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Literature review on ship and ice discrimination

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Summary

Ice melting in the Arctic leads to more ship traffic, fishing, and new opportunities for oil searching and production in the High North. Maritime Domain Awareness (MDA) is of interest for Norway, and thus it is of importance to monitor higher latitudes. To be able to help ships to navigate and to plan ship traffic, it is necessary to get an overview of where ice and icebergs are in ice infested waters. The use of Satellite SAR (Synthetic Aperture Radar) data is a reliable day and night and all-weather capability, and is good to use to get a situational picture of the vessel traffic and ice situation at sea. It is significant to be able to discriminate between ships and icebergs in open sea and within the ice.

The report gives an overview of some of the research that has been carried out in the fields of ship detection, iceberg detection, and ship and iceberg discrimination. The focus is on dual-polarization data since the ship detector will only do ship and iceberg discrimination in dual-polarization data.

It seems like Canada has done the most work and already has an operational ship and iceberg discriminator. FFI’s goal is to find a ship and iceberg discrimination method that works in our waters, and to implement this method in the automatic ship detector Aegir.

Sammendrag

Issmelting i Arktis fører til mer skipstrafikk, fiske, og nye muligheter for oljesøk og oljeproduksjon i nordområdene. Maritime Domain Awareness (MDA) er av stor interesse for Norge, og derfor er det viktig å overvåke nordområdene. For å kunne hjelpe skip til å navigere og til å planlegge skipstrafikken, er det nødvendig å få en oversikt om hvor is og isfjell i sjøområder med is. Satellitt-SAR (Syntetisk Aperture Radar) er en pålitelig kilde dag og natt og i all type vær til å gi data for å få et situasjonsbilde av skipstrafikken og issituasjonen på sjøen. Det er viktig å kunne se forskjell på skip og isfjell i åpen sjø og inni isen.

Denne rapporten gir en oversikt over noe av forskningen som er gjort innenfor feltene skipsdeteksjon, isfjelldeteksjon og skip- og isfjelldiskriminering. Fokuset er på data med dual-polarisasjon siden skipsdetektoren bare vil utføre skip- og isfjelldiskriminering i dual-polarisasjonsdata.

Det virker som om Canada er dem som har gjort mest arbeid innen skip- og isfjelldiskriminering, og har allerede en operasjonell skip- og isfjelldiskriminator. FFIs mål er å finne en skip- og isfjelldiskriminerings-metode som virker i våre farvann, og implementere denne i den automatiske skipsdetektoren Aegir.

Content

Summary **3**

Sammendrag **4**

Content **5**

1 Introduction **7**
- 1.1 SAR satellites 7
- 1.2 Radar backscatter 8

2 Ship detection **9**

3 Iceberg detection **11**
- 3.1 Iceberg detection in dual-polarimetry data 13
- 3.2 Iceberg detection in quad-polarimetry data 17
- 3.3 Iceberg detection in compact-polarimetry data 17

4 Ship and iceberg discrimination **18**
- 4.1 Ship and iceberg discrimination in dual-polarimetry data 18
- 4.2 Ship and iceberg discrimination in quad-polarimetry data 22
- 4.3 Ship and iceberg discrimination in compact-polarimetry data 23

5 Further work **23**

6 Conclusion and recommendations **24**

References **26**

Abbreviations **33**

1 Introduction

Global warming causes more of the polar ice to melt, and shipping, exploration, fishing, and production of oil and gas move toward higher latitudes. It is of environmental and economic interest, maritime safety and security, and health to be able to monitor higher latitudes. It is important to get an overview of where the ice and icebergs are in potentially ice infested waters to help ships navigate and to plan ship traffic. There are huge oil and gas reserves that are undiscovered in the northern hemisphere (see Figure 1.1). For Maritime Domain Awareness (MDA) it is also important to be able to discriminate between vessels and icebergs to get a situational picture of the vessel traffic at sea.

This report will give an overview of some of the existing literature for ship detection and iceberg detection, as well as ship and iceberg discrimination. Possible further research and implementation in existing ship detection software will be presented. Our focus is on dual-polarization Synthetic Aperture Radar (SAR) data since the study is done to find methods for ship and ice discrimination that can be used operationally (dual-polarization data).

