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Potential of RADARSAT-2 data for operational sea ice monitoring

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Abstract. Synthetic aperture radar (SAR) data from RADARSAT-1 are an important operational data source for several ice centres around the world. Whereas RADARSAT-1 is only capable of acquiring data at a single polarization, RADARSAT-2 will be capable of acquiring dual-polarization data in many wide-swath modes (most importantly ScanSAR) and fully polarimetric SAR data in a narrow 25-km swath mode. In this paper, we consider the ice information requirements for operational sea ice monitoring at the Canadian Ice Service and the potential for RADARSAT-2 to meet those requirements. Primary parameters are ice-edge location, ice concentration, and stage of development; secondary parameters include leads, ice thickness, ice topography and roughness, ice decay, and snow properties. Iceberg detection is included as an additional ice information requirement. The dual and fully polarimetric modes of RADARSAT-2 are expected to enhance our ability to measure these parameters. For ice operations, the dual-polarization data are expected to be most useful, as they will provide the required wide coverage in a number of modes. Although ScanSAR is the recommended mode of operation, the properties of other modes are also discussed. To illustrate the expected improvements from polarimetry, we review the conclusions of past work and add some new results using ENVISAT ASAR and simulated RADARSAT-2 data.

Résumé. Les données RSO de RADARSAT-1 constituent une source de données opérationnelles importante pour plusieurs services des glaces autour du monde. Alors que RADARSAT-1 n'est capable d'acquérir des données qu'en fonction d'une seule polarisation, RADARSAT-2 sera capable d'acquérir des données en polarisation double, dans plusieurs modes à faisceau large (le plus important étant le mode ScanSAR) et des données RSO polarimétriques dans un mode faisceau étroit de 25 km. Dans cet article, nous examinons les besoins en information sur la glace pour le suivi opérationnel de la glace de mer au Service canadien des glaces et la capacité de RADARSAT-2 à combler ces besoins. Les paramètres primaires sont la localisation de la limite de la glace, la concentration de la glace et le stade de développement de la glace alors que les paramètres secondaires comprennent les chenaux, l'épaisseur de la glace, la topographie et la rugosité de la glace, la désagrégation de la glace et les propriétés de la neige. La détection des icebergs est incluse à titre de besoin additionnel au plan de l'information sur la glace. Les modes en polarisation double et polarimétrique de RADARSAT-2 devraient améliorer notre capacité à mesurer ces paramètres. Pour les opérations sur la glace, les données à polarisation double devraient être très utiles étant donné qu'elles fourniront la couverture large requise pour un certain nombre de modes. Quoique le mode ScanSAR soit le mode d'opération recommandé, on discute également des propriétés des autres modes. Pour illustrer les améliorations prévues au plan de la polarimétrie, nous passons en revue les conclusions de travaux antérieurs et nous présentons de nouveaux résultats à l'aide des données ASAR d'ENVISAT et des données simulées de RADARSAT-2.
[Traduit par la Rédaction]

Introduction

RADARSAT-1 has been a primary source of synthetic aperture radar (SAR) data for sea ice monitoring since it became operational in 1996. This has revolutionized the way in which several national ice monitoring agencies now operate. For example, the United States National Ice Center (NIC) use of RADARSAT-1 data has approached 6000 scenes annually to meet their global ice mapping objectives, and the Canadian Ice Service (CIS) has consumed, on average, between 3500 and 4500 scenes annually covering Canadian waters.

With the future launch of RADARSAT-2, the CIS is looking forward to continuity of RADARSAT-1 data to meet its operational needs. RADARSAT-2 will offer the entire suite of legacy beams of RADARSAT-1. Besides data continuity, RADARSAT-2 promises several enhancements to the payload and the space and ground segments (see this RADARSAT-2 special issue of the *Canadian Journal of Remote Sensing*, Vol. 30, No. 3). Ramsay et al. (2004) summarize the potential benefits of a number of these enhancements for operational ice monitoring. The space segment will offer higher resolution, multiple polarization, and fully polarimetric modes. The capability of RADARSAT-2 to measure two or four polarizations is expected to enhance the measurement of parameters (e.g., ice-edge location, ice concentration, stage of development) that are important for operational ice monitoring. The focus of this paper is on the potential of some of these modes for meeting operational ice information requirements, with an emphasis on dual polarization.

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Previous studies of the potential of dual-polarization and fully polarimetric SAR data for sea ice monitoring have been limited to a small number of datasets. The most authoritative are based on fully polarimetric data acquired by the Jet Propulsion Laboratory (JPL) AIRSAR system over the Beaufort and Bering seas during 1988 along with extensive ground truth (Rignot and Drinkwater, 1994; Nghiem et al., 1995; Rignot et al., 1992). Several other studies have been conducted using data from the Danish EMISAR (Skriver and Pedersen, 1995; Thomsen et al., 1998) and the Canadian Convair-580 SAR system (Livingstone et al., 1996; Scheuchl et al., 2003a; 2003b). The SIR-C mission in 1994 was the first to acquire fully polarimetric spaceborne SAR data over sea ice. These images have been studied by Eriksson et al. (1998) and Scheuchl et al. (2001a; 2001b). In 2002, ENVISAT ASAR came into operation. The first results using its alternating polarization data are reported by De Abreu et al. (2003).

These results are not a fully representative indication of RADARSAT-2 performance, however, because of the differing noise level, incidence angle, resolution, and coverage area of these sensors. These differences are more pronounced in the case of airborne SARs, which generally have finer resolution and lower noise levels but cover less area than spaceborne SARs.

In this paper, we first identify the key ice information requirements for operations at the CIS. Second, we briefly review the current use of RADARSAT-1 single-polarization data as the primary information source. Expected improvements for sea ice monitoring using RADARSAT-2 are discussed, emphasizing the advantages of dual and fully polarimetric data. Examples of real ENVISAT ASAR data and simulated RADARSAT-2 polarimetric data are used to illustrate some of these points. We conclude with recommendations for the use of RADARSAT-2 data.

Ice information requirements

Ice information requirements span a variety of temporal and spatial scales and a range of geographical zones and seasons, and thus vary with the specific application and situation. The Canadian Ice Service, Ice and Marine Services Branch of the Meteorological Service of Canada, has a mandate to provide ice information to support safe marine navigation and operations in Canadian waters. Ramsay et al. (1993) summarize sea ice information requirements from the operational perspective in the context of RADARSAT-1, and Barber et al. (1992) summarize ice information requirements from the science viewpoint. The science and operational requirements overlap to a large extent, differing primarily in the spatial and temporal scales. In this paper, we focus primarily on the operational ice information requirements as identified by the CIS.

