 multiple polarization and polarimetric data for operational sea ice monitoring", *Canadian Journal of Remote Sensing*, this issue.

Fox, P., A. Luscombe, and A. Thompson. (2004). "SAR mode development and utilization", *Canadian Journal of Remote Sensing*, this issue.

Gaddis, L. (1992). "Lava-flow characterization at Pisgah volcanic field, California, with multiparameter imaging radar", *Bulletin of the Geological Society of America*, Vol. 104, pp. 695-703.

Gray, A.L., N. Short, K.E. Mattar, and K.C. Jezek. (2001). "Velocities and flux of the Filchner Ice Shelf and its tributaries determined from speckle tracking Interferometry", *Canadian Journal of Remote Sensing*, Vol. 27, No. 3, pp. 193-206.

Huadong, G., L. Jingjuan, W. Changlin, W. Chao, T.G. Farr, and D.L. Evans. (1997). "Use of multifrequency, multipolarization Shuttle Imaging Radar for volcano mapping in the Kunlun Mountains of Western China", *Remote Sensing of Environment*, Vol. 59, No. 4, pp. 364-374.

Johannessen, J.A., R.A. Shuchman, D.R. Lyzenga, C. Wackerman, O.M. Johannessen, and P.W. Vachon. (1996). "Coastal ocean fronts and eddies imaged with ERS-1 synthetic aperture radar", *Journal of Geophysical Research*, Vol. 101, No. C3, pp. 6651-6667.

Kneppeck, I.D. and F.J. Ahern. (1989). "Stratification of a regenerating burned forest in Alberta using Thematic Mapper and C-SAR images", In: *Proceedings of the IGARSS 1989 Symposium; Quantitative Remote Sensing: An Economic Tool for the Nineties*, Vancouver, 10-14 July 1989, Vol. III, pp. 1391-1396.

Le Toan, T., A. Beaudoin, J. Riom, and D. Guyon. (1992). "Relating forest biomass to SAR data", *IEEE Transactions on Geoscience and Remote Sensing*, Vol. 30, No. 2, pp. 403-411.

Lukowski, T.I., B. Yue, F.J. Charbonneau, F. Khellah, and R.K. Hawkins. (2004). "Detection of crashed aircraft in polarimetric imagery: studies at Natural Resources Canada", *Canadian Journal of Remote Sensing*, this issue.

MacKay, M.E. and P.J. Mouginis-Mark. (1997). "The effect of varying acquisition parameters on the interpretation of SIR-C radar data: the Virunga volcanic chain", *Remote Sensing of Environment*, Vol. 59, No. 2, pp. 321-336.

Mattia, F., T. Le Toan, J.C. Souyris, G. De Carolis, N. Floury, F. Posa, and G. Pasquariello. (1997). "The effect of surface roughness on multifrequency polarimetric SAR data", *IEEE Transactions on Geoscience and Remote Sensing*, Vol. 35, No. 4, pp. 954-965.

McNairn, H. and B. Brisco. (2004). "The application of polarimetric SAR for agriculture", *Canadian Journal of Remote Sensing*, this issue.

McNairn, H., K. Hochheim, and N. Rabe. (2004). "Applying polarimetric radar imagery for wheat condition mapping", *Canadian Journal of Remote Sensing*, this issue.

Morena, L., K. James, and J. Beck. (2004). "An introduction to the RADARSAT-2 mission", *Canadian Journal of Remote Sensing*, this issue.

Schaber, G.G., J.F. McCauley, and C.S. Breed. (1998). "The use of multifrequency and polarimetric SIR-C/X SAR data in geologic studies of Bir Safsaf, Egypt", *Remote Sensing of Environment*, Vol. 59, No. 4, pp. 337-363.

Schuler, D.L., J.S. Lee, D. Kasilingam, and G. Nesti. (2002). "Surface roughness and slope measurements using polarimetric SAR data", *IEEE Transactions on Geoscience and Remote Sensing*, Vol. 40, No. 3, pp. 687-698.

Short, N. and A.L. Gray. (2004). "Potential of RADARSAT-2 interferometry: glacier monitoring using speckle tracking", *Canadian Journal of Remote Sensing*, this issue.

....Singhroy, V. (1996). "Environmental and geological site characterization in vegetated areas: image enhancement guidelines", In: V.Singhroy, D.Nebert, & A.Johnson (Eds.), Remote Sensing and GIS: Applications and Standards, American Society for Testing and Materials, pp. 5-17.

Sokol, J. and T.J. Pultz. (2004). "Case studies demonstrating hydrological applications of C-band multi-polarized and polarimetric SAR", *Canadian Journal of Remote Sensing*, this issue.

Sokol, J., T.J. Pultz, and A.E. Walker. (2004). "Passive and active airborne microwave remote sensing of snow cover", *International Journal of Remote Sensing*, in press.

Thomsen, B.B., S.V. Nghiem, and R. Kwok. (1998). "Polarimetric C-band SAR observations of sea ice in the Greenland Sea", In: *Proceedings of the IGARSS 1998 Symposium; Sensing and Managing the Environment*, Seattle, 6-10 July 1998, Vol. V, pp. 2502-2504.

