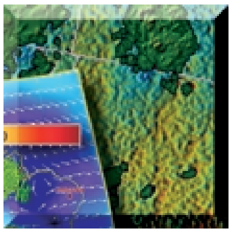

Canadian Progress Toward Marine and Coastal Applications of Synthetic Aperture Radar

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With Radarsat-1 presently in operation and Radarsat-2 approved, Canada is starting to develop synthetic aperture radar (SAR) applications that require imagery on an operational schedule. Sea ice surveillance is now a proven near–real-time application, and new marine and coastal roles for SAR imagery are emerging. Although some image quality and calibration issues remain to be addressed, ship detection and coastal wind field retrieval are now in demonstration phases, with significant participation from the Canadian private sector. (Keywords: Ice, Ocean, SAR, Ship, Wind.)

INTRODUCTION

The development of marine and coastal synthetic aperture radar (SAR) applications in Canada has to date involved data from platforms such as the CV-580 airborne SAR, the European Remote Sensing (ERS) satellite SARs, and the Radarsat SAR in research, demonstration, and operational roles. An emerging theme is the development of new operational applications as we approach the Envisat and Radarsat-2 eras. These new sensors will broaden the observation space (in particular by providing more polarization choices) and will present enhanced application opportunities. In this article, we focus on emerging and operational Radarsat marine and coastal applications in Canada.

The Canadian Ice Service is the main Canadian operational user of Radarsat data. However, Radarsat SAR ship detection is now in demonstration trials with the Canadian Department of Fisheries and Oceans and Department of National Defense (DND) using Satlantic, Inc.'s Ocean Monitoring Workstation (OMW) and IOSAT, Inc.'s Sentry, a transportable satellite ground station. In addition, the imaging of meteorological features in SAR images over the ocean presents new opportunities for both research and new operational applications. To better cater to the needs of offshore data users, Radarsat International, the commercial Radarsat data distributor, has introduced new services for data programming, processing, and delivery.

We begin by discussing some research issues. We first consider several Radarsat image quality and calibration factors that can influence the opportunity to use Radarsat SAR data quantitatively. We then discuss ship detection, wind field retrieval, and SAR imaging of atmospheric phenomena such as hurricanes and polar lows. Next we describe a few demonstration activities that are now ongoing in Canada, specifically the improvement and demonstration of information products from the OMW for ship detection. Finally, we discuss some operational activities, specifically the use of Radarsat SAR data for sea ice surveillance and the support that Radarsat International has provided for marine users. Some other Canadian activities are dealt with separately (see Gower and Skey, also Werle et al., this issue).

RADARSAT SAR RESEARCH ISSUES

Canada's Radarsat SAR (C band with horizontal transmit and horizontal receive [HH] polarization) was launched in November 1995 and has now been operational for over 3 years. The SAR provides images in 22 nominal single-beam modes and 4 multiple-beam (i.e., ScanSAR) modes. This flexibility provides a variable acquisition swath with the potential for repeat observations within 0.5 to 5 days, depending on the latitude and the selected beam mode. Image resolution can be traded off for swath coverage.

Full operational capability of the satellite was achieved in June 1996. Calibration of the single beams at the Canadian Data Processing Facility was completed in February 1997. However, there are ongoing image quality problems for the ScanSAR modes.

Analog-to-Digital Converter Operation

Early in the Radarsat mission it was noted that dark, rangeward bands sometimes appeared in Radarsat SAR imagery of the coastal zone. These bands were visible over land or ice when water was in the near range, and they arose because Radarsat's automatic gain control (AGC) was implemented essentially on the basis of the power level returned from the near-half swath. Therefore, if the return power was higher from the far-half swath than from the near-half swath, the radar's 4-bit analog-to-digital converter (ADC) could saturate, causing dark bands in the far-half swath.