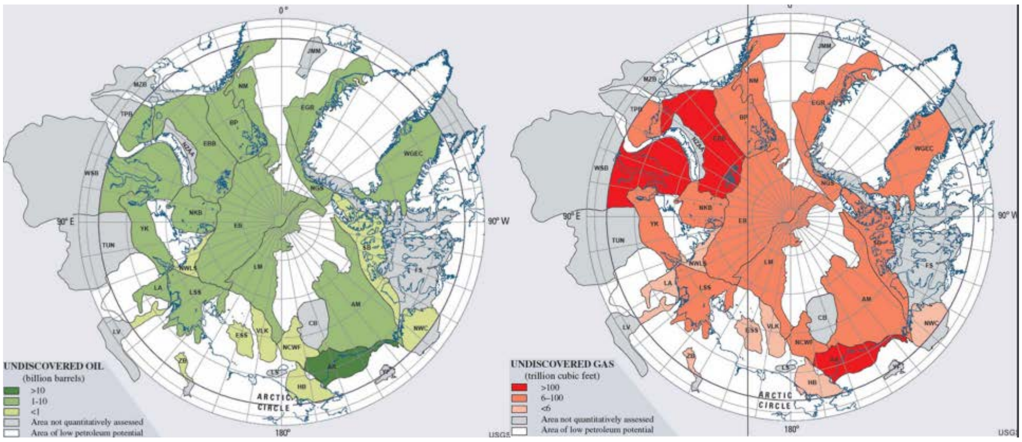

Figure 1.1. Undiscovered oil and gas in the northern hemisphere. ©USGS (US Geological Survey)

1.1 SAR satellites

SAR satellites operate in the microwave region, and are today used to get an overview of the sea ice extent and to detect and discriminate between vessels and ice/icebergs. There are many different SAR satellites in orbit that can be used, for example the Canadian RADARSAT-2, the German satellites TerraSAR-X and Tandem-X, the Italian COSMO SkyMed satellites, as well as the European Sentinel-1A and -1B satellites. The two last ones have open and free data policy, thus providing easy access. Spaceborne SAR gives excellent opportunity to do effective surveillance of the vast Arctic ocean areas. Both ships and vessels can be detected by SAR, and they can be monitored in all weather conditions, cloud cover, and both day and night.

All the above mentioned satellites use linearly polarized radar pulses, and thus transmit either horizontally or vertically polarized signals. The receivers can receive horizontally (H) or vertically (V) polarized backscatter or both polarizations simultaneously. In the following we use a two-letter annotation XY for transmit and receive polarization where X denotes transmitted polarization and Y denotes received polarization. Both X and Y may be H or V.

