Summary of previous research in iceberg and ship detection and discrimination in SAR

Report R-13-060-1098, Revision 4.0

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EXECUTIVE SUMMARY

This document reviews historical and current research on Synthetic Aperture Radar (SAR)-based ship and iceberg detection and discrimination. The report summarizes information gleaned from open source literature and C-CORE technical reports on this topic within the last 10 years. As a consequence, this review provides a comprehensive understanding of the state of the art on ship and iceberg monitoring abilities using SAR data. The typical techniques in the operational and research levels are reviewed and their performance and limitations are evaluated. By analyzing the methodologies and results of the publications and technical reports, a gap analysis on the current algorithms has also been conducted to indicate future directions for further work on detection and discrimination performance.

Detection Techniques

There is extensive literature on ship detection using SAR. The detection of icebergs with SAR has to some degree followed these developments. Regarding algorithms, one simple but widely used technique is threshold-based detection. Because ships and icebergs usually appear as bright targets against the dark background of the ocean, they can be detected. However, the detection algorithms cannot identify the target; as a consequence, discrimination algorithms have to be employed. The detection threshold is usually calculated from the statistics of the local background. Methods include N-sigma, the constant false alarm rate (CFAR) method and receiver operating characteristic (ROC) curves.

Concerning optimal polarization preference for detection, there are some clear trends for both ship and iceberg targets. Quad polarization offers the best overall choice, but the limited availability and swath width precludes its use in an operational context. This leaves dual and single polarization options. In this case, the cross polarization channel is preferred over other choices for small incidence angles. In many case, even large targets (tankers) can be missed in the co-polarized channel. Nonetheless, the relatively high noise equivalent sigma zero (NESZ) of spaceborne SARs significantly contaminate iceberg backscatter; this was confirmed using low noise CV580 airborne SAR data. Ship targets generally do not suffer the same effect in the cross polarization channel due to their higher backscatter. For large incidence angles, dual cross polarization is preferred for iceberg targets, while for ship targets the co-polarized channel (HH) is preferred. Generally, for maritime surveillance involving all types of targets, HH+HV is a safe choice.

Given the benefits noted above offered by quad polarization, compact polarimetry is worth consideration since this will be available for all modes on RADARSAT Constellation Mission (RCM). Compact polarization is seen to be an excellent compromise between dual and quad polarization; compact polarization provides much of the information context of quad polarization, while retaining the wide swath of dual polarization. Given that quad polarization is the best overall choice for detection, it is reasonable to believe that compact polarimetry will

provide enhanced detection performance compare to single and dual polarization. Evidence of this comes via a recent publication that highlights the benefit of compact polarimetry for iceberg detection.

Discrimination Techniques

Relative to detection, few publications have been found on ship and iceberg discrimination. The most extensive information has been gleaned from C-CORE contract reports. The discrimination algorithm used by C-CORE is a classic pattern recognition-based approach, using features gleaned from the SAR data with ground truth to describe the unique characters of the ship, iceberg and other classes. It has been tested using various kinds of SAR data acquired by RADARSAT-1, ENVISAT ASAR, CV580, RADARSAT-2, TerraSAR-X and Cosmo Skymed. The discrimination rates are generally high, particularly for high resolution SAR data.

Iceberg and ship discrimination has been demonstrated to be viable in various resolutions and polarizations of SAR data. Two important trends are observed; first, iceberg and ship discrimination improves as a function of increased resolution and decreasing NESZ levels. Second, the general idea that quad polarization offers improved discrimination over dual polarization systems and dual polarization systems offer improved discrimination over single polarization systems held true. As with detection, this fact points to consideration being given to compact polarimetry modes on RCM. Compact polarization has not been extensively studied with respect to ship/iceberg detection and discrimination. Since quad polarization has indeed shown some benefits for discrimination, it is reasonable to believe that compact polarimetry will provide enhanced discrimination performance.

Gap Analysis

Although ship and iceberg detection in SAR imagery is often accomplished through a simple adaptive threshold, the desire to extend the detection capabilities to regions with heterogeneous background clutter, such as that due to variable ocean backscatter or sea ice, requires that other approaches be considered. Among the techniques that show potential under such conditions are sub-aperture and multi-polarization analyses. The applicability of these approaches should be evaluated with the goal to improve on current operational software.

Combining the advances in both SAR sensor technologies and analysis techniques, it would be of interest to characterize the detection rates achievable for particular classes of ship and iceberg targets, and for the particular SAR modes of interest for ocean surveillance. This could also include consideration of data from multiple SAR and other sensors, such as maritime AIS. The contributions from potential SAR constellations would ideally consider the possible frequency, resolution, polarization, noise-floor and swath-width options. Constellations of satellites also point to the possibility of iceberg tracking using a high revisit frequency of observations.

Beyond the detection of ship and iceberg targets, refinement is required in the discrimination among ships, icebergs and false alarms caused by ocean features, environment clutters, sea ice and image artifacts. The false alarm rejection algorithm is recognized as a major gap in the ship or/and iceberg discrimination algorithms using SAR data. Some of the techniques to be investigated include sub-aperture or polarization coherence, coupled with classic pattern recognition techniques, such as that used for ship/iceberg discrimination. As suggested earlier, an important future consideration is the potential of compact polarization modes, which is a confirmed capability of RCM. Compact polarimetry seems to offer an excellent compromise between quad and dual polarization modes. The relatively high noise floor environment in RCM points to the need for an in-depth study of how compact polarimetry could overcome some of the NESZ shortcomings for both iceberg and ship detection and discrimination.

TABLE OF CONTENTS

LIST OF TABLES

1 ICEBERG AND SHIP DETECTION AND DISCRIMINATION USING SAR

This report summarizes the current capabilities and potential for iceberg and ship detection and discrimination using synthetic aperture radar (SAR). Of particular interest is the detection of ships and icebergs in difficult backgrounds, such as in high and variable ocean backscatter and in sea ice. Work on these problems has benefitted from the more recent SAR sensors, which include multi-polarization and multimode capabilities. In concert with the improvement in sensor capabilities, continuing developments in analysis techniques have contributed to the potential for detection of targets in high clutter backgrounds.

The representative literature publications and technical reports reviewed in this study are summarized in Appendix A and Appendix B—specifically, the highlights of the work in terms of the detection and discrimination goals, the methodology used, and the SAR sensor and location for any imagery that has been analyzed. The literature papers are selected to represent the state of the art published by the recognized research institutes, universities and national organizations in Germany, United States of America (USA), China, Canada, Norway, United Kingdom (UK), Korea, Italy, and others.