There are now two options for selection of acquisition gain. With dynamic gain (i.e., AGC on), the AGC operates with the property just noted and presents the possibility of dark rangeward bands in the coastal zone. With this option, it is best to keep water of interest in the near range to ensure an appropriate automatic gain setting. With fixed gain (i.e., AGC off), the user selects an appropriate constant gain setting. Obviously, for ocean scenes, *a priori* knowledge of the wind speed is required to make an appropriate gain selection. While fixed gain settings solve the banding problem over land, they may not be appropriate for large cross-sectional, distributed targets, which could suffer power loss and radiometric calibration errors. A similar problem was encountered with the ERS-1 and ERS-2 SARs, with their 5-bit ADCs and fixed gain acquisitions.[1] From experience gained with ERS-1 and ERS-2, it is now possible to compensate for modest amounts of ADC saturation power loss by carrying out a signal data saturation analysis and applying a spatially variable scaling, on the basis of the power loss characteristics of a 4-bit ADC, either to the signal or to the image data. An example of this compensation for a fixed gain acquisition over Hurricane Mitch in the Gulf of Mexico in 1998 is shown in Fig. 1.

Ship Detection

A model for Radarsat ship detection performance provides predictions of the minimum detectable ship size for the various Radarsat beam modes, subject to assumptions about the image fading statistics, the ocean clutter, and the ship cross section. The model allows a relative comparison of the available Radarsat beam modes, as well as selection of optimal Radarsat beam modes based on surveillance requirements,[2] and has been used as the basis for a ship detection algorithm implemented in the OMW.

The Canada Center for Remote Sensing (CCRS) has validated the OMW ship detection algorithm based on data from several dedicated field validation programs.[3] Twenty-seven Radarsat SAR images, together with supporting ship validation information such as name, type, size, and location, were acquired in 1996 and 1997. Validation data were derived from DND aurora surveillance flight reports, from Canadian Coast Guard fisheries surveillance, and from dedicated field programs.

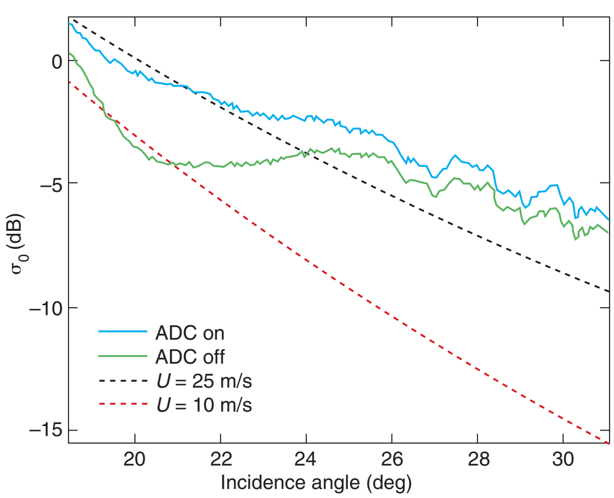

Figure 1. Plot of Radarsat widebeam mode 1 C-band HH polarization radar cross section (σ_0) transect measured over Hurricane Mitch on 27 October 1998. The solid curves show the cross section both with (ADC on) and without (ADC off) the ADC saturation power loss correction to account for the fixed gain acquisition that was used in this case. Note that this data set suffered up to a 3-dB power loss. The dashed curves are C-band HH hybrid wind-retrieval model outputs for the indicated wind speeds with U blowing across the radar look direction (i.e., with a relative wind direction ϕ = 90°). It is evident that the power loss could have caused errors in the retrieved wind speed in excess of 15 m/s.

The validation procedure involved comparison of known ship positions with Radarsat/OMW candidate target positions. Figure 2a shows a sample validation scene; the Radarsat image was acquired on 7 October 1996 off the west coast of Vancouver Island and contains a group of fish factory trawlers. The accompanying map (Fig. 2b) shows validation data collocations. Table 1 lists the ship validation information.

Within the 27 images used in this study, 174 ships, ranging from 20 to 294 m in length, were validated for a range of Radarsat beam modes and wind conditions (0.4 to 13.2 m/s). Unfortunately, there were very few validation opportunities for smaller fishing vessels. Detection rates ranged from 77% for modes that are less favorable for ship detection (i.e., modes having small incidence angles, in particular standard beams 1 to 3, and widebeams 1 and 2) to 97% for modes that are recommended for ship detection (i.e., modes having larger incidence angles, in particular fine beams 1 to 5, standard beams 4 to 7, and widebeam 3). The detection rate for two ScanSAR narrow far mode images was 81%. Overall, the detection rate was 84%.