Toutin, T. (2004). "Evaluation of mapping potential of RADARSAT-2", *Canadian Journal of Remote Sensing*, this issue.

Touzi, R., F.J. Charbonneau, R.K. Hawkins, and P.W. Vachon. (2004a). "Ship detection and characterization using polarimetric SAR", *Canadian Journal of Remote Sensing*, this issue.

Touzi, R., R. Landry, and F.J. Charbonneau. (2004b). "Forest type discrimination using calibrated C-band polarimetric SAR data", *Canadian Journal of Remote Sensing*, this issue.

Ufermann, S. and R. Romeiser. (1999). "Numerical study on signatures of atmospheric convective cells in radar images of the ocean", *Journal of Geophysical Research*, Vol. 104, No. C11, pp. 25,707-25,719.

Vachon, P.W., J.W.M. Campbell, and F.W. Dobson. (1997). "Comparison of ERS and RADARSAT SARs for wind and wave measurement", In: *Proceedings of the 3rd ERS Symposium on Space at the Service of our Environment*, Florence, 17-21 March 1997, Vol. 3, pp. 1367-1372.

Vachon, P.W., J. Wolfe, and R.K. Hawkins. (2004). "Comparison of C-band wind retrieval model functions with airborne polarimetric SAR data", *Canadian Journal of Remote Sensing*, this issue.

van der Sanden, J.J. and S.G. Ross. (2001). *Applications Potential of RADARSAT-2 - A Preview.* Ottawa, Natural Resources Canada, Canada Centre for Remote Sensing, 117 p. (http://dweb.ccrs.nrcan.gc.ca/ccrs/db/biblio/paper_e.cfm?BiblioID=13103)

Table 1. Anticipated effect of new RADARSAT-2 features on applications potential in terms of data information content. Key: '-' minor, '-/+' moderate, '+' major.

Table 2. Applications potential [1] of RADARSAT-1 and RADARSAT-2. Key: '-' minimal, '-/+' limited, '+' moderate, '++' strong.

	RADARSAT-2 Feature						Satellite	
Application	**Selective Single Polarization (SSP)**	**Selective Dual Polarization (SDP)**	**Quad Polarization (QP)**	**Ultra-Fine Spatial Resolution**	**Selective Look Direction**	**Improved Orbit Control**	**RADARSAT-1**	**RADARSAT-2**
Agriculture								
Crop type	-	-/+	+	-	-	-	-/+	++
Crop condition	-	-/+	+	-/+	-/+	-	-/+	++
Crop yield	-	-	-/+	-/+	-	-	-	-/+
Cartography								
DEM interferometry	-	-	-	+	-	+	+	+
DEM stereoscopy	-	-	-	+	-	-/+	++	++
DEM polarimetry	N.A.	N.A.	+	N.A.	-	-/+	N.A.	-/+
Cartographic feature extraction	-	-	-/+	+	-	-/+	+	++
Disaster Management								
Floods	-	-	-	-	+	-	++	++
Geological hazards	-	-/+	-/+	-/+	+	- (+)[1]	-/+	+
Hurricanes	-/+	-	-/+	-	+	-	+	+
Oil spills	-/+	-	-	-/+	+	-	+	+
Search and rescue	-	-	+	-/+	+	-/+ (+)[1]	-/+	+
Forestry								
Forest type	-	-	-/+	-/+	-	-	-/+	-/+
Clearcuts	-/+	-	-	-/+	-	-	-/+	+
Fire-scars	-/+	-	-	-/+	-	-	-/+	+
Biomass	-	-	-	-	-	-	-	-
Geology								
Terrain mapping	-	-/+	-/+	-/+	-	- (+)[1]	-/+	+
Structure	-	-/+	-/+	-/+	-	-	+	++
Lithology	-	-	-	-	-	-	-/+	-/+
Hydrology								
Soil moisture	-	-	-/+	-	-/+	-	-/+	+
Snow	-	-	-/+	-	-/+	-	-/+	+
Wetlands	-	-/+	-/+	-/+	-	-	-/+	+
Oceans								
Winds	-/+	-	-	-	-	-	+	++
Ships	-/+	-/+	-/+	+	-/+	-/+	+	++
Waves	-	-	-/+	-	-	-	-/+	-/+
Currents	-/+	-	-	-	-	-	-/+	+
Coastal zones	-/+	-/+	-/+	-/+	-	-	-/+	+
Sea and Land Ice								
Sea ice edge and ice concentration	-/+	-	-/+	-	-/+	-	+	++
Sea ice type	-	-	-/+	-	-	-	+	+
Sea ice topography and structure	-/+	-	-/+	-	-/+	-	-/+	++
Icebergs	-/+	-	-/+	+	-/+	-/+	-/+	+
Polar glaciology	-/+	-	-/+	-	+	- (+)[1]	-/+	+

1) Using InSAR techniques (Table 1)

1) Use of single date images assumed (Table 2)