The technical reports have been produced by two companies in Canada, specifically C-CORE and MacDonald Dettwiler Associates (MDA[1]) in the last ten years. C-CORE, being the leading company on SAR-based research into iceberg monitoring, has conducted broad studies and data analysis in the last ten years to improve iceberg and ship monitoring performance using SAR techniques. C-CORE's research into satellite-based iceberg detection has resulted in C-CORE offering a service for iceberg surveillance. This service was initially launched through Polar View[2], a European Space Agency (ESA) project that was funded via the Global Monitoring of the Environment and Security[3] services element. The service has matured over the years, largely built though the research and development projects presented in this report. The service is offered to a large number of clients, including government agencies, oil & gas companies and recreational boaters. Much of the C-CORE owned intellectual property on the service (detection and discrimination of icebergs) is contained within Iceberg Detection Software (IDS) that is mentioned within this report.

Section 2 of this report discusses some of the recent publications on iceberg and ship detection and discrimination, highlighting the potential advances that may be made. Section 3 then summarizes the specific work that has been done at C-CORE, through work with the Canadian Ice Service (CIS), the Canadian Space Agency (CSA), Defence Research and Development Canada (DRDC), MDA and RADARSAT International. Section 0 contains gap analysis and

[1] One of the reports is from RADARSAT International, now known as MDA Geospatial Services International.
[2] www.polarview.org
[3] This initiative is now called Copernicus (http://www.copernicus.eu/); Copernicus was initially funded by ESA, but it is now funded by the European Commission.

recommendations for further work, with particular consideration of the more promising advances that are likely to lead to improved operational capabilities.

2 LITERATURE REVIEW

There is extensive literature on ship detection using SAR, and much of this has been summarized in the Australian Defence Science and Technology Organization (DSTO) review by Crisp (2004). The detection of icebergs with SAR has to some degree followed these developments, with the algorithms for ship detection being applied to icebergs.

One of the simple but widely used algorithms is threshold-based detection. The algorithm can be thought of as bright target detection on the sea. A pixel is considered detected as long as it passes the selection criteria (threshold), regardless of what it is. Because ships and icebergs usually appear as bright targets against the dark background of the ocean, they can be detected. However, the detection algorithms cannot identify the target; as a consequence, discrimination algorithms have to be employed to label the target as a ship, an iceberg or a false alarm.

The threshold is usually calculated from the statistics of the local background. One typical method, called N-sigma, uses the simple statistics mean and standard deviation of the background; the threshold value is set to N times the standard deviation above the expected value of the background. A more advanced and well known method is the constant false alarm rate (CFAR) method. This algorithm models the probability density function of the target and background. The threshold is set so that the percentage of *modeled* background pixel values that lie above the threshold is constant. In the literature, the commonly used distribution functions are K- and Gaussian distributions. Another similar threshold method is the so called receiver operating characteristic (ROC) curve method, in which a threshold is sought to satisfy the trade-off between the probability of missed detection and the false alarm rate based on the probability density functions of the target and background pixels.

Once the threshold is calculated, the detection algorithm can be applied to single polarization or multi-polarization SAR data. For multi-polarization data, detection can be performed in two ways: (1) Process the polarization channels separately as done for single polarization data and combine the detection results afterwards; 2) Combine the polarizations before the detection based on various decomposition methods or experiments (e.g., such as a ratio image between different polarizations) to generate one decision variable, and then, detection is conducted using that variable.

The detection and discrimination problem is made much easier with high resolution, multi-polarization, and low noise floor SAR. However, there are invariably trade-offs in these parameters, especially with respect to the desire for wide swath coverage, so that the need still exists for reliable detection and discrimination in the lower resolution and limited polarization modes. Among the papers reviewed in this study, the detection algorithms used by Brusch et al. (2011), Pastina, Fico & Lombardo (2011), Hannevik (2012) and English, Hewitt, Power & Tunaley (2013) all fall into this threshold-based category.

Below are brief summaries of some of the more recent techniques that have been applied to the detection of icebergs and ships, often using multi-polarization radar. While the intent of many of these techniques is to improve detection in high and variable background clutter, in most cases they have as yet only been tested in limited cases, and therefore their potential for enhancing operational software needs to be further evaluated. It should be noted that a more extensive review of the literature that includes the development of these techniques is not given here, but may be followed through the works cited in the given references.

The application of a CFAR detector to identify ships in sea ice has been reported by Brekke & Anfinsen (2011). K-distributions were modeled based on the local image statistics in RADARSAT-2 Fine VV and VH channels separately. The examples included areas of homogeneous sea ice and mixed sea ice and open water. All ships were detected, though the instance containing both sea ice and open water yielded numerous false alarms.

Wesche & Dierking (2012) investigated iceberg signatures in the Weddell Sea region of Antarctica, and compared the HH (ENVISAT Advanced Synthetic Aperture Radar (ASAR)) and VV (ERS-1) iceberg backscatter to that of sea ice and open water. The authors did not collect ground truth for this study; rather they selected targets that had a high likelihood of being icebergs, based on their size, shape, distinctive backscatter and the presence of a shadow. The iceberg backscatter was analyzed as a function of seasonal and geographic variation, as well as the radar incidence angle and the relative orientation of the icebergs and the radar. The backscatter distributions of icebergs, sea ice and open water were modeled by K-distributions, and then intensity thresholds as a function of radar incidence angle were determined. The classification accuracy was increased when an enhanced Lee speckle-filter was used.

Dierking & Wesche (2012) also studied the polarimetric characteristics of icebergs and sea ice. Using RADARSAT-2 Fine quad-polarimetric imagery of the Weddell and Bellingshausen Seas in Antarctica, they compared the co and cross-polarization intensities, ratios, phase difference and correlation, as well as the polarimetric entropy, anisotropy and alpha angle (H/A/α). The parameters from the polarimetric analysis can reduce the overlap between the iceberg and sea ice signatures, though not in all cases. Earlier work, for example by Touzi, Charbonneau, Hawkins & Vachon (2004) and Yeremy, Campbell, Mattar & Potter (2001), characterized the polarimetric scattering from ships, though no direct comparison to scattering from sea ice has been made.

Wavelet transforms for target detection are chosen to take advantage of the differences in the statistical characteristics between ships and the background clutter. Tello, López-Martínez & Mallorqui (2005) used Haar wavelets to decompose SAR images, and then multiplied the resulting horizontal, vertical and diagonal sub-band images such that the coherent ship targets were enhanced while the background clutter was reduced. A simple threshold was then applied to yield a robust detection with no false alarms for the few examples that were presented.