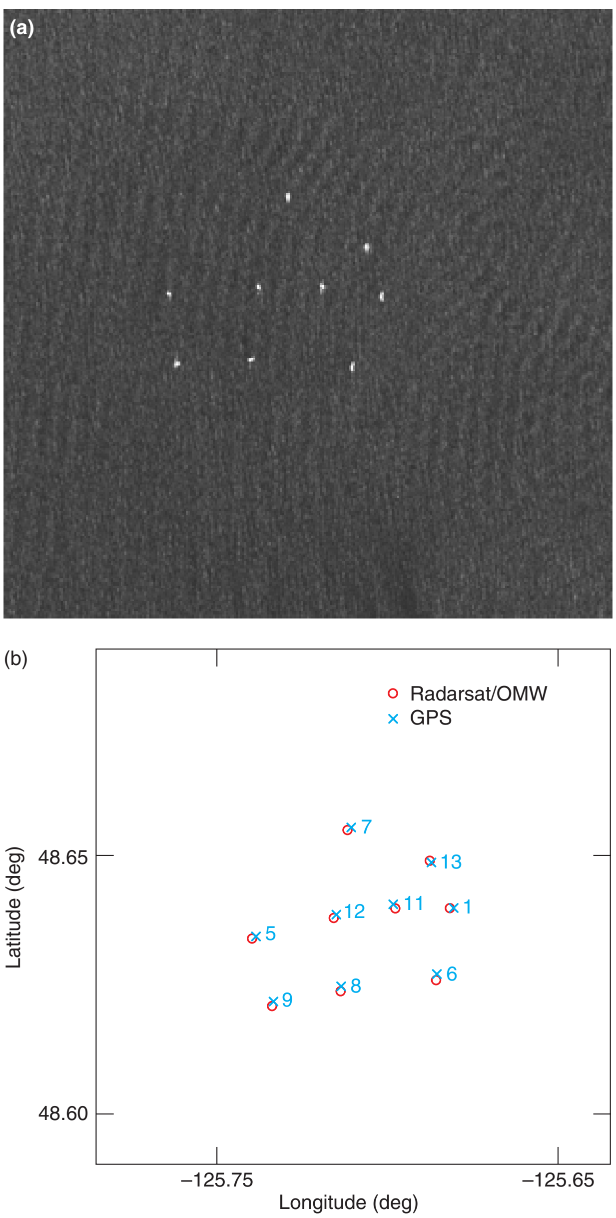

Figure 2. (a) Radarsat standard mode 5 subimage from 7 October 1996 off the west coast of Vancouver Island. (© Canadian Space Agency, 1996.) (b) Map showing validation data collocations for ships listed with assigned numbers in Table 1. The subimage covers an area of 12.5 × 12.5 km.

Table 1. Ship validation information for the validation collocations of Fig. 2.

Ship number	Ship name	*D* (m)	*L* (m)
1	*W. Locznik*	87	88
5	*Cassiopeia*	88	103
6	*Rekin*	143	89
7	*Tunek*	133	90
8	*Aquarius*	88	103
9	*Gemini*	89	88
11	*Langusta*	100	94
12	*Sirius*	77	88
13	*Otol*	56	90

Note: Validation source in all cases is the Global Positioning System (GPS). (*D* = the distance between the Radarsat/OMW ship location and the GPS ship location; *L* = the actual ship length.)

Wind-Vector Retrieval

Wind vectors estimated from SAR ocean images have many possible roles: they yield additional information to aid interpretation of SAR images acquired for ship detection, oil slick detection, or search and rescue; facilitate site-specific weather forecasting in the coastal or marginal ice zones or in lakes or estuaries; offer an approach to near-shore wind climatology over small spatial scales; provide information for assimilation into coupled atmosphere–ocean models; and aid in the study of atmospheric processes at the ocean surface, such as atmospheric gravity waves, wakes, hurricanes, cold air outbreaks, and polar lows.

There are two main approaches to estimating wind speed from SAR ocean images. In the first, the wind speed is estimated from the measured radar cross section, with the wind direction and SAR geometry known.[1] This approach requires a wind-retrieval model that relates ocean wind speed to radar cross section. Such models have been developed for ocean wind scatterometry. The wind direction is estimated by measuring the orientation of long-scale coherent structures in the SAR image. In the second approach, the wind speed is estimated from the degree of azimuth cutoff of the SAR image spectrum. This approach requires a robust measurement of the spectral width, as well as a model describing the relationships among the cutoff wavelength, the wind speed, and the ocean wave spectrum.[4]