Sea ice information requirements for operations and navigation are often categorized into two types, strategic and tactical, which differ in their scale and timeliness (Ramsay et al., 1993; Hirose, 1991). **Table 1** summarizes the parameters that are important for both types, which depend on the particular situation or application. For the purposes of this table, strategic refers to the level of detail and information required for the preparation of a Canadian Ice Service Daily Ice Analysis Chart, an example of which is given in **Figure 1**. Tactical refers to the level of detail and information required to support daily operations and ship navigation in ice. As an example of the use of strategic and tactical levels of information, the CIS deploys ice service specialist (ISS) field personnel onboard the Canadian Coast Guard icebreakers. The ISS can use the Daily Ice Analysis Chart to assist the captain in preliminary route planning. In contrast, tactical information of finer detail is collected in the vicinity of the vessel, e.g., by helicopters, to support immediate operations. Some airborne and spaceborne imagery potentially meets tactical requirements and can be used if available. In addition to information on sea ice, the detection and tracking of icebergs are part of the CIS mandate and are included here as a separate requirement.

Daily coverage of an area is important for many ice information requirements, in particular, all primary requirements as outlined in **Table 1**. Generally, this requires wide-swath imaging, as provided by RADARSAT ScanSAR modes, whose spatial resolution of 50–100 m satisfies strategic and many tactical requirements. ScanSAR wide is more suited for regular wide-area monitoring, and ScanSAR narrow is preferable for monitoring areas requiring a greater level of detail.

Single-beam modes can be used for monitoring tasks requiring higher resolutions, for example, monitoring busy shipping routes and iceberg detection. The tradeoffs for increased detail are reduced area coverage and less frequent revisit times. The wider swath, single-beam modes (wide and standard) are preferred over the fine mode to optimize coverage. In terms of incidence angle, modes providing shallower incidence angles (e.g., S3–S7, W2–W3) are more suited for detecting the ice edge and icebergs with copolarization, particularly in rough seas. However, time-critical considerations will limit the incidence angle choice for an area of interest.

Primary ice information requirements

The first and primary task for sea ice mapping is to identify the location of the boundary between ice and open water (the ice edge) with sufficient spatial coverage and temporal repetition. Generally, the backscatter contrast between the ice and open water determines the capability to accurately define the ice edge. For copolarized data, the contrast varies greatly depending on incidence angle, ice type, sea state, and wind conditions. In relation to incidence angle, the ocean clutter level is highest at steeper angles. Increased surface roughness due to wind and waves will also increase the ocean clutter level. The most problematic situation for ice-edge delineation is when the ocean clutter conditions result in backscatter conditions similar to those of sea ice signatures. Accurate estimation of ice concentration is a derivative of the ability to

Table 1. Summary of operational ice information requirements for the Canadian Ice Service.

Ice information requirement	Primary: Ice-edge location	Primary: Ice concentration	Primary: Stage of development[a]	Secondary: Presence and location of leads (open water)
Spatial resolution				
Strategic	5 km	±10% requires resolution <100 m	50–100 m	50–100 m similar to ice concentration
Tactical	<1 km	±5% requires resolution <25 m	<20 m	<20 m
Temporal resolution				
Strategic	Daily	Daily	Daily	Daily
Tactical	6 h	6 h	6 h	6 h
Description	In case of a diffuse ice edge, the CIS defines the ice–water boundary as 10% ice concentration	Percentage of ice-covered area; ice concentration is a key parameter in the WMO egg code[d] (MSC, 2002)	Ice classes are defined by the WMO (MSC, 2002)	Leads and polynyas

Note: Values are based on Lapp and Lapp (1982), Barber et al. (1992), and Ramsay et al. (1993) and were refined following a discussion with J. Falkingham (personal communication, 2003), Chief of Operations, Canadian Ice Service. Temporal and spatial resolution describe the frequency and accuracy, respectively, in which the information requirement must be measurable. The temporal requirement of daily revisit makes ScanSAR the mode of choice for the CIS.

[a]New, thin, first-year, and multiyear ice.
[b]More specifically, ice strength.
[c]Thickness, wetness, density.
[d]World Meteorological Organization (WMO) international ice symbology, known colloquially as the “egg code”.

discriminate between ice and open water but requires finer spatial resolution.

The ability to discriminate different ice stages of development is very dependent on the geographic region and season (Ramsay et al., 1993). Based on CIS experience, HH can be used to discriminate between the two major categories of multiyear and first-year ice in cold winter conditions. Backscatter over multiyear ice is increased owing to volume scattering. Under wet conditions, volume and surface scattering from overlying snow dominate the backscattered signal, thus masking the contrasts between the underlying ice stages of development. Discrimination of ice stages of development is also aided by the identification of large-scale ice structures (e.g., floes) and deformation features (e.g., ridges, fractures). The separation of thin and new ice from open water and smooth landfast ice is a major problem with single-polarization SARs.

Secondary ice information requirements

Few of the secondary ice information requirements are met using existing imaging systems. Visual reconnaissance and modelling tools are used where possible, however, to provide some of this information.

The ability to reliably separate sea ice from open water also allows the detection of leads, which are openings in the ice. Aside from their thermodynamic relevance, leads are important for route planning and navigation.

Presently, ice thickness cannot be measured directly using single-polarization SAR. Rather, it is inferred from analysis and interpretation of ice stages of development (e.g., grease, nilas, grey, grey–white, first year, and multiyear according to the Meteorological Service of Canada (MSC, 2002)), which are a proxy for ranges of ice thickness.

Ice topography, structure, and ice deformation features, such as ridging, are important parameters, as these features pose a significant hazard and impediment to navigation. Several researchers (Pearson et al., 1980; Johansson, 1989; Simila et al., 1992; Melling, 1998) have examined the potential of using SAR imagery for identifying deformed ice and characterizing ice topography. Johnston and Flett (2001) assessed the potential of using ScanSAR imagery for ridge detection. Results for ridge detection were not very promising because of the coarser resolution (100 m) relative to the lateral and longitudinal ridge dimensions and sail heights (3.5–4.0 m) observed in the study. Although ScanSAR data can be used successfully to identify areas of deformed ice, it was concluded that identification and measurement of specific ridges are not feasible. Higher resolution modes (e.g., fine, standard) will be more successful at ridge identification but would not support daily revisits. In

Table 1 (*concluded*).

Secondary				
Ice thickness	Ice topography and roughness	Ice decay state[b]	Snow properties[c]	Iceberg detection
5 km for average thickness over an area to ±20% of total thickness	<50 m to determine extent of ridging; need average ridge heights to within ±20%	20 km for average strength over an area to ±20% of total strength	5 km for average snow depth to ±20%	<50 m
<100 m to determine average and maximum thickness (including rafting) over an area to ±10% of total thickness	<10 m to determine mean and maximum ridge heights to within ±10%	5 km for average strength over an area to ±10% of total strength	1 km for average snow depth to ±10%	<5 m
Twice per week	Daily	Weekly	Weekly	
Daily	6 h	Daily	Daily	
Important for navigation and (or) loads on structures (rafts show double or more than double the undeformed floe thickness)	Presence, location, and height of ridges; roughness indicated by concentration of ridges (in % or in number per unit area) minus ridge density plus average height (or total thickness) of ridges	Identification of melt onset and ponding	To determine hull friction for ship resistance; also important for ice strength	Detection and tracking, possibly classification of type (MSC, 2002)

addition, modes with higher incidence angles approaching those of airborne SARs are preferable (Melling, 1998).