Meyer & Hinz (2009) extended this approach for ship detection with inhomogeneous backgrounds. They combined wavelet prescreening, filtering of the resulting objects, and adaptive thresholding. The wavelet transforms were calculated for several decomposition levels to include the size range of the ships, and then the resulting sub-band images at each level were combined, and a preliminary threshold applied to isolate potential targets. These objects were then filtered based on their spatial extent, which reduced the number of potential targets by around 90%. A statistically significant value was then computed based on the background intensity statistics and the target intensity over the spatial extent determined previously in the wavelet prescreening. The selection of the final targets was made through a comparison of an adaptive threshold with the product of the statistically significant value and the magnitude of the combined response in the wavelet domain. Evaluation of ship detection for ALOS PALSAR and RADARSAT-1 ScanSAR data with inhomogeneous backgrounds, including sea ice, yielded detection of valid ships of better than 70%, with around 25% extra false alarms.

Sub-aperture cross-correlation magnitude (SCM) has been applied to ship detection by Brekke, Anfinsen & Larsen (2013). The technique relies on the fast decorrelation of open water, such that the magnitude of the cross-correlation between the complex scattering coefficients of two sub-apertures can be used for target detection. It has been shown to enhance the contrast of ships to the background clutter, for a range of sub-aperture bandwidths, including partial overlap of the sub-apertures.

Time-frequency polarimetric coherence analysis has been shown by Hu, Ferro-Famil, Brekke & Anfinsen (2013) to yield promising results for detection of ships in complicated and variable background clutter, such as that from sea ice. The sub-band images are obtained by first transforming the SAR data into the frequency domain, and then splitting the spectral band into several components. The polarimetric coherence over the sub-bands is evaluated, and can be used to separate targets of different coherence, such as ships, icebergs, sea ice, and open water. The analysis successfully detected a ship in sea ice as imaged in three separate SAR scenes. It was also possible to separate ships from small islands and from image artifacts such as range ambiguities. It is intended to apply this technique to dual and compact polarization modes.

Polarimetric notch filters have been applied to both ship and iceberg detection. These filters use a polarimetric perturbation approach to reject the background clutter, such as from open water or from sea ice, and detect features with a different polarimetric signature. The algorithm uses local estimates of the polarimetric signature for the background clutter in determining the filter. The performance of this filter has been examined on multi-polarization images of ships, buoys, and off-shore wind farms (Marino, Hajnsek & Walker, 2012; Marino & Walker, 2011). All the ships and wind turbines were detected, and for RADARSAT-2 Fine quad-polarization data, 76% of the buoys were detected compared to 48% detected through a CFAR approach with the HV channel. The detection of icebergs in sea ice was examined by Marino &

Hajnsek (2012) through TerraSAR-X quad-polarimetric data of the Northwest Passage. While it appears that icebergs as well as some sea ice structures were isolated by the filter, no ground validation was available to confirm the actual targets.

In summary, the methodologies that were reviewed in the literature are listed in Table 1 along with the detection and discrimination goals and the main results. The SAR image modes analyzed in the reviewed documents are listed in

Table 2.

Table 1. Iceberg and ship detection and discrimination methods in the literature.

Method	Detection	Discrimination	Results	Reference
Adaptive threshold	Ships in sea ice		False alarms in region of mixed sea ice and open water.	Brekke & Anfinsen, 2011
	Icebergs in sea ice		High and low intensity icebergs; Classification improved with speckle filtering.	Wesche & Dierking, 2012
	Icebergs in sea ice	Icebergs/sea ice (minimum distance)	High rate of false alarms and missed detections	Hughes & Wadhams, 2012
Polarimetric decompositions	Icebergs in sea ice	Icebergs/sea ice	Polarimetric parameters may help reduce overlap in signatures	Dierking & Wesche, 2012
Wavelet prescreening	Ships in sea ice	Ships/false alarms (filtered by spatial extent; threshold of wavelet response and statistical significance)	Detected ~70% of ships, with ~25% extra false alarms	Meyer & Hinz, 2009
Sub-aperture cross correlation magnitude	Ships		Enhances ship response, but not yet applied to detection in sea ice	Brekke et al., 2013
Time-frequency polarimetric coherence	Ships in sea ice	Ships/ghosts/islands/ice	Can separate targets of different coherence; limited results thus far	Hu et al., 2013
Polarimetric notch filters	Ships, buoys, wind turbines		Good for ships; better than CFAR for buoys	Marino & Walker, 2011
	Icebergs in sea ice		Visual interpretation, no ground truth	Marino et al., 2012

Table 2. SAR image modes analyzed in the literature.

SAR Sensor	Image Mode	Polarization	Resolution Az x rg, m	Swath km	Reference
Literature Publications					
ERS-2		VV			Wesche & Dierking, 2012
RADARSAT-1	ScanSAR	HH			Tello et al., 2005
	ScanSAR Narrow (SCN-B) and ScanSAR Wide (SCW-B)				Meyer & Hinz, 2009
ENVISAT ASAR					Tello et al., 2005
	Image, Wide Swath	HH			Wesche & Dierking, 2012
	WS	HH	150	400	English et al., 2013
ALOS PALSAR	WB1, FBS				Meyer & Hinz, 2009
RADARSAT-2	Fine, Wide, SCN, SCW	HH-HV VV-VH			Brekke & Anfinsen, 2011
	Fine	Quad	5.3 x 4.7	25	Dierking & Wesche, 2012 Kim et al., 2011 Hannevik, 2012 Brekke et al., 2013 Hu et al., 2013
	Standard				Brekke et al., 2013
	SCW	HH-HV			
	SCW	VV VH	100x160-72.1	500	Hannevik, 2012 English et al., 2013
AIRSAR		Quad		10 or 20	Yin, Yang & Zhang, 2011
SIR-C/X SAR		Quad	30 x 10-26	15-60	Yin et al., 2011
TerraSAR-X		Quad			Marino & Hajnsek, 2012
		HH-VV Quad			Marino & Walker, 2011; Marino et al., 2012
	StripMap	HH	1.0 x (0.6-1.5)	≤1650 x 30	Brusch et al., 2011
COSMO-SkyMed,	Spotlight	HH	0.92 x 0.75	10	Pastina et al., 2011

3 C-CORE TECHNICAL REPORTS REVIEW

The ship and iceberg detection algorithm used by C-CORE is the threshold-based method which is described in the previous section. However, few publications have been found on ship and iceberg discrimination. The discrimination algorithm used by C-CORE has been developed and refined through several C-CORE projects; the first research in this area was in 1997, however, this review includes reports starting from 2004. It has been tested using various kinds of SAR data acquired by RADARSAT-1, ENVISAT ASAR, CV580, and RADARSAT-2. The discrimination rates are generally high, particularly for high resolution SAR data.