Over the past 7 years, CCRS has compiled a large set of ERS and Radarsat SAR ocean images that are spatially and temporally collocated with *in situ* validation information consisting of wind-vector and ocean-wave spectrum measurements. Figure 3a shows a histogram of the difference between the *in situ* measured wind direction and the SAR-derived wind direction after the ambiguity in the 180° wind direction is resolved for both the Radarsat and ERS SAR cases. The horizontal dashed line represents a uniform distribution of directional differences that would apply if the SAR-derived wind directions were random. The uniform distribution has a standard deviation of 52°. The root-mean-square (rms) error for the SAR-derived wind direction is 40°. The SAR-derived direction was found to be within about 30° of the *in situ* measurement for roughly 50% of the cases. In general, the SAR-derived wind direction is most accurate when determined under higher wind and unstable atmospheric conditions.

Figure 3b shows a regression of the SAR-derived wind speed with *in situ* measured wind speed, assuming that the wind direction is known. On the basis of 115 observations, the wind speed was estimated with an rms error of 2.7 m/s. The rms error was 1.9 m/s for the 56 ERS observations and 2.8 m/s for the 59 Radarsat observations. From the regression plot, it is evident that the Radarsat wind speeds are overestimated, especially at higher wind speeds, suggesting inadequacies in the C-band HH-polarization wind-retrieval model used.

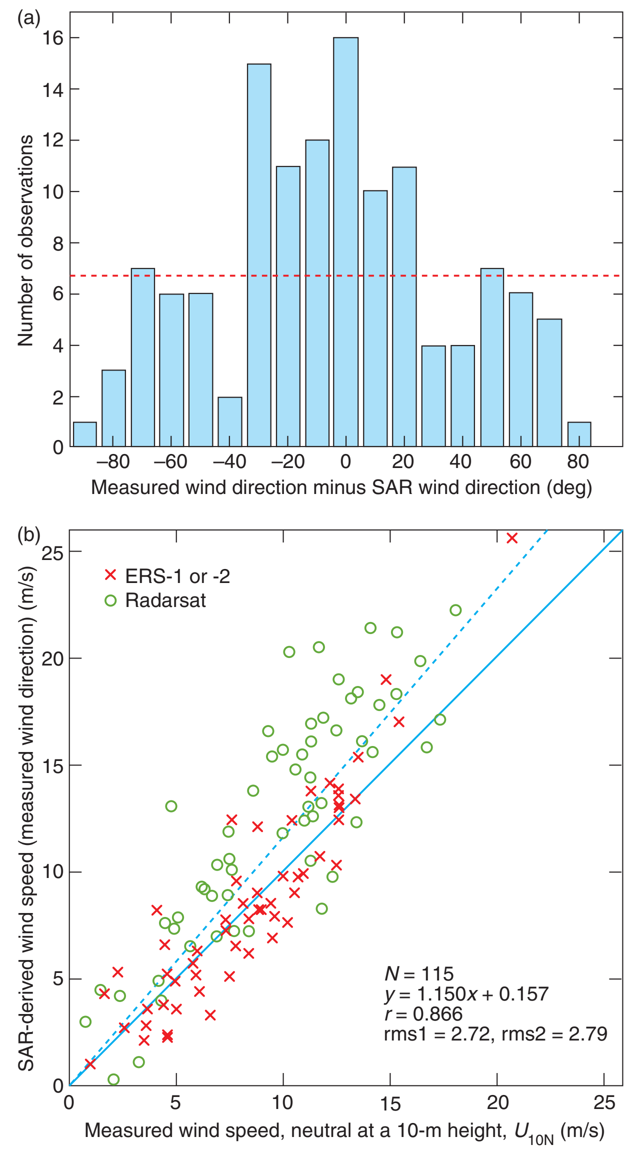

Figure 3. (a) Histogram of the difference between the SAR-derived wind direction (ambiguity removed) and the *in situ* measured wind direction. Horizontal dashed line represents a uniform distribution of directional differences that would apply if the SAR-derived wind directions were random. (b) Regression of SAR-derived wind speed using *in situ* measured wind direction and wind speed for ERS-1, ERS-2, and Radarsat data. Dashed line is the best fit, and solid line would represent a perfect fit. (N = number of observations; y = best fit line; r = correlation coefficient; rms1 = root-mean-square error with respect to the best fit line through the data; rms2 = standard deviation of the difference between the measurement pairs.)