Currently, the CIS is exploring the use of RADARSAT-1 data, in combination with other sources of information, for assessing sea ice spring melt. The goal is to reliably identify and monitor the state of ice decay, and ultimately infer ice strength. Part of this relies on the ability to accurately determine when ponding begins on the ice surface and when the water begins to drain though the ice. The drainage is a precursor to fracture and breakup, and also an indication of weakening or decay. ScanSAR data have proven effective at identifying "winter" and "snowmelt onset" stages of the sea ice evolution. However, the "ponding" stage is more susceptible to misidentification owing to the high sensitivity of water backscatter to wind-induced roughness over much of the ScanSAR swath (De Abreu et al., 2001).

Information on snow cover is important because of its effects on the decay and breakup of sea ice, and the associated impact on marine navigation. Snow plays an important role in the thermodynamic evolution of the snow and sea ice cover. Barber and Nghiem (1999) further note that understanding the relationship between the thermodynamic state of the snow–ice system and SAR backscatter will lead to information on snow thickness classes over thick first-year ice.

Iceberg detection

The radar backscatter from an iceberg arises from several mechanisms, mostly surface and volume scattering (Haykin et al., 1994). Multi-bounce scattering is also a contributing factor, depending on the shape of the iceberg. An overview of different iceberg shapes is given in Power et al. (2001). As a result of these scattering mechanisms, icebergs, like ships, often manifest themselves in C-band radar images as bright point targets with intensities above that of the ocean backscatter (clutter). Iceberg validation studies on the detection limits of RADARSAT-1 indicate a high probability of detection for icebergs of size on the order of the resolution cell of the selected beam mode (Power et al., 2001). High wind conditions and high sea states limit iceberg detection, owing to increased sea clutter. Icebergs larger than the resolution cell can be detected more reliably, even in rough sea states. Wide 3 is the recommended mode for operational use (C-CORE, 2004) to balance detection and discrimination capability with coverage (150-km swath). For this mode and resolution (nominally 30 m), it has been shown that small-, medium-, and large-class icebergs can be detected with a probability of at least 0.7 under wind conditions up to 20 kn (C-CORE, 2004). Some discrimination of ships from icebergs is currently possible with single-channel systems, primarily using higher resolution (e.g., fine) beam modes (C-CORE, 2000). Airborne radars are frequently used for operational iceberg detection and tracking.

Expected improvements using RADARSAT-2 data

Based on a review of the literature, observations from practical operational experience, and experiments with ENVISAT ASAR data, a number of areas can be identified where the capabilities of RADARSAT-2 are expected to provide improvements. These improvements are discussed in this section with emphasis on dual-polarization and fully polarimetric data.

The estimation of polarimetric parameters is affected by the strength of the signal relative to the system noise level, as defined by the noise-equivalent sigma zero (NESZ, where sigma zero is the backscatter coefficient σ^0). There is a variation of up to 2.5 dB in the NESZ of the different RADARSAT-2 standard beams but no marked trend with look angle of the beam. The higher NESZ for RADARSAT-2 as compared with those of several airborne sensors can result in a low signal-to-noise ratio (SNR) for areas with low backscatter (e.g., calm water). This is particularly important for analysis involving the cross-polarized backscatter, which is generally lower than the backscatter of the two copolarized channels. **Table 2** summarizes the estimated RADARSAT-2 NESZ levels.

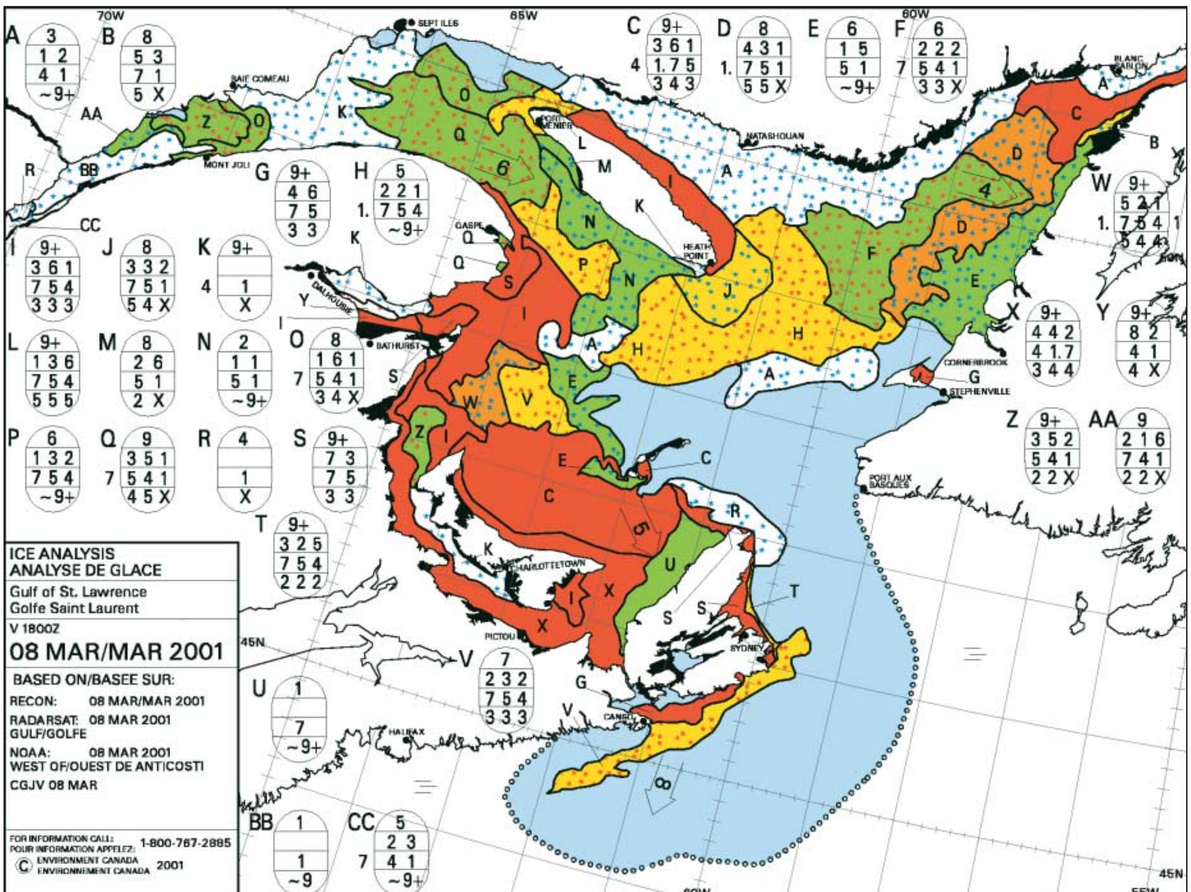

Figure 1. Example of a Canadian Ice Service Daily Ice Analysis Chart, which covers approximately 900 000 km^2. Ice information is provided by the colour in the chart, and more detailed information is given in the egg codes. Colour and egg codes are described in detail in the *Manual of standard procedures for observing and reporting ice conditions* (MSC, 2002).