The algorithm is a classic pattern recognition-based approach, using features gleaned from the SAR data with ground truth to describe the unique characters of the ship, iceberg and other classes (i.e., including all bright targets not falling into the ship or iceberg class). For algorithms that are developed solely for iceberg discrimination, only two classes (i.e., iceberg and other classes) are identified. Several feature groups are included in the feature set of each class such as target morphology, radar cross section and polarimetric decompositions. Given the feature set, various well-known classification methods have been investigated including linear discriminant, quadratic discriminant (QD), neural network, K-nearest neighbour, and support vector machines. Any one of these methods may at times outperform the others, depending on the data to be classified. However, quadratic discriminant analysis was found to outperform the other methods if the data is normally distributed, based on the Bayesian minimum error rate. The quadratic method is also attractive since its run-time application is computationally efficient. A big advantage of the QD algorithm is its ability to incorporate new features to the feature set as long as the new features can further improve the discrimination rate. For example, in the case of features extracted from future compact polarimetry data sources, polarimetric decomposition features can be introduced to the feature set to test the utility of this new data source.

Much of the early work at C-CORE characterized the detection capabilities of the various modes of RADARSAT-1, as a function of the radar resolution and incidence angle, the iceberg size and the wind speed. With the launch of ENVISAT and RADARSAT-2, this work was extended, and included initial evaluations of multi-polarization capabilities.

In work supported by DRDC, QD was studied for the detection and discrimination of icebergs and ships in multi-polarization SAR data (C-CORE, 2012a). The evaluation was based on ROC analysis to determine the detection rate versus the false alarm rate trade-off, along the lines presented by Liu, Vachon & Geling (2005). SAR data from the CV580 and the ENVISAT ASAR dual polarization sensors provided over 2200 iceberg and ship targets. The target feature selection was optimized using a sequential forward selection (SFS) algorithm. Dual-polarization modes were shown to generally provide better detection and discrimination results. It was noted, however, that for a sensor with a very low noise floor, such as the CV580, the cross-polarization channel provided a superior iceberg detection capability. For ship detection, the cross-polarization channels provided the best detection results for radar incidence angles less than 27 degrees, while for larger angles, ship detection was more easily achieved, with HH-HV dual-polarization being preferred. Discrimination between ships and icebergs varied from around 93% to 100% depending on the SAR resolution and polarizations. As expected, dual-polarization imagery provided better discrimination than single-polarization. However, for the samples considered here, quad-polarization provided only marginal improvement over the already high discrimination rates obtained with dual-polarization SAR.

More recently, in a study for the Centre for Arctic Resource Development (CARD), QD models were developed to detect icebergs in sea ice using dual-polarization SAR, as well as to reduce the high number of false alarms that arise from the sea ice backscatter (C-CORE, 2012b). This approach was applied to RADARSAT-2 Wide and TerraSAR-X Stripmap SAR images. For the RADARSAT-2 data, 103 icebergs were used to characterize the iceberg backscatter, and then QD was applied to 196 icebergs in 12 SAR images of the Labrador Shelf. For the TerraSAR-X data, 31 icebergs were used for the iceberg backscatter, with QD then being applied to 55 icebergs in four SAR images of the Labrador Shelf and one image of the west coast of Greenland. The false alarms within the sea ice were eliminated using a QD model. The features chosen for this discrimination, determined by sequential forward selection, were the target area, the HH mean backscatter and the HV maximum backscatter. Approximately 97% of the false alarms were eliminated, while 97% of the icebergs in the RADARSAT-2 imagery and 100% in the TerraSAR-X imagery were retained. Software based on this approach to iceberg detection in sea ice has been implemented within C-CORE's IDS software and is used operationally for services by C-CORE.

Another recently completed project was conducted with support from the CSA Earth Observation Application Development Program (EOADP). This work focused on developing a ship and iceberg discriminator for RADARSAT-2 SCN and Maritime Satellite Surveillance Radar (MSSR) mode (C-CORE, 2013a). Since real MSSR mode data were not available in the time frame of the project, a simulation tool capable of simulating MSSR and SCN data was developed to generate the simulated data from RADARDAT-2 Fine and Fine Quad mode data. Both SCN and MSSR classifiers were generated; the SCN classifier generated an accuracy of 85% and the MSSR classifier generated an accuracy of 95.6%. However, the low ship count used for the MSSR classifier (7 vessels) lead to a low ship classifier accuracy of 57%. Recommendations from this report included revisiting the MSSR classifier with a larger database of ship targets. In addition, the classifier should be revisited when real MSSR data are available for analysis.

Current work in iceberg detection is being done for Petroleum Research Newfoundland and Labrador (PRNL) (C-CORE, 2012c). This work is scheduled to be completed in March 2014 and it involves work with RADARSAT-2, TerraSAR-X and Cosmo SkyMed. Refinement of the detection capabilities were made using dual-polarized SAR, applied especially to high clutter areas that arise from atmospheric effects, ocean currents, and sea ice. An iterative algorithm has been developed for areas with a high density of icebergs, such that the background statistics can be recalculated as the targets are identified, yielding a more accurate estimate of the background clutter distribution. Iceberg size is also estimated from the iceberg radar cross-sections. With the aim of improving the detection capabilities of SAR, the iceberg detection software used at C-CORE is being upgraded to include functionality for analysis of dual-polarization data, along with improvements to the user interface and the calibration, geo-referencing, and land-masking algorithms.

Another ongoing project is using space-based Automated Identification System (S-AIS) data to collect vessel and iceberg signatures from SAR to develop robust classifier algorithms (C-CORE, 2013b). The concept of this work is to collect a large database of vessel and iceberg targets from SAR using S-AIS data to identify the vessel targets in the SAR data. The SAR data being used here is SCW; classifiers developed to date have accuracies of 80-85%. This project is being funded through the CSA EOADP.

Table 3 lists the representative ship and iceberg detection and discrimination results obtained from C-CORE project reports of 2004 to 2013[4]. Several common conclusions obtained from these projects are:

1. For iceberg detection there was a clear trend in polarization preference. That is, quad polarization offers the best overall choice, but the limited availability and swath width precludes its use in an operational context. Considering dual and single polarization modes, for high resolution – low noise floor CV580 SAR, the cross polarization channel is preferred even over dual polarization modes. However, this trend did not hold for ASAR iceberg data sets. The iceberg signatures in this higher noise floor data all had significantly limited cross polarization signatures. From this, if future C-band SAR sensors have a particularly low noise floor similar to that of the CV580 SAR, a cross polarized channel is recommended for iceberg detection. Otherwise, if C-Band sensors have a particularly high noise floor (e.g., compared to the sensors evaluated here), the dual polarization HH+HV or HH+VV are recommended for detection. The RADARSAT-2 noise floor is superior to that of ASAR, and has the potential to be better than either RADARSAT Constellation Mission (RCM) or Sentinel-1, particularly in the cross polarization channel.
2. From the work on iceberg backscatter as a function of incidence angle, current spaceborne SAR mode selection should generally favor HH and dual polarization combinations that contain HH. When considering the HV channel and the relatively "clean" appearance of icebergs observed and proven to be detectable in the CV580 SAR data, it is obvious that current noise floor levels of spaceborne SAR significantly contaminate iceberg backscatter. Specifically, when considering the HV channel for iceberg target detection, the mean target signatures ranged between -21 and -38 dB,

[4] The MDA report is a subcontract report from C-CORE.

depending on local incidence angle, among other factors. Considering that most of the current spaceborne SAR sensors have a Noise Equivalent Sigma Zero (NESZ) ranging nominally from -20 to -25 dB in the cross polarization channel depending on the imaging mode, the iceberg probability of detection in the cross polarization channel is in most instances, significantly restrictive.