1.2 Radar backscatter

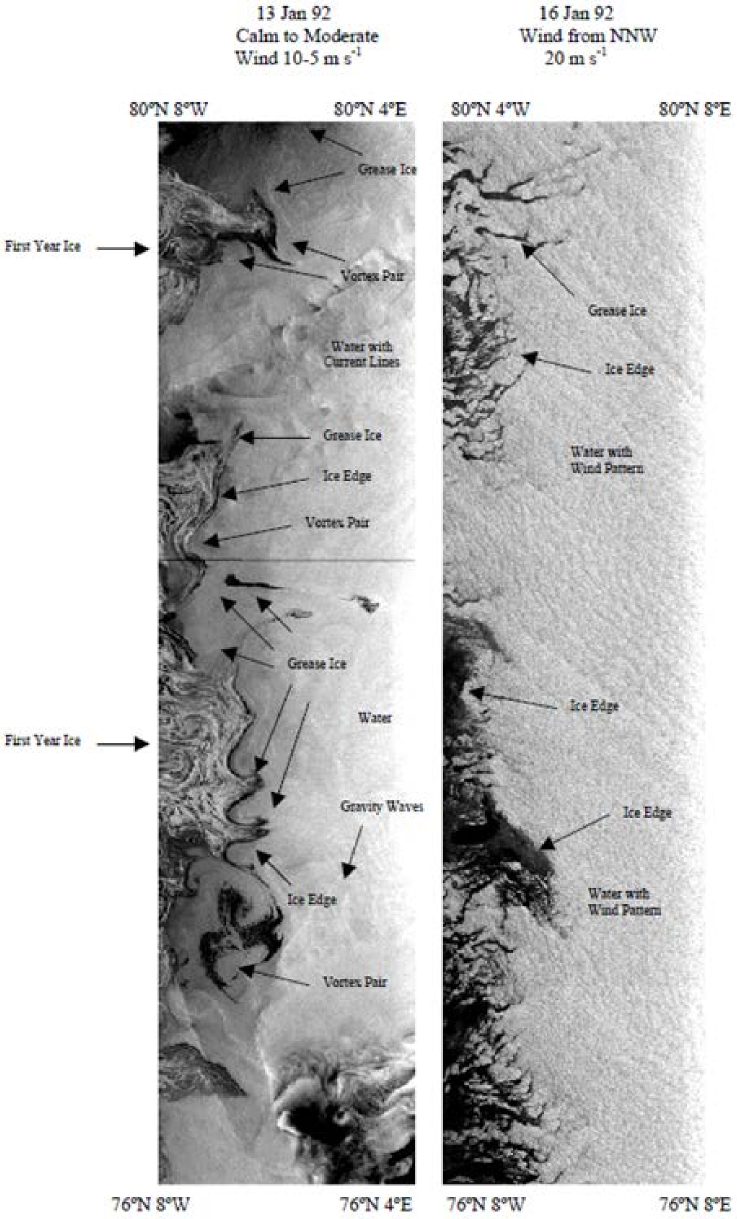

Figure 1.2 ERS-1 images from the Greenland Sea on January 1992 showing rapid ice edge due to strong off-ice winds. ©[54]

The radar backscatter from the ocean and sea ice differs. The backscattered reflection back to the satellite varies with the surface's electrical properties, the surface's roughness, the surface's geometrical structure, radar's frequency, polarization, and the incidence angle, θ. For ice, the backscatter depends on how wet the ice is, salinity, snow cover, and melt water. The ocean backscatter is influenced by the incidence angle, sea state, wind strength, and wind direction. See [25] for more information about surfaces and radar reflection. Figure 1.2 shows how complicated a SAR image can be and how difficult it is to see the difference between ice edge, water, rough sea, vessels, and icebergs.

2 Ship detection

Only literature that reports research on dual-polarimetry data is mentioned in this section. Some of the papers have done tests on both dual-polarization and quad-polarization data.

Radar scattering mechanisms from vessels have higher intensities compared to icebergs [37], due to for example strong backscattering from the area around the vessel's bridge. The large backscatter return is due to multiple reflections from the deck and the superstructure (pseudocorner) and also between the vessel and the sea surface. The backscatter from the ocean can be modelled by a K-distribution, which is a combination of the Rayleigh and Gamma distributions, representing small wind waves (short decorrelation times) and larger swell waves (longer decorrelation times), respectively. Other distributions that may be used for the clutter are Rayleigh, Gamma, Weibull, and the log-normal.

Quad-polarization is the best choice for ship detection because it gives the most information about the vessel and the surroundings. But quad-polarization data has limited swath width, thus making it difficult to use this data type operationally. Single-polarization or dual-polarization images have larger swath widths, and are used operationally today by the Norwegian Defence in Norway and Canadian Ice service (CIS) and the project Polar Epsilon in Canada (among others). Cross-polarization is preferred for smaller incidence angles (15° - 27°) [47] over all other dual-polarized combinations. HH/HV or VV/VH is preferred over HH/VV. Tankers of several hundred are often missed in wide swath modes in co-polarization at low incidence angles. Dual cross-pol mode performs better than either single polarized HH and VV or dual-polarized HH/VV [73]. Dual cross-polarization at steep incidence angles is better than HH, VV, and HH/VV. Using ENVISAT ASAR (Advanced Synthetic Aperture Radar) and CV580 SAR data sets as a test bed, it is shown that all polarization channels perform satisfactory at incidence angels above 27° [47].

Dual-polarization images are good, because the same images can be used for both oil spill detection and ship detection. To be able to do ship detection successfully, the right incidence angles and polarization channels must be selected, to be able to get the best ship to sea contrast.

For large incidence angles, both HH and HV can be used for ship detection [5] and [22]. Cross-polarization should be preferred for smaller incidence angles, while HH and HV can be used for larger incidence angles. The findings in [5], [22], and [35] are all in agreement with findings by KSAT. Using polarimetric data will reduce the number of false alarms in iceberg-prone areas [57].