Characterizing Atmospheric Mesoscale Phenomena

Radarsat ScanSAR, with its 300- to 500-km swath widths, can provide both synoptic-scale and small-scale views of the imprint of mesoscale meteorological processes and features on the ocean's surface. Atmospheric phenomena can appear in SAR images when the spatial variability of their associated surface wind field modulates the short-scale roughness on the ocean surface.

Polar Lows

Atmospheric mesoscale cyclonic vortices may develop in the regions between sea ice (or cold land) and the ocean during cold air outbreaks. Often referred to as polar lows, these intense mesoscale cyclones are formed poleward of major jet streams in cold air masses or frontal zones. Since polar lows usually occur in data-sparse regions, satellite images have been a useful tool for the detection and characterization of these phenomena.

Figure 4 shows several Radarsat ScanSAR wide images of intense mesoscale cyclones over the Labrador Sea.[5] The images illustrate, in detail, the spiral-form structure of the surface wind fields around the "eye" (the ellipsoid-shaped patterns) of the lows. The surface wind convergence zone near the cores of the lows is characterized by sharp wind field gradients across the frontal boundary that converges toward the eye. The advection of cold air from the continent to the warmer open water is apparent as the bright areas in the images; the strong airflow tends to become organized downstream from the ice edge into a second-order flow with