3. For ship detection, there was also a clear trend in polarization preference. Several sources point to quad polarization as providing superior detection performance. Considering the wider swath dual and single polarization modes, for steeper incidence angles that range from 15 to 27 degrees, the cross polarization channel is preferred over all other polarization combinations. When comparing ASAR HH+VV to either HH+HV or VV+VH (dual polarization VV and VH channels), the ship detection rate is significantly higher for both the dual-polarized modes containing the cross polarized channel. A separate important inference point from the ship detection results presented here can be made; that is, large vessels such as tankers on the order of hundreds of meters in length have a significant missed detection rate at steep incidence angles in wide swath co-polarization SAR modes. Typically these modes range in incidence angles from 20 to 45 degrees. From this, ship detection using a dual cross-polarized wide swath mode SAR at steeper incidence angles will significantly improve operational maritime surveillance over single polarized HH, VV and dual co-polarized modes. The ASAR analysis results demonstrate that ship detection performance degradation in the relatively high HV noise floor of Sentinel-1 and RCM missions will not lead to the same level of detection performance degradation for icebergs considering the cross polarization channel. Considering ship detection with incidence angles greater than 27 degrees, for CFAR point target detection with the ASAR and CV580 SAR data sets, all polarization channels produced near perfect detection results.
4. Iceberg and ship discrimination has been demonstrated to be viable in various resolutions and polarizations of SAR data. Here, results ranged from 85.9%-95% and 99% for ASAR HH+HV and HH+VV, and 100% for full resolution VV+VH CV580 SAR data. Two important trends were observed; first, iceberg and ship discrimination improves as a function of increased resolution and decreasing NESZ levels. Second, the general idea that quad polarization offers improved discrimination over dual polarization systems and dual polarization systems offer improved discrimination over single polarization systems held true. However, the dual polarization combinations HH+HV and VV+VH performed only marginally worse than the quad polarization modes in the CV580 SAR data.

Table 3. Ship and Iceberg detection and discrimination results, 2004-2012 technical reports

RADARSAT-1													
Reports	Image Mode	No. of Images	No. of Ships	No. of Icebergs	Ship Detection		Iceberg Detection		Discrimination		Location	Client	IP Ownership
					Rate	CFAR	Rate	CFAR	Feature	Accuracy			
C-CORE, 2009	W2,W3		16	27					Intensity, morphology	91%	NL	CSA	C-CORE
MDA, 2006; Sub-contract report to C-CORE	W1				0.0% 30m Ship	10^{-4}-10^{-9}						CSA	Co-Owned, C-CORE, MDA
	SCN				0.0% 30m Ship	10^{-4}-10^{-9}							
	W3				100.0% 30m Ship	10^{-4}-10^{-9}							
	SCN				100.0% 30m Ship	10^{-4}-10^{-9}							

ENVISAT ASAR													
Reports	Image Mode	No. of Images	No. of Ships	No. of Icebergs	Ship Detection		Iceberg Detection		Discrimination		Location	Client	IP Ownership
					Rate	CFAR	Rate	CFAR	Feature	Accuracy			
RSI, 2004 (C-CORE was subcont.)	AP HH	5	19	20	100.0% (IS 4,6 7)	N/A[5]	100.0%	N/A			Iceberg: (NL) Ship: (NL)	CSA	Co-Owned, C-CORE, MDA
	AP HV				94.7% (IS 4,6,7)	N/A	20.0%	N/A					
	AP HH HV	14	140	92		N/A		N/A	Intensity, morphology	Iceberg:86% Ship:81%			
C-CORE, 2009	AP HH HV		324	215		10^{-9}		10^{-9}	Intensity, morphology	95%	Labrador (NL)	CSA	C-CORE
C-CORE, 2012a	AP HH	49	593	236	98.1% (IS3-7)	10^{-9}	92.5% (IS4-6)	10^{-9}			Image: Coastal Labrador, (NL) Ship targets: Gibraltar, Dover	DRDC	DRDC
	AP HV				99.3% (IS3-7)		28.9% (IS4-6)						
	AP HH HV				99.1% (IS3-7)		93.4% (IS4-6)		Intensity, morphology	Iceberg:96% Ship: 94%			
	AP HH	14	456	48	94.0% (IS3-7)	10^{-9}	93.8% (IS6)	10^{-9}					
	AP VV				95.0% (IS3-7)		95.8% (IS 6)						
	AP HH VV				96.0% (IS3-7)		100.0% (IS 6)		Intensity, morphology	Iceberg: 100% Ship: 99%			
	AP VV	11	565	0	97.9% (IS3-7)	10^{-9}		10^{-9}					
	AP VH				99.2% (IS3-7)								
	AP VV VH				99.0% (IS3-7)								

[5] C-CORE used a N-Sigma method for this report rather than CFAR

CV580

Reports	Image Mode	No. of Images	No. of Ships	No. of Icebergs	Ship Detection		Iceberg Detection		Discrimination		Location	Client	IP Ownership
					Rate	CFAR	Rate	CFAR	Feature	Accuracy			
C-CORE, 2012a	HH	22	66	243	100.0%	10^{-9}	79.4%	10^{-9}	Intensity, morphology	100%	Icebergs: Coastal Labrador (NL) Ships: CRUSADE and MARSIE trials	DRDC	DRDC
	HV				100.0%		90.1%						
	VV				100.0%		78.6%						
	HH HV				100.0%		79.4%						
	HH VV				100.0%		79.4%						
	VV VH				97.0%		79.4%						

RADARSAT-2

Reports	Image Mode	No. of Images	No. of Ships	No. of Icebergs	Ship Detection		Iceberg Detection		Discrimination		Location	Client	IP Ownership
					Rate	CFAR	Rate	CFAR	Feature	Accuracy			
C-CORE, 2012b	Wide HH HV	12		196			97%					C-CORE	C-CORE
C-CORE, 2013a	SCN HH HV[6]		42	90					Intensity, morphology	Ship: 79% Iceberg: 88%	Various Locations	CSA	C-CORE
	MSSR[7]		7	84						Ship: 57% Iceberg: 99%			
C-CORE, 2013b	SCWA HH		189	2157					Intensity, morphology	Ship: 79.9% Iceberg: 79%	West coast of Greenland	CSA	C-CORE
	SCWA HH,HV		189	2157						Ship: 86% Iceberg: 84%			
C-CORE, 2012c[8]	Fine, Wide, SCN/W, HH HV	TBD	TBD	TBD	TBD	TBD	TBD	TBD	Intensity, morphology	TBD	TBD	PRNL	C-CORE

[6] Simulated using RADARSAT-2 fine, fine quad and wide modes.
[7] Simulated using RADARSAT-2 fine and fine quad modes.
[8] This project is a work in progress and full results will be available in early 2014. RADARSAT-2 results will update all previous iterations, i.e., (C-CORE, 2013a,b).