The most usual method to automatically detect vessels is the threshold-based detection method. A bright target is detected if the target is above the selected threshold. In general, 10 dB is an appropriate threshold to detect vessels for SAR data with more than three looks [2]. Vessels appear as bright targets on a darker sea background. The background clutter is estimated using a K distribution. A very simple method is the N-sigma method, but the downside of this method is that the threshold has to be set manually each time. The Constant False Alarm Rate (CFAR) method is a more advanced method, and is for example used in the automatic ship detector Aegir at FFI [23],[4] and by the SUMO ship detector at Joint Research Centre (JRC) [21]. After the threshold has been found, the detection can be performed. The automatic ship detection in Aegir can be done on each available polarization channel separately or the polarization channels can be combined, and the detection can be done on the fused channel. The SUMO ship detector [21] is built up in the same way, and has shown good performance for a wide range of SAR modes (1 m to 100 m resolution) and for all vessel sizes and types. The SUMO ship detector removes azimuth ambiguities. Both Aegir and SUMO can run in semi-automatic mode where a user can interfere during the ship detection process and a fully automatic mode. Fully automatic ship detectors are needed when more SAR satellites are becoming available. The European Sentinel-1A and -1B satellites are acquiring many images each day. The satellites have an open data policy, which means that many images can be downloaded daily over an area of interest. It is time-consuming to analyze all these images manually, and an automatic ship detector is needed.

Vachon et al [56] (1997) presented a statistical approach by using RADARSAT-1 HH-polarization SAR data to do point target detection in a cluttered background. The different modes on the satellite were compared with the expected ship detection performance. ScanSAR Narrow Far was a good compromise between swath width and resolution. The paper presents a validation of these model predictions using data off the coast of Halifax, Nova Scotia under a RADARSAT SAR ship detection/validation field program in 1996. Ground truth data were from buoy measurements of wind and wave conditions and the SAR data had known vessels in the images. Some assumptions are done, and the validation of the hybrid C-band HH-polarization ocean cross-section model, ship radar signatures, and image probability density function (K-distribution) are presented in the paper. The paper gives good background theory of SAR ocean image statistics and radar cross section of ships.

Liu and Meek [41] presented the Likelihood Ratio Test (LRT) Polarimetric SAR (PolSAR) Ship Detection Application, which detects vessels in different polarimetric SAR systems, single-polarization, dual-polarization, and quad-polarization. The likelihood ratio test uses Neyman-Pearson criterion. The algorithm is based on the assumption that the target return is not close to the clutter level, so for weak targets the detection performance is not good enough. Optimization of the algorithm is needed at the time of the publication of the paper on three fields: 1) modified threshold calculation for small image areas, 2) weak target detection, and 3) reducing computation time. The software has the following features: point detection, statistical calculations, Pauli decomposition, and various image displays. Classification algorithms and new features for ship detection were under development at the time of publication. Future features needed are a clustering and segmentation capability (to detect and to reduce false alarms), the possibility to combine the different available polarization channels to reduce false alarms, land masking, calculating different statistical quantities, reducing ambiguities, decomposition methods to support target feature extraction, and image display options. The goal is that the algorithm can be used in wide area ocean surveillance for the Canadian Forces.

Howell et al [28] (2008) used multi-polarization SAR data to detect targets at sea. Convair-580 and ENVISAT ASAR HH/HV and HH/VV data were used in the analysis and receiver operating curves (ROC) were used to do the detection [42], which gives the opportunity to extract the detection and false alarm trade-offs.

There are cases where detection of large vessels at steep incidence angles gives best results using single-polarization cross-pol over dual-pol or single co-polarized channel. For incidence angles lower than 27°, cross-polarization is preferred for ship detection. For larger incidence angles, ship detection is easier, and dual-polarization HH/HV gives the best result. Most methods have only been tested in limited cases. More testing and research are needed to find out if the methods are reliable and which methods are well suited for the different scenarios.

There are some papers that do tests on how to reduce the false alarms, but they only consider one source of false alarms. Azimuth ambiguities were removed by Brusch et al [6], and Pastina et al [45] tried to discard false alarms by looking at the detected target's shapes and dimensions in SLC (Single Look Complex) COSMO SkyMed data.