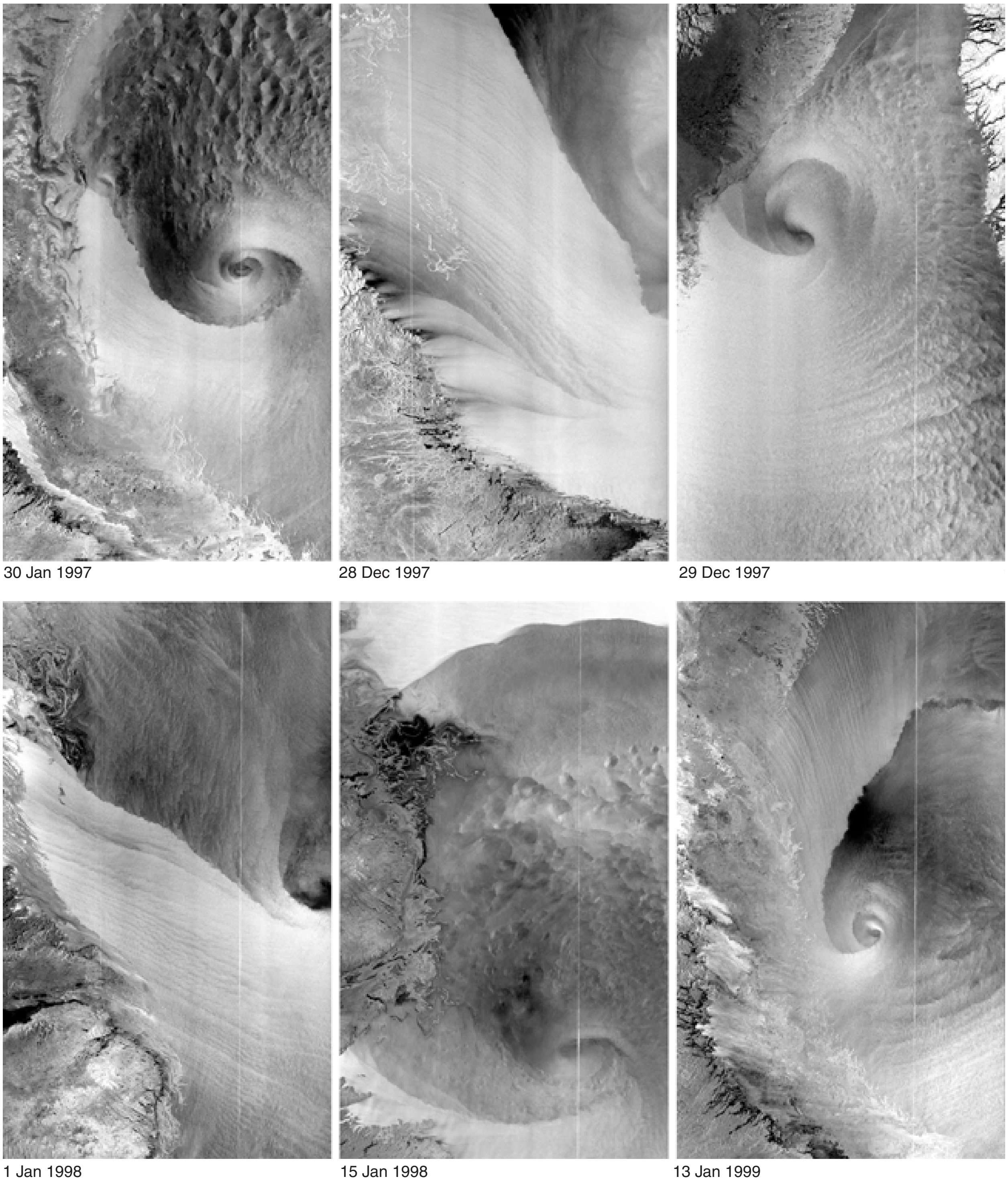

Figure 4. Radarsat ScanSAR wide images of the Labrador Sea, each showing mesoscale flow patterns, including synoptic and polar lows. Each image covers roughly 500 km from left to right. (© Canadian Space Agency, 1997, 1998, and 1999.)

roll vortices that appear on the image as spiral-form cloud streets. Deep cellular convection is often evident north of the eye.

Radarsat SAR images can be used to distinguish the fine structure of the wind field over different stability and convective regimes associated with high-latitude, low-pressure systems. This capability, combined with existing satellite and numerical studies of polar lows, may be useful for studying the mechanisms that drive the initiation, development, and maintenance of these phenomena. In addition, the retrieval of the low-level wind field structure from Radarsat images of polar lows may help to improve numerical simulation and forecasting of the phenomena.

Hurricanes

Hurricanes are strong, nonfrontal, synoptic-scale low-pressure systems that occur over tropical or subtropical waters. They usually contain organized convection and have surface winds with sustained speeds of at least 33 m/s (64 kt, 74 mi/h) which blow in a spiral pattern around a relatively calm eye. Hurricanes represent interesting wind-retrieval validation opportunities for SAR. Radarsat SAR images provide a unique, high-resolution sea surface view of hurricane morphology. When used together with cloud pattern imagery and precipitation radar information, three-dimensional high-resolution perspectives of the storm morphology can be developed. Examples of Radarsat ScanSAR wide images of hurricanes are presented and discussed by Katsaros et al. (this issue).

APPLICATION DEMONSTRATIONS OF RADARSAT DATA

The Ocean Monitoring Workstation

Developed by Satlantic, Inc., the OMW has been designed to extract marine information from Radarsat SAR, Advanced Very High Resolution Radiometer (AVHRR), and Sea-viewing Wide Field-of-View Sensor (SeaWiFS) ocean imagery in near–real time. The workstation contains several SAR information extraction algorithms, together with tools for analyzing ocean color and visible and near-infrared data. The SAR algorithms include ship and oil spill detection, wind and wave retrieval, and ocean feature classification.[6] The Canadian Department of Fisheries and Oceans has been operationally evaluating the vessel-detection products of the OMW as an alternative information source for enforcement of fishing licenses and surveillance of fishing activity. Of particular interest is the region beyond the 322-km (200-mi) economic zone, where management of fishing under the North Atlantic Fisheries Organization agreements is enforced.

Through the Defense Research Establishment Ottawa (DREO), DND is also evaluating SAR technology for offshore ship surveillance. Their current research emphasis is on reducing the false alarm rate of the OMW ship detection algorithms, modifying the algorithms to work with the fully polarimetric modes of Radarsat-2, and integrating the data, along with other sources of data, into the Recognized Maritime Picture. The imagery component of DREO research deals with the development of the Operational Digital Imagery Navigator (ODIN), which is a military all-source workstation for the generation of imagery-derived information for DND decision support. ODIN contains modules for ship detection (i.e., OMW), ship classification, terrain assessment, three-dimensional visualization, and land-target detection and situation analysis.