TerraSAR-X													
Reports	Image Mode	No. of Images	No. of Ships	No. of Icebergs	Ship Detection		Iceberg Detection		Discrimination		Location	Client	IP Ownership
					Rate	CFAR	Rate	CFAR	Feature	Accuracy			
C-CORE, 2012b	Stripmap HH, HV	4		55			100%					C-CORE	C-CORE
C-CORE, 2012c[6]	ScanSAR HH	TBD	TBD	TBD	TBD	TBD	TBD	TBD	Intensity, morphology	TBD	TBD	PRNL	C-CORE
Cosmo Skymed													
Reports	Image Mode	No. of Images	No. of Ships	No. of Icebergs	Ship Detection		Iceberg Detection		Discrimination		Location	Client	IP Ownership
					Rate	CFAR	Rate	CFAR	Feature	Accuracy			
C-CORE, 2012c[6]	Himage Huge HH	TBD	TBD	TBD	TBD	TBD	TBD	TBD	Intensity, morphology	TBD	TBD	PRNL	C-CORE

4 ALGORITHM GAP ANALYSIS

Although ship and iceberg detection in SAR imagery is often accomplished through a simple adaptive threshold, the desire to extend the detection capabilities to regions with heterogeneous background clutter, such as that due to variable ocean backscatter or sea ice, requires that other approaches be considered. Among the techniques that show potential promise under such conditions are sub-aperture and multi-polarization analyses, including SCM, time-frequency polarimetric coherence, and polarimetric notch filters. The applicability of these approaches should be evaluated with the goal to improve on current operational software.

Combining the advances in both SAR sensor technologies and analysis techniques, it would be of interest to characterize the detection rates achievable for particular classes of ship and iceberg targets, and for the particular SAR modes of interest for ocean surveillance. This includes, for example, the MSSR mode on RADARSAT-2 and the future Ship Detection mode on RCM. This could also include consideration of data from multiple SAR and other sensors, such as maritime AIS. The contributions from potential SAR constellations would ideally consider the possible frequency, resolution, polarization, noise-floor and swath-width options. Constellations of satellites also point to the possibility of iceberg tracking if the revisit was on the order of 24-48 hours; data correlation of targets from sequences of SAR images would require the use of an iceberg drift model that used hindcast winds, ocean waves and ocean currents as inputs.

Beyond the detection of ship and iceberg targets, refinement is required in the discrimination among ships, icebergs and false alarms caused by ocean features, environment clutters, sea ice and image artifacts. Few systematic and widely tested false alarm rejection algorithms can be found in the literature so far. In the reviewed documentations, only several papers include false alarm rejection processing, and they only considered one false alarm source. Brusch et al. (2011) tried to separate ships from false alarms by rejecting false alarms generated by azimuth ambiguities; Pastina et al. (2011) tried to discard false alarms from the ship class by evaluating the detected segments' shapes and dimensions; Kim et al. (2011) used a polarimetric decomposition method to separate icebergs from sea ice. And no documentation has been found discussing false alarm rejection methodologies when ships and icebergs are present simultaneously.

The false alarm rejection algorithm is recognized as a major gap in the ship or/and iceberg discrimination algorithms using SAR data. Some of the techniques discussed above may detect targets based on their unique sub-aperture or polarization coherence, and therefore provide an initial class separation. Further discrimination could also be explored by including the feature sets for the false alarm classes using C-CORE quadratic discriminant algorithms.

Future considerations include the potential of compact polarization modes, which could be included in several next generation SARs and is a confirmed mode in RCM. The information content in compact polarization modes are more than typical dual polarization, but less than quad polarization (Dubois-Fernandez, Souyris, Angelliaume & Garestier, 2008). Compact polarization has not been extensively studied with respect to ship/iceberg detection and discrimination, however, quad polarization has indeed shown some benefits (RSI, 2004; C-CORE, 2012a). Nonetheless, those benefits presently do not warrant the practical use of quad polarization in operations due to the narrow swath width of available modes (i.e., RADARSAT-2). In the case of RCM, compact polarization is available on all modes and may help mitigate some potential limitations from RCM's elevated noise floor (compared with RADARSAT-2). A recent publication by Denbina & Collins (2012) highlights the potential benefit of compact polarimetry for iceberg detection. C-CORE has submitted proposals[9] to the Natural Sciences and Engineering Research Council (NSERC) and to the Defence Industrial Research Program (DIRP) to investigate RCM modes. The NSERC work involves fundamental research on compact polarization scattering, and the DIRP work involves the development of detection and discrimination algorithms for RCM. The DIR program proposes to concentrate on Ship Detection (variable resolution), Low Noise (100 m) and Medium Resolution (50 m, 30 m) modes.

[9] C-CORE has received a notification from Public Works and Government Services Canada (PWGSC) that the DIR submission has passed all mandatory and point rated criteria and is now being considered for funding.

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APPENDIX A – LITERATURE PUBLICATION SUMMARY

Ship Detection in Ice-Infested Waters Based on Dual-Polarization SAR Imagery.
Camilla Brekke and Stian Normann Anfinsen.
IEEE Geoscience and Remote Sensing Letters, 8(3), 391-395.

- **Detection**: Ships in sea ice;
- **Discrimination**:
- **Sensor**: RADARSAT-2 Fine, dual-polarization, VV and VH;
- **Location**:
- **Methodology**: K-distribution for sea ice clutter; shape parameter obtained using Method of Log Cumulant and Method of Moments.

Subband Extraction Strategies in Ship Detection with the Subaperture Cross-correlation Magnitude:

Camilla Brekke, Stian Normann Anfinsen, and Yngvar Larsen
IEEE Geoscience and Remote Sensing Letters, 10(4), 786-790

- **Detection:** Ships;
- **Discrimination:**
- **Sensor:** RADARSAT-2 quad-polarimetric Fine and Standard;
- **Location:** Norwegian Sea;
- **Methodology:** Subaperture cross-correlation magnitude; effects of subaperture bandwidths; polarimetric channels are analyzed separately.