Table 2. Estimated performance values (dB) for RADARSAT-2 noise-equivalent sigma zero (NESZ).

	Standard mode (quad-polarization)	Fine mode (quad-polarization)	Wide mode (dual-polarization only)	ScanSAR narrow (dual-polarization only)	ScanSAR wide (dual-polarization only)
NESZ	–31	–28	–23	–23	–23

Dual-polarization modes

The RADARSAT-2 dual-polarization options include HH–HV or VV–VH modes. The additional information provided by the cross-polarization channel can be very useful, as the cross-polarization channel responds to different scattering mechanisms than the copolarization channel. These dual-polarization data are available in all beam configurations, giving a wide choice in resolution, coverage, and incidence angle. Most importantly, dual polarization will be available for ScanSAR modes, the modes most used at CIS for RADARSAT-1 data. Operational experience by CIS analysts based on several thousands of images over the last 10 years results in a preference for HH polarization over VV. The increased sea clutter from the VV-polarization results in more interpretation confusion across the entire incidence angle range.

Nghiem and Bertoia (2001) analysed AIRSAR data of the Beaufort Sea, focusing on the simulation and validation of ENVISAT beam modes. They suggest the use of different dual-polarization combinations depending on incidence angle and wind speed (if open water is present). The authors conclude that dual-polarization wide-swath modes, such as RADARSAT-2 ScanSAR, will give better results for sea ice mapping compared with single-polarization SAR.

Primary ice information requirements

The HV backscatter response from water is generally low and is relatively independent of wind-induced surface roughness conditions, whereas HV backscatter from sea ice is affected by surface roughness, volume scattering, and multibounce scattering. Thus, at steeper incidence angles, the ice–ocean contrast of HV can be expected to be greater than that for either of the copolarization channels, especially at high-wind conditions. This is confirmed by results of Nghiem et al. (1995), who found that surface scattering is dominant up to 30° incidence and volume scattering is dominant above this value. The combined use of copolarization and cross-polarization channel gives better results across a wider range of incidence angles.

Improved separation between multiyear ice and first-year ice has been demonstrated for HV (Flett, 1997; Onstott, 1992). Thus, cross-polarization ScanSAR data would be advantageous if discrimination between these two primary stages of development is a high priority. Although there appears to be some incremental benefit with the availability of cross-polarization ScanSAR data for multiyear ice – first-year ice discrimination, use of cross-polarization alone for thin ice detection is not recommended, as intensity differences due to surface scatter are suppressed (Onstott, 1992).

Secondary ice information requirements

Cross-polarization data can enhance the structural information of sea ice and have demonstrated some utility for improving discrimination between smooth and deformed ice. This is a function of the combined volume scattering and multiple-reflection surface scattering in the ice ridges

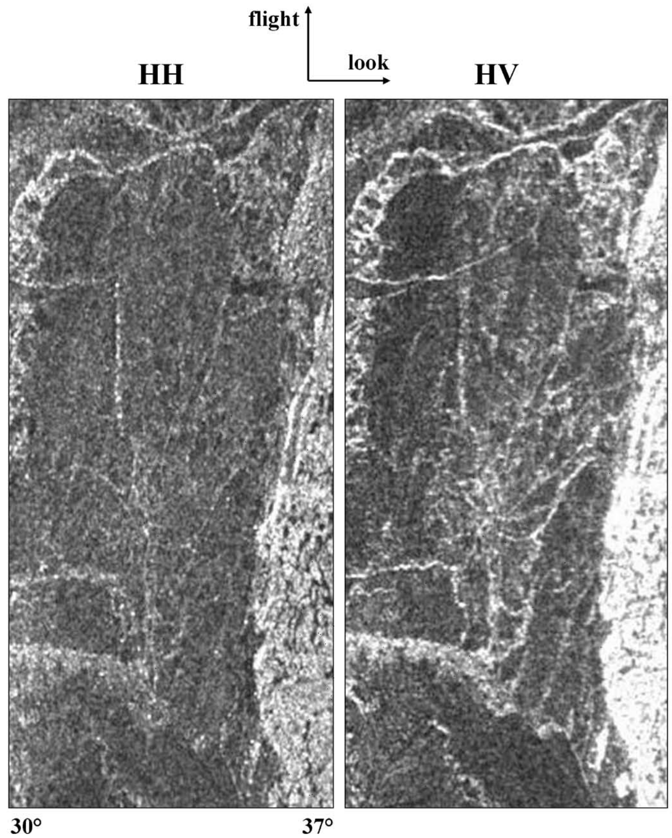

Figure 2. Convair-580 C-band HH-polarization image (left) and HV-polarization image (right) acquired in May 1993 in Resolute Passage. The image dimensions are approximately 1 km in range and 2.5 km in azimuth, and the incidence angle range is about 30°–37°. Data analysis was performed on 4 pixels × 4 pixels. The left-hand two thirds of each image is first-year ice, with ridging and deformation throughout. The brighter feature at the right-hand side of each image is a multiyear ice floe. The cross-polarization data show much greater ice surface topography and structural detail within the first-year ice than in the copolarization data.

enhancing the cross-polarization radar returns (Livingstone, 1994). Observations of C-band scatterometer measurements of Baltic Sea ice by Makynen and Hallikainen (1998) quantitatively illustrated that the backscatter contrast between level ice and ice ridges is larger at cross-polarization than copolarization. **Figure 2** illustrates this contrast with airborne C-band HH and HV data for cold winter ice conditions (Flett, 1997). As a result, cross-polarization ScanSAR data from RADARSAT-2 are expected to be an improvement over the current like-polarization case for better detection of ice topography and structure. There will still be limitations, however, as a function of resolution and incidence angle as noted earlier.

Operationally, the effects discussed earlier can improve the detection of hazards to navigation in ice, specifically traces of multiyear ice in a matrix of first-year ice and the detection of pressure ridges. Both of these features are small compared with the resolution of the wide-swath radar modes generally used, however, so their detectability will likely remain resolution limited. Melt conditions will also limit the detectability of roughness features due to the masking of the ice surface as a result of the free water on the surface and (or) in the snow pack.

Cross-polarization data will assist in resolving some of the ambiguity in detecting the presence or absence of surface water on decaying ice now encountered with like-polarization data (R.A. De Abreu, personal communication, 2001). Similar to the case for open water versus ice discrimination, the cross-polarization data will assist in identifying melt ponds on the ice surface, particularly under wind-roughened conditions.

Iceberg detection

The reduced sensitivity of HV to sea state as compared with HH leads to the conclusion that cross-polarization data will be advantageous for detecting icebergs, particularly at steeper incidence angles below about 35° and in high sea states. The limiting factors for detection are radar resolution, iceberg size, sea state, and signal to clutter–noise ratio. RADARSAT-2 will offer a high-resolution, single-polarization mode (ultrafine, HV not available), which is expected to enhance iceberg detection and classification capabilities but only over 20-km swaths.