The Sentry Ground Station

In support of faster information turnaround, IOSAT, Inc., has developed Sentry, a transportable, self-contained, multisatellite receiving and processing ground station that can directly receive Radarsat SAR data and provide near–real-time processing. To evaluate the potential of Radarsat and the Sentry–OMW system for maritime surveillance, a real-time operational trial was conducted for the Maritime Combined Operational Training (MARCOT) and NATO Unified Spirit 1998 naval exercise off the east coast of Canada during June 1998. The exercise included approximately 15,000 personnel and 40 warships from 9 countries. During the exercise, 30 Radarsat images were acquired and analyzed. The fastest turnaround from SAR data acquisition to quality controlled OMW products was 26 min; on average, the turnaround was approximately 54 min.[7] The combination of Radarsat SAR with the Sentry–OMW system was able to meet and exceed the satellite surveillance requirements for the MARCOT/ Unified Spirit '98 operations.

OPERATIONAL USE OF RADARSAT DATA

Near–Real-Time Ice Information

The Canadian Ice Service (CIS) is responsible for providing ice information over Canada's offshore areas and is the largest single user of Radarsat data. The service has a history of operational ice reconnaissance using optical and radar sensors, including AVHRR, Special Sensor Microwave Imager (SSM/I), airborne Side-Looking Aperture Radar (SLAR) and SAR, and the ERS SARs. Since January 1996, CIS has received over 6000 Radarsat ScanSAR scenes for operational analysis.

Radarsat data are typically ordered 2 to 3 weeks in advance based on climatology and forecasts of ice conditions for regions with active commercial shipping. For routine ice monitoring, CIS uses ScanSAR data, as they provide good geographic coverage and revisit with adequate resolution for the detection of significant ice features.

The image data are received at CIS in Ottawa from the Gatineau Satellite Station through a dedicated communication line. Radarsat International guarantees fast turnaround, with actual delivery times averaging less than 2 h. Once received, the image data are automatically taken in, processed, catalogued, and made available for display and analysis.

The image interpretation is still done visually by experienced ice analysts. The Geographic Information System capabilities of the display system are used to produce the final "ice chart," as well as a variety of other image and map products. The Radarsat-derived ice analysis charts and Radarsat subimages are products that can be relayed to marine customers. CIS's main customer is the Canadian Coast Guard. All major Coast Guard icebreaking vessels and the Ice Operations Offices are equipped with communication and display systems (Ice-VU) for the capture and display of Radarsat and ancillary data.

CIS research activities include assessing Radarsat capabilities for detecting icebergs and developing algorithms for automated information extraction such as ice classification and ice-motion measurement.[8] A sample ice-motion product, generated from two sequential Radarsat ScanSAR wide images acquired on 26 and 29 April 1998 over Baffin Bay, is shown in Fig. 5. Such