Radar Polarimetry—Useful for Detection of Icebergs in Sea Ice?

Wolfgang Dierking & Christine Wesche
SeaSAR 2012, Tromsø, Norway

- **Detection:** Icebergs in sea ice;
- **Discrimination:** Co and cross-polarization intensities, ratios, pahse difference, and correlation; polarimetric entropy, anisotropy, alpha H/A/α;
- **Sensor:** RADARSAT-2 Fine quad-polarimetric;
- **Location:** Antarctica;
- **Methodology:** Comparison of polarimetric characteristics: co and cross-polarization intensities, ratios, phase difference, and correlation; polarimetric entropy, anisotropy, alpha H/A/α.

SHIP DETECTION USING POLARIMETRIC RADARSAT-2 DATA AND MULTI-DIMENSIONAL COHERENT TIME-FREQUENCY ANALYSIS

Canbin Hu, Laurent Ferro-Famil, Camilla Brekke, Stian Normann Anfinsen
Proc. POLInSAR 2013, Frascati, Italy

- **Detection:** Ships with ocean and sea ice background;
- **Discrimination:** Ships, ghosts, islands, ice;
- **Sensor:** RADARSAT-2 Fine Quad;
- **Location:** San Francisco and Vancouver; Svalbard;
- **Methodology:** Time-frequency polarimetric coherence.

Dual-Polarization SAR Sea Ice Type Classification and Iceberg Detection in the western Fram Strait

Nick Hughes and Peter Wadhams
ESA Conference on Earth Observation and Cryospheric Science, Frascati, Italy, November 13-16, 2012

- **Detection:** Icebergs in sea ice;
- **Discrimination:** For sea ice, cluster analysis, with minimum distance classifier for ice types;
- **Sensor:** RADARSAT-2 ScanSAR Wide HH+HV;
- **Location:** Western Fram Strait;
- **Methodology:** CFAR threshold; filtering of false alarms based on target location and characteristics; ~93% false detections and ~50% missed detections.

ICEBERGS DETECTION WITH TERRASAR-X DATA USING A POLARIMETRIC NOTCH FILTER

Armando Marino and Irena Hajnsek
IGARSS 2012, 3273-3276

- **Detection:** Icebergs in sea ice;
- **Discrimination:** Qualitative only for sea ice types and icebergs;
- **Sensor:** TerraSAR-X quad-polarimetric;
- **Location:** Northwest Passage;
- **Methodology:** Polarimetric perturbation analysis (notch filter) – differences in the polarimetric characteristics of the sea ice and targets. No ground-truth available.

SHIP DETECTION WITH QUAD POLARIMETRIC TERRASAR-X DATA: AN ADAPTIVE NOTCH FILTER

Armando Marino, Nick Walker
IGARSS 2011, 245-248

- **Detection:** Ships, wind turbines;
- **Discrimination:**
- **Sensor:** TerraSAR-X quad and dual (HH,VV) polarization;
- **Location:** North Sea;

- **Methodology:** Polarimetric perturbation analysis (adaptive notch filter); quad and dual (HH,VV) polarization; similar results for quad and dual pol analysis.

AUTOMATIC SHIP DETECTION IN SPACE-BORNE SAR IMAGERY

F. Meyer and S. Hinz
International Archives of Photogrammetry, Remote Sensing, and Spatial Information Sciences, XXXVIII-1-4-7/W5

- **Detection:** Ship; ocean / sea ice;
- **Discrimination:**
- **Sensor:** ALOS PALSAR WB1, FBS, RADARSAT-1 ScanSAR (SNB, SWB);
- **Location:** Alaska;
- **Methodology:** Wavelet based prescreening, object analysis, adaptive threshold: wavelet decomposition, spatial correlation, followed by a relaxed general threshold; object selection based on geometrical object properties; combine magnitude of object response in wavelet domain and significance values from the adaptive threshold; robustness with respect to sea ice features; limited discrimination of wavelet prescreener for lower look images.

A Novel Algorithm for Ship Detection in SAR Imagery Based on the Wavelet Transform

M. Tello, C. López-Martínez and J.J. Mallorqui
IEEE Geoscience and Remote Sensing Letters, 2(2), 201-205

- **Detection:** Ships
- **Discrimination:**
- **Sensor:** RADARSAT ScanSAR, ENVISAT;
- **Location:**
- **Methodology:** Wavelet

Iceberg signatures and detection in SAR images in two test regions of the Weddell Sea, Antarctica

Christine Wesche and Wolfgang Dierking
Journal of Glaciology, 58(208), 325-339

- **Detection:** Icebergs in open water and sea ice;
- **Discrimination:**
- **Sensor:** ENVISAT ASAR Image and Wide-Swath mode, HH; ERS-2 VV;
- **Location:** Southern Weddell Sea and Antarctic Peninsula;
- **Methodology:** Thresholding; backscatter distributions used to partition pixels into classes of iceberg, sea ice, and water; speckle and morphological filters used.

Ship Surveillance with TerraSAR-X

Brusch, S., S. Lehner, T. Fritz, M. Soccorsi, A. Soloviev, and B. van Schie
IEEE Trans. on Geoscience and Remote Sensing, Vol. 49, No. 3, 2011, *pp. 1092-1103.*

- **Detection:** Ships;
- **Discrimination:** Ships and azimuth ambiguities;
- **Sensor:** TerraSAR-X StripMap HH;
- **Location:** Somali coast;
- **Methodology:**
  - CFAR, multi-look ground-range detected SM product, Gaussian distribution;
  - n-signal $xt > \mu b + \sigma bt$ ⇔*TARGET;*
  - *azimuth ambiguities, use lookup table for land and open water strong point target scatterers.*

On the ship detection performance with compact polarimetry

Yin, J., J. Yang and X. Zhang
IEEE Radar Conference, 2011, pp. 675-680.

- **Detection:** Ships;
- **Discrimination:** Ships and azimuth ambiguities;
- **Sensor:** AIRSAR quad, SIR-C/X quad;
- **Location:** Sydney coast, Hong Kong Victoria port;
- **Methodology:**
  - Likelihood ratio (probability of ship /probability of ocean), multi-variate Gaussian distribution of ocean and ship pixels;
  - PWF;
  - Eigen-value decomposition to reduce azimuth ambiguities. A target exist strong depolarized scattering component due to its complex structure whereas the ambiguities do not.

Iceberg Detection using full-polarimetric RADARSAT-2 SAR Data in West Antarctica

Kim, J.-W., D.-J. Kim, S.-H. Kim, and B.-J. Hwang.
3rd International Asia-Pacific Conference on Synthetic Aperture Radar, 2011, pp. 1-4.