Fully polarimetric modes

The quad-polarimetric mode of RADARSAT-2 is expected to provide additional information compared with dual- and single-polarization data. The narrow coverage (25-km swath), however, will limit its utility for operational sea ice monitoring. The potential for repeat acquisition of fully polarimetric data over the same area throughout an ice season will lead to an increased understanding of sea ice signatures and improved techniques for extracting information from fully polarimetric data.

Primary ice information requirements

Using SIR-C data acquired near the Newfoundland coast in April 1995, Scheuchl et al. (2001a) characterize the improved ice–water separation potential of single-channel, cross-polarization data and similar potential using the copolarization channel ratio. The authors also found some utility in the anisotropy parameter for ice–water segmentation. Generalization of the results is difficult, as the data used in this study were acquired during melting conditions.

Estimation of the ice stage of development will benefit from the availability of polarimetric data. Drinkwater et al. (1991) conclude that additional phase information embedded in the correlations between the different polarizations is important information for ice typing and classification. The use of one copolarization channel with the copolarization ratio is suggested in Eriksson et al. (1998). In RADARSAT-2, this parameter is available only in the fully polarimetric modes. Thomsen et al. (1998) examine C-band polarimetric sea ice data in the Greenland Sea and note that no single polarimetric parameter can adequately discriminate between all ice types. They found, however, that better classification can be achieved by combining various polarimetric parameters. Detailed information of the scattering mechanism symmetries can be used to separate frazil and congelation ice in newly formed leads and open water. The copolarization ratio is useful for separating multiyear ice from rough thin ice and open water. Drinkwater et al. (1991) conclude that the ability to separate thin ice from open water is limited at C-band but better at longer wavelengths, such as L- and P-bands. Automation of classification is presented in Rignot and Drinkwater (1994), Hara et al. (1995), and Scheuchl et al. (2001a; 2001b).

Secondary ice information requirements

Polarimetric SAR data show some potential for ice thickness measurement. Winebrenner et al. (1995) measure ice thickness up to 50 cm using L-band, and Kwok et al. (1995) use C-band data and Shih et al. (1998) use time series polarimetric C-band data to measure the thickness of thin ice.

D.G. Barber (personal communication, 2002) suggests that there is some potential for snow cover information extraction using time series polarimetric C-band data from RADARSAT-2, coupled with a thermodynamic model.

Iceberg detection

It is expected that fully polarimetric radar systems will further facilitate the discrimination of icebergs from ships and possibly iceberg detection in pack ice, presently not possible with RADARSAT-1. The improvements in ship detection with fully polarimetric SAR (e.g., Touzi, 2000; Touzi and Charbonneau, 2002) provide some guidance for icebergs, which have similar (but not identical) scattering response.

Analysis results using simulated RADARSAT-2 data

The following results are by no means comprehensive and are presented mainly to illustrate the advantages of both dual-polarization and fully polarimetric data. In both cases an effort was made to simulate RADARSAT-2 data to make the results more relevant to this discussion.

Dual-polarization data

Figure 3 shows an ENVISAT ASAR IS4 alternating polarization (HH + HV) scene acquired on 7 February 2003 in the Gulf of St. Lawrence south of Anticosti Island. Covering an incidence angle range from 31° to 35°, the image dimensions are approximately 67.5 km in range and 100 km in azimuth. The modelled wind speed and direction are shown in **Figure 3b**. The ENVISAT data were processed to a 25-m resolution (through reduction of bandwidth) to more closely resemble RADARSAT-2 ScanSAR narrow data. The region just south of Anticosti Island is open water, and the rest of the area is covered in new and young ice (see labels in **Figure 3b**).

The HH image (**Figure 3a**) shows high backscatter for the open-water area due to wind, thus making delineation of the ice edge difficult. The HV image (**Figure 3b**) provides better contrast between open water and new ice but not necessarily

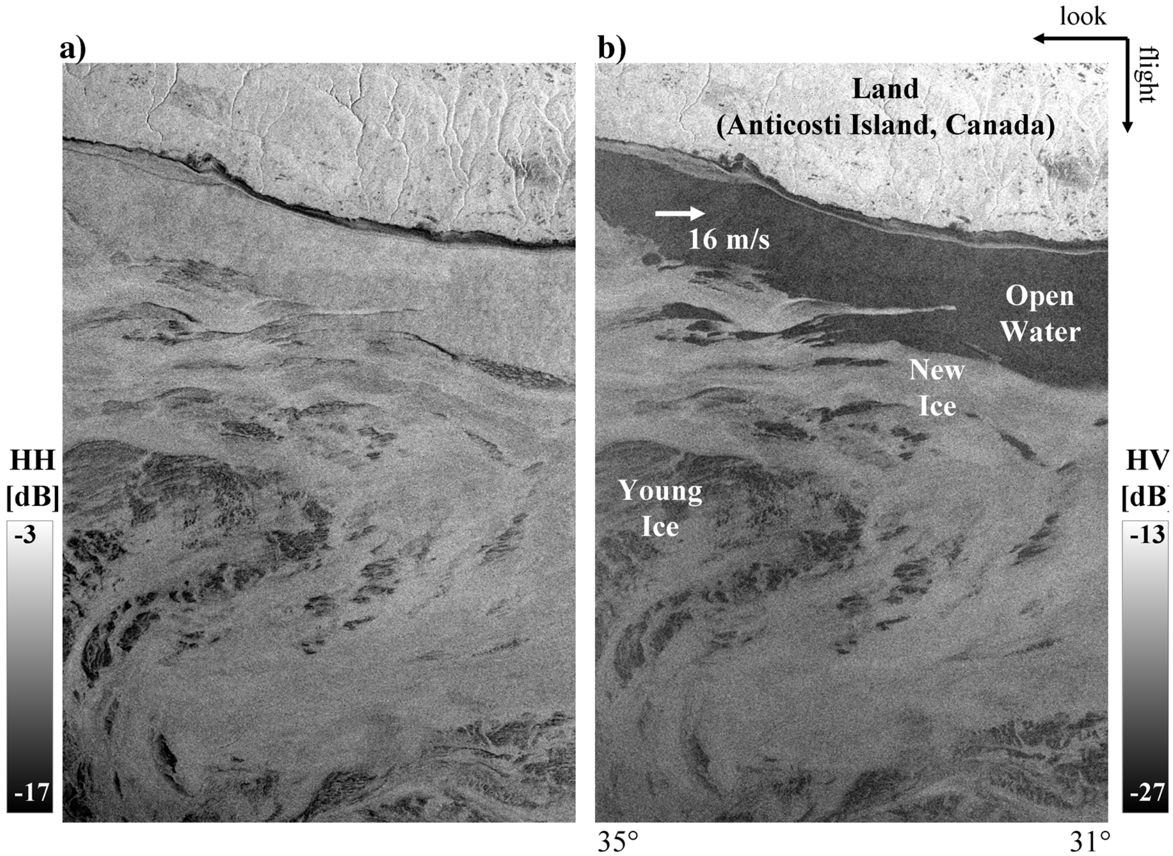

Figure 3. ENVISAT ASAR alternating polarization data (HH + HV, IS4) acquired on 7 February 2003 in the Gulf of St. Lawrence. The image dimensions are approximately 67.5 km in range and 100 km in azimuth. The data were processed to 25 m resolution to more closely resemble RADARSAT-2 ScanSAR narrow data. Wind speed and direction are given in (b).

young ice. The backscatter of HV is significantly lower (10 dB difference in the grey-level scaling).