3 Iceberg detection

It is important to be able to detect icebergs in the Arctic waters. With today's radar satellites, which deliver near-real-time (NRT) data, and the effective detection algorithms that exist, it is possible to provide iceberg locations for ice management for offshore operations, ship traffic etc. Icebergs frequently cross shipping routes, making a potentially hazard, and thus monitoring of sea ice and icebergs is important. Extensive research has been done since 1998 on satellite detection of icebergs [1], and SAR satellites have been used operationally since 1998 in Norway for ship detection and since 2003 in Canada for iceberg monitoring. To detect icebergs against a sea background a number of methods are being used based on first and second order statistics. The three most well-known methods are Probability Distributions Functions (PDF), Wavelet Transform and CFAR [20].

Radar scattering mechanisms from icebergs are from volume and surface scattering (see Figure 3.1), but have lower intensities than from vessels. Volume scattering is due to dielectric discontinuities from air pockets in the ice as well as lower absorption in non-saline glacial ice. Surface scattering depends on the surface structure of the iceberg, for example if the iceberg is covered by water or snow. The factors contributing to the total backscattered intensity are [37]:

- Orientation of the local surface roughness
- Vertical relief relative to other parts of the iceberg/sea surface

Only in rough sea/high clutter and with small icebergs relative to the SAR resolution, will it be hard to detect the iceberg.

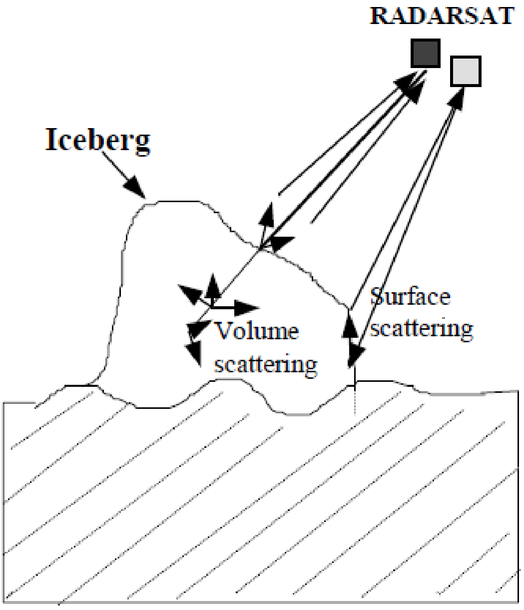

Figure 3.1. Volume and surface scattering from an iceberg. © [37]

The three most used methods for iceberg detection are N-sigma, CFAR and Receiver Operation Characteristics (ROC) curves.

Amec Earth & International wrote a report for Canadian Hydraulics Centre [1] in 2007 about the current state-of-the-art of iceberg management. The focus area was Grand Banks of Newfoundland on the East Coast of Canada. The report describes magnitude and range of iceberg conditions and summarizes algorithms to detect icebergs. The probability of detection is between 50 % and 75 % under strong wind conditions.

Silva and Bigg [55] (2005) tested a computer-based method to identify icebergs in higher resolution SAR images. To identify an iceberg it has to be detected, automatically segmented, and classified as iceberg or non-iceberg. User intervention is needed in the classification step used in by Silva and Bigg. After classification, icebergs are tracked between different SAR images using size and shape of the icebergs. The system was tested on three ERS-1 PRI (Precision Image Product) images during wintertime around Kapp Norvegia on the Eastern Weddell Sea coast. Both identification and tracking were shown to be successful.

3.1 Iceberg detection in dual-polarimetry data

When the noise floor is low, as for example on Convair-580, cross-polarization performs well for iceberg detection.

Randell et al [50] (1999) used RADARSAT-1 Fine mode data for iceberg detection off Newfoundland and Antarctic through research projects ADRO-1 and ADRO-2 for ESA and CIS.