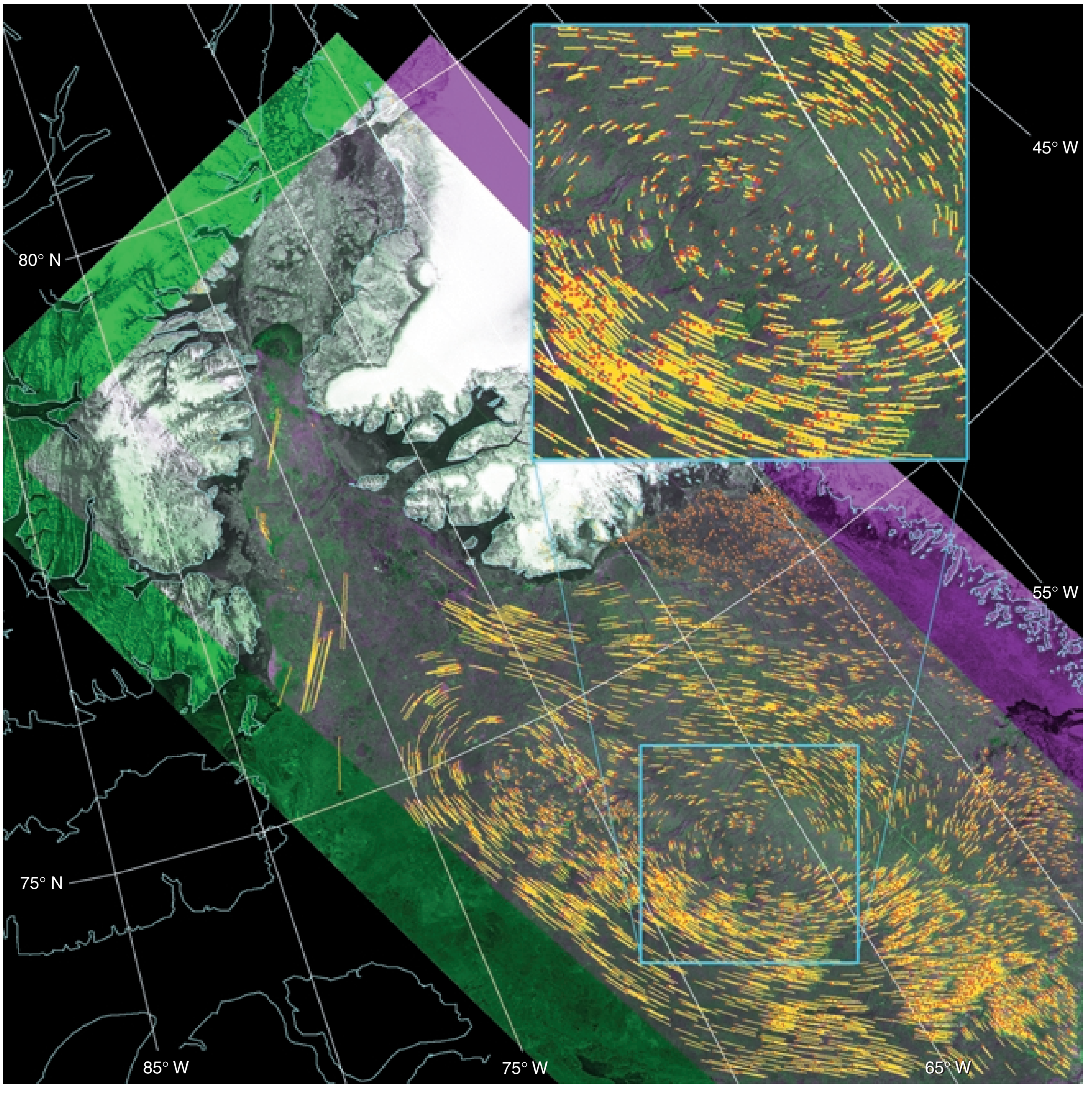

Figure 5. An Ice Tracker product showing sea ice motion vectors in yellow (relative to their origins at the red dots). The product was generated from two time-sequential Radarsat ScanSAR wide images acquired on 26 and 29 April 1998 over Baffin Bay, Canada. (© Canadian Space Agency, 1998, and Noetix Research, Inc., 1998; used by permission.)

ice-motion products can be generated within 2 h of data receipt at CIS.

Marine Surveillance Support

The detection of features on the ocean surface by SAR is dependent on the environmental conditions, especially the wind speed. For many surveillance applications, such as ship detection and oil pollution monitoring, timely data acquisition and near–real-time data delivery are the key variables. However, applications such as oil seep detection are sensitive primarily to wind speed. To accommodate these application constraints, Radarsat International provides a number of programming options and has introduced several services.

Programming options such as "urgent" (for which requests must be submitted at least 2 days in advance) and "emergency" (which is suited to disaster management response, and for which requests may be submitted as late as 24 h in advance) have been available for more than 3 years. In addition, a "meteorological" option is available, and allows clients to order data but reserve processing depending on the environmental conditions at the time of imaging.

More recent services include the offshore exploration service, designed for clients who require SAR imagery to support offshore exploration such as oil seep detection; the monitoring service, available for end-users who require large volumes of data; and the emergency response service, designed for clients who require dependable delivery of time-sensitive geographic information to manage emergencies such as oil spills or flooding. A key element in these new services is the flexibility to address user requirements.

CONCLUSIONS

Significant effort has been undertaken in Canada to develop, validate, and demonstrate marine and coastal applications of Radarsat SAR. Sea ice surveillance is a mature application, and the CIS routinely utilizes Radarsat data operationally as its primary data source. Automated algorithms for vessel detection, such as those in the OMW, are maturing and have been validated over a broad range of image modes and ocean sea states. The capability of the ERS and Radarsat SARs to provide wind-vector data has also been validated using *in situ* information and empirical models; algorithms to extract wind-vector information have been developed and are currently being validated and demonstrated.

With the advent of new operational satellite programs such as Radarsat-2, the marine community is anticipating new benefits, such as an increased frequency of radar coverage, new information opportunities from selectable polarimetric modes of operation, and more accurate information retrieval, all on operational schedules.

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