Figure 4a shows a colour representation of the data using the HV/HH channel ratio, in addition to the two individual channels. Visual image interpretation plays a significant role in the CIS operational environment, and the use of colour will aid ice analysts in their work. **Figure 4b** shows a classification result using an automated classifier modified for dual-polarization data (Lee et al., 2001). No training data were needed to initialize the algorithm. Instead, simple thresholds were used to divide the marine area of the scene into three initial classes. These classes were then refined using 10 iterations of the modified Wishart classifier. A land mask was used to exclude land areas from the classification. Spatial averaging of 4 pixels × 4 pixels was performed to reduce the effect of speckle. Resulting classes were manually assigned to new ice (white), young ice (grey), and open water (blue). The result, while still noisy, illustrates the potential of dual-polarization data for machine classification, and even ice concentration estimates.

An HV versus HH scatterplot based on the classification result is shown in **Figure 5**. The crosses indicate class mean values, with a spread of ± one standard deviation in each dimension. The colouring of the scatterplot is used to show the density of the plot, with brighter colours representing higher density. Although ice and open-water classes appear to come from a single large cluster of data points, making simple visual interpretation of the scatterplot difficult, the classes are reasonably well separated in the two-dimensional space. Neither of the channels alone would be sufficient to classify the scene. Young ice and open water show the same average HV level, whereas new ice and open water show the same average HH level. HV is close to or at the noise level in the open-water and young ice areas. Land is shown here for comparison only.

Fully polarimetric data

Figure 6a shows simulated RADARSAT-2 fully polarimetric data in a colour composite image. The simulation is based on single-look complex data from a Convair-580 acquisition in Northumberland Strait, Canada, on 8 March 2001 (Scheuchl et al., 2003a; 2003b). The data were filtered in range and azimuth directions to reduce the bandwidth to match that of RADARSAT-2 data, and noise was added to raise the noise level to values representative of the spaceborne system. A more detailed description of the simulation process can be found in

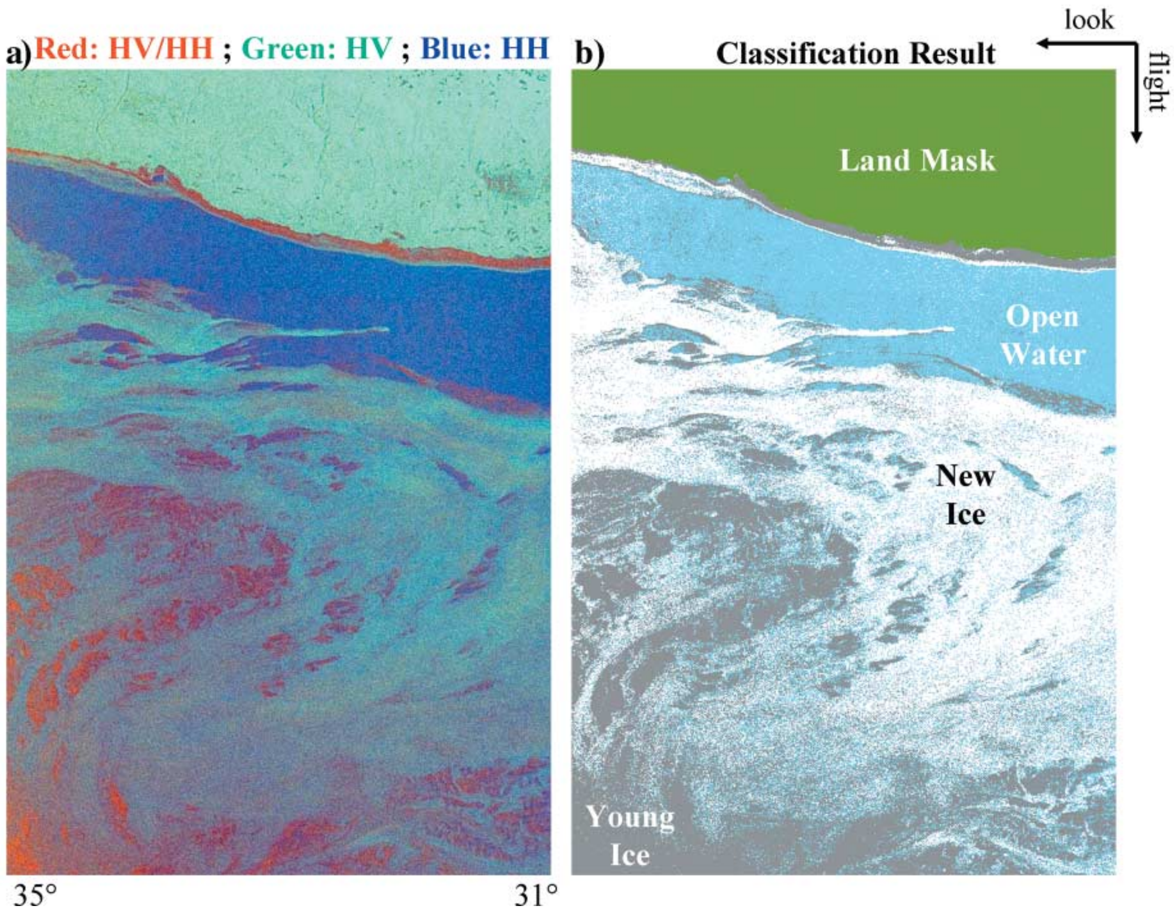

Figure 4. (a) Colour composite image and (b) classification result. A more detailed description is given in the text.

Scheuchl et al. (2003b). The image covers a 6.4-km wide swath (compared with 25 km of RADARSAT-2) at an incidence angle range of 41°–64° (compared with 20°–49° for RADARSAT-2). The RGB scene contains mostly first-year ice (FYI; purple, white), with several leads shown in black and a young ice area in the top left corner (reddish colour). Spatial averaging was performed (6 pixels × 6 pixels) to reduce the effect of speckle and allow a sufficiently accurate parameter estimation.

Climate reports for Moncton, New Brunswick, and Charlottetown, Prince Edward Island, from 7, 8, and 9 March 2001 indicate an average temperature in the area of approximately –4.2° C. An extended melt-free period prior to data acquisition is also reported. An ice chart provided by the CIS (see **Figure 1**) indicates a mix of ice types surrounding Prince Edward Island (40% thick first-year ice (>120 cm thick), 40% medium first-year ice (70–120 cm thick), 20% thin first-year ice (30–70 cm thick)). Floe sizes (between 20 and 500 m) are reported.