- **Detection**: Sea ice and icebergs;
- **Discrimination**: Sea ice and icebergs;
- **Sensor**: RADARSAT-2 Fine quad;
- **Location**: West Antarctica;
- **Methodology**:
  - Freeman-Durden, H/A decomposition to distinguish sea ice and iceberg.

Detection of Ship Targets in COSMO-SkyMed SAR Images

Pastina, D., F. Fice, and P. Lombardo
IEEE Radar Conference, 2011, pp. 928-933

- **Detection and Discrimination**: Ship and other bright targets whose shape and dimension are not compatible with ships;
- **Sensor**: COSMO-SkyMed Spotlight HH;
- **Location**: Messina, Naples, Cyclades and Istanbul areas;
- **Methodology**: CFAR.

Analysis of Sentinel-1 Marine Applications Potential

Vachon, P. W., J. Wolfe, H. Greidanus.
IGARSS 2012, pp. 1734-1737.

- **Detection**: Ship, iceberg;
- **Sensor**: Models for RADARSAT-1 and 2, ENVISAT SENTINEL-1;
- **Location**:
- **Method**: CFAR (K-distributed ocean clutter).

Multi-channel and multi-polarization ship detection

Hannevik, T.N.A
IGARSS 2012, pp. 5149-5152.

- **Detection:** Ship;
- **Sensor:** RASARSAT-2 Fine quad, ScanSAR VV, VH;
- **Location:** Norway ocean areas;
- **Methodology:**
  - N-sigma;
  - CFAR, K-distribution;
  - Single channel + combine the results (HH, VV, VH, HV), or combine multi-polarizations as one channel (1) multiplying the double bounce and the volume scattering (HH-VV)*HV, (2) When dual-polarization data are available the co and cross-polarization channels are multiplied and then divided by a constant.

ICE-SAIS - Space-based AIS and SAR for Improved Ship and Iceberg Monitoring

English., J., R. Hewitt, D. Power, and J. Tunaley.
IEEE Radar Conference, 2013, pp. 1-6.

- **Detection:** Ship and iceberg;
- **Discrimination:** Ship and iceberg;
- **Sensor:** RADARSAT-2 ScanSAR VV, VH, ENVISAT WS HH;

- **Location:** Newfoundland and Labrador, Gulf of St. Lawrence;
- **Methodology:**
    - N-sigma;
    - Supervised quadratic discriminant based on features (intensity, morphology, polarimetric, radar cross section) gleaned from the SAR data;
    - SAIS data was used to validate and tracking.

APPENDIX B – TECHNICAL REPORT SUMMARY

Analysis of single, dual and polarimetric SAR data for iceberg/ship detection and discrimination — ASAR and Convair-580 SAR datasets from 2003 to 2007.

C-CORE, R-08-090-673, 2012

- **Detection:** Icebergs and ships;
- **Discrimination:** QD SFS;
- **Sensor:** ASAR dual-polarimetric HH-HV, HH-VV; Convair-580 SAR quad-polarimetric;
- **Location:**
- **Methodology:** CFAR, QD; Notes: ROC were used to evaluate the detection vs. false-alarm trade-offs.

Iceberg Detection in Sea Ice — Technology Advancement with Dual and Quad Polarization SAR.

C-CORE, R-12-027-844, 2012

- **Detection:** Icebergs in sea ice, sea ice drift;
- **Discrimination:** QD, SFS;
- **Sensor:** RADARSAT-2 Wide; TerraSAR-X Strip map, dual-polarimetric;
- **Location:**
- **Methodology:** Visual techniques; MD, CFAR; Filtering of sea ice speckle via QD-SFS; Sea ice drift via tracking leads.

Enhanced Satellite Radar-Based Iceberg Detection and Sea Ice Monitoring — 2012 Interim Project Report

C-CORE, R-12-091-949, 2012

- **Detection:** Icebergs and sea ice, icebergs in high clutter, icebergs and vessels;
- **Discrimination:** Pixel-based, QD;
- **Sensor:** RADARSAT-2 Fine, Wide, SCN, SCW; TSX; CSK; Dual-polarimetric data;
- **Location:** West Greenland, Newfoundland and Labrador
- **Methodology:** CFAR; QD; Notes: algorithm and s/w development; Iceberg size estimation.

Ship Iceberg Discrimination: Determination of RADARSAT-2 Capabilities in Preparation for Improved Maritime Surveillance and Management Activities.

RADARSAT International (C-CORE subcontract), CSA File No. 9F028-3-4910/A, December, 2004.

- **Detection:** Ship and iceberg;
- **Discrimination:** Ship and iceberg;
- **Sensor:** ENVISAT AP (HH-HV and HH-VV), CV580 Quad;

- **Location:** Newfoundland and Labrador;
- **Methodology:**
  - CFAR
  - Supervised quadratic discriminant based on gleaned from the SAR data

Review of SAR Capability for Ship and Wake Detection, Contract Report to C-CORE

MDA. April, 2006.

- **Detection:** Ship
- **Discrimination:**
- **Sensor:** RADARSAT-1 SCN, Wide
- **Location:**
- **Methodology:**
  - CFAR, k-distribution

Iceberg and Ship Detection and Classification: Demonstration of Improved Marine Surveillance and Management, EOADP Report Volume 2 of 5 – Technical/Commercial Report

C-CORE, R-08-058-359, 2009

- **Detection:** Ship and iceberg;
- **Discrimination:** Ship and iceberg;
- **Sensor:** RADARSAT-2 Fine (HH,VV);
  - ENVISAT WS (HH), AP (HH+HV and HH+VV);
  - RADARSAT-1 Fine, SCN, SCW, Wide;
- **Location:** Newfoundland and Labrador;
- **Methodology:**
  - Supervised quadratic discriminant based on features (intensity, morphology, polarimetric (Freeman, Cameron, SSCM, H/A, Pauli etc.), radar cross section) gleaned from the SAR data
  - QD;

Satellite Applications for Sovereignty and Environment of the North – Final Report.

C-CORE, R-13-010-825, 2013

- **Discrimination:** Ship and iceberg;
- **Sensor:** Simulated RADARDAT-2 SCN and MSSN using RADARSAT-2 Fine and Fine Quad mode;
- **Location:**
- **Methodology:**
  - QD.

ICE-SAIS - Space-based AIS for Ship and Iceberg Monitoring - Milestone 2 Report.

C-CORE, R-12-115-947, 2013

- **Discrimination:** Ship and iceberg;
- **Sensor:** RADARDAT-2 SCWA (combination of four beams W1,W2, W3 and S7);
- **Location:** West coast of Greenland;
- **Methodology:** QD;

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