Also shown in **Figure 6a** are four selected areas, each covering different ice types (two first-year ice types, young ice) and one lead. **Figures 6b–6e** show mean value and standard deviation of these four areas in two-dimensional plots. The four examples illustrate class separability and the potential of fully polarimetric data for ice type classification. Leads appear in HV very close to the noise level (**Figure 6b**), thus it is likely that the lead to ice ratio is reduced in this particular case. The copolarized intensity ratio (**Figure 6c**) shows potential for separating first-year ice from young ice and leads.

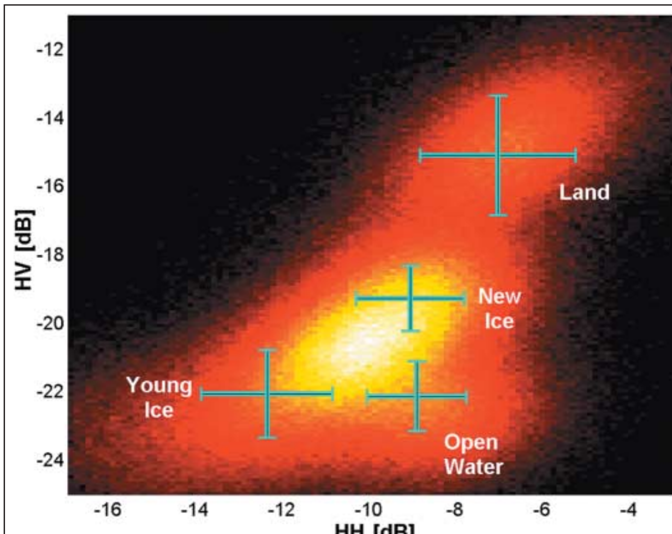

Figure 5. HV–HH scatterplot. Brighter colours in the scatterplot indicate higher data density. The cross centres denote class mean values ± one standard deviation indicated by the crossbars.

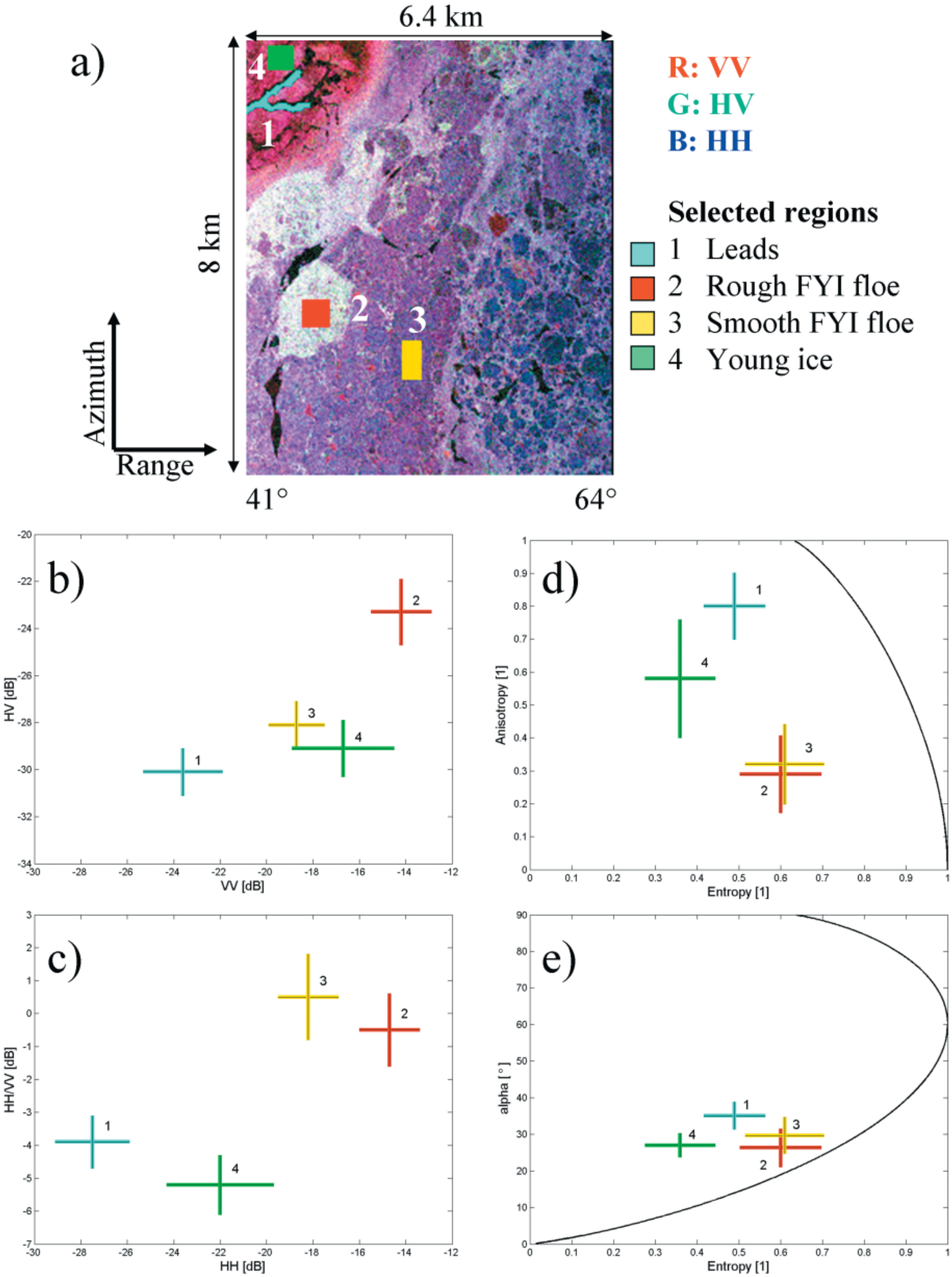

Figure 6. (a) Simulated RADARSAT-2 fully polarimetric data (based on a CV-580 airborne acquisition in Northumberland Strait). (b–e) Spatially averaged (6 pixels × 6 pixels) and selected two-dimensional plots for areas 1–4. The black lines in (d) and (e) represent the natural bounds for this space.

Figure 7 shows a number of polarimetric parameters of the data. This selection is by no means comprehensive and is intended only to illustrate the increased amount of information available from fully polarimetric SAR data. HH and VV (**Figures 7a, 7b**) appear similar except for the young ice in the top left corner of the image. HV (**Figure 7c**) is much weaker

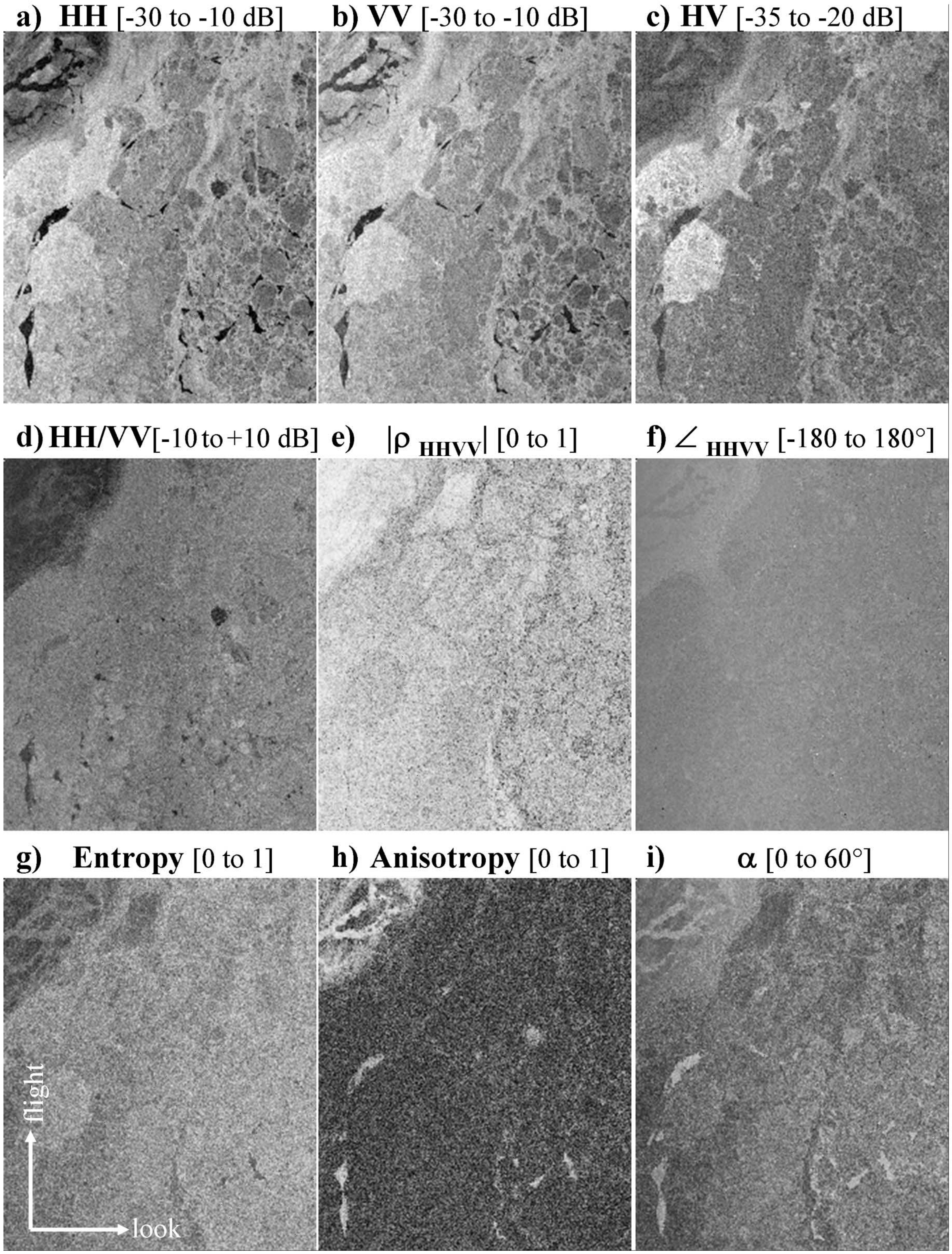

Figure 7. Selection of polarimetric parameters estimated from spatially averaged data (6 pixels × 6 pixels) to ensure reasonably accurate parameter estimation. A more detailed description is given in the text.

(different grey-level scaling), with the backscatter from leads and young ice lower than that from first-year ice. More contrast between ridged and smooth ice compared with HH and VV can be noted. The ice of the two bright floes in the image is interpreted as older, rougher, and more deformed first-year ice and therefore has rough surface and multibounce scattering dominating the return.

The copolarized intensity ratio (HH/VV) is greater over first-year sea ice than over young ice and leads (**Figures 6c, 7d**). The magnitude of the correlation coefficient (ρ) for the two copolarized channels (**Figure 7e**) is higher over areas of smooth ice (i.e., the bigger floes) than for ridged and compressed ice between the floes. The phase (**Figure 7f**) shows some spatial variability that can be related to stages of development.

Entropy, anisotropy, and α angle (**Figures 6d, 6e, 7g, 7h,** and **7i**) are a form of scattering decomposition and can be used for a physical interpretation of the scattering mechanisms. They are also used in classification schemes for polarimetric data (Cloude and Pottier, 1997; Lee et. al., 1999). The young ice region and the leads show a different signature from that of first-year ice, particularly for anisotropy and α angle, otherwise there is only limited variation in ice stages of development. Observed values for α angles (<40°) combined with low entropy (around 0.5) indicate dominant surface scattering, which is expected for this scene.

Conclusions and recommendations

The launch of RADARSAT-2 will provide continuity of RADARSAT data, the main information source for the Canadian Ice Service (CIS). The second-generation SAR satellite will not only offer the entire suite of legacy beams of RADARSAT-1 but also will offer higher resolution, multiple polarization, and fully polarimetric modes. These new capabilities provide increased information and can be expected to come closer to fulfilling the ice information requirements outlined in this paper.

RADARSAT-2 dual-polarization data, which are available for many modes including ScanSAR, will provide a significant improvement over single-polarization data. The availability of multichannel SAR data and thus the opportunity to use colour visualization will enhance visual data interpretation by ice analysts. In general, the cross-polarization channel will play an important role for ice monitoring, preferably used in combination with a copolarization channel. The cross-polarization channel intensity shows promising results for ice-edge detection. The cross-polarization ratio has been shown to increase the contrast between first-year and multiyear ice. Better iceberg detection is expected, as the cross-polarized channel is less sensitive to ocean surface roughness and the contrast between target and background will be improved. Similarly, there is more contrast between smooth and deformed ice. However, the system noise level and the signal-to-noise ratio of the cross-polarized channel will impact these capabilities.

The fully polarimetric modes of RADARSAT-2 will provide data that allow a more complete characterization of the area of interest in terms of scattering mechanisms and show promise for ice type classification. For operational sea ice monitoring, these modes will be of limited utility because of their narrow swath. For operations, maximizing daily coverage is more important than increased information content. The exception would be for specific locations and situations where detailed information is desired and can be acquired without compromising wide area monitoring requirements. Regardless, spaceborne fully polarimetric data will play a significant role for research in the future. It will enable researchers to learn more about (*i*) sea ice signatures (both cross-polarization and fully polarimetric), as data will be collected operationally over many seasons; (*ii*) noise floor requirements; (*iii*) most suitable incidence angle ranges for sea ice monitoring; (*iv*) resolution requirements; and (*v*) calibration accuracy requirements. Thus the data can be used to develop better analysis methods and guide the design of future systems.

The new RADARSAT-2 capabilities are expected to add substantial information for ice monitoring purposes. However, it will not be until operational experience is gained over a complete ice season that these predictions can be verified. Until the launch of RADARSAT-2, airborne fully polarimetric data and ENVISAT ASAR alternating polarization data will continue to be useful to develop analysis methods and establish what utility there will be for operational ice centres.

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