Spaceborne SAR has high Noise Equivalent Sigma Zero (NESZ) values, which can contaminate iceberg backscatter [47]. Ship targets usually have higher backscatter, and will not be contaminated in the same way, and will be detectable in cross-polarization images. For larger incidence angles, HH-polarization is preferred for ship detection and cross-polarization is preferred for iceberg detection. For high resolution and low noise floor, as on the Convair-580, single cross-polarization is preferred, even if dual-polarization is available. For lower resolution and higher noise floor (ENVISAT ASAR) the icebergs have limited signatures in cross-polarization [73]. Cross-polarization is recommended if the sensor has a noise floor similar to the noise floor on Convair-580 (NESZ = -48 dB) and HH/HV or HH/VV is recommended if the noise floor is approximately at the level of ENVSIAT ASAR (NESZ better than -25 dB). A safe choice for maritime surveillance will be HH/HV. RADARSAT-2 has a noise floor better than both Sentinel-1 and RCM (Radarsat Constellation Mission), especially in the cross-polarization channel [47]. After the RADARSAT-2 era, it will be a degradation of the possibility to have operational iceberg detection [73]. Current space borne SAR systems have a NESZ ranging between -20 to -25 dB. The mean target signatures for icebergs in cross-polarization ranged between -21 and -38 dB, thus restricting the iceberg probability of detection [47].

Power et al [49] presented results from a study on iceberg detection done in May to June 2000 on RADARSAT-1 HH-polarization data on the East coast of Canada. Wide 2, Wide 3, and ScanSAR Narrow B data were used. Ground truth data were collected by aerial photography. SAR signatures of the icebergs were documented. Probability of iceberg detection as a function of iceberg size, wind speed, and incidence angle was found based on CFAR techniques. For incidence angles over 35 degrees, it is possible to detect icebergs at the same size, or larger, as the resolution of the SAR mode. Even in rough sea state, it is possible to detect larger icebergs.

Howell et al [32] (2012) developed models and tested them, and all iceberg targets embedded in sea ice were detected. The method focused on detection, false alarm removal, and false alarm prioritization. Ground truth is visual inspection of the polarization channels using false colour visualization methods. Iceberg size and shape are two important factors that will affect the probability of detection. Icebergs with more complicated structures have brighter radar returns than smoother surfaces. The QD (Quadratic Discriminant) detection algorithm was used to quantify dual-polarization detection as a function of iceberg shape, iceberg size, sea ice type, and sea ice concentration. Dual-polarization, over single-polarization, gives the possibility to differentiate between sea ice speckle and small icebergs, due to the fact that speckle are not correlated between polarizations. The model tested assumes a multivariate Gaussian distribution for sea ice and icebergs. The study has shown that sea ice backscatter not always is modelled well by a multivariate normal or K-distribution. More research needs to be done to examine this phenomenon. The QD method was used to remove 96 % of the sea ice speckle targets without removing too many iceberg targets. The Sequential Forward Algorithm (SFS) selected the features area, maximum HV, and mean HH for datasets from TerraSAR-X and RADARSAT-2. Sea ice speckle of size of the order of pixel spacing has minimal HV-backscatter and considerable HH-backscatter. The probability of detecting icebergs depends on iceberg size, icebergs shape, local incidence angle, sea ice ablation state, sea ice partial concentration, and sea ice type. Wind direction and wind speed are not major factors here, unlike iceberg detection in open water. The sensor noise floor is also important if it is not sufficient low enough.

C-Core performed a study on iceberg detection for Petroleum Research Newfoundland (PRNL) using dual-polarized RADARSAT-2, TerraSAR-X, and Cosmo SkyMed data [8]. High clutter areas, such as atmospheric effects, ocean currents, and sea ice, were used to refine the detection capabilities. As the targets are being identified, an iterative process recalculates the background statistics, thus producing a more accurate background clutter distribution. Radar cross section estimates are used to estimate the iceberg size. The C-Core software was being upgraded, at the time of the publication of the report (2013), to include dual-polarization SAR data and to improve the user interface, calibration, geo-referencing, and land masking [47].

Wesche and Dierking [58] used a pixel-based methodology to be able to automatically identify smaller icebergs, with longitudinal axis between 100 m and 18.5 km, in SAR images (HH and VV) from the Weddell Sea, Antarctica. SAR images acquired during different seasons and for different sea ice conditions have been analyzed. Icebergs, sea ice, and open water were analyzed in the images and radar backscattering coefficients were determined. Iceberg detection in their surroundings (sea ice or open water) depends on meteorological, oceanographic, and sea-ice conditions as well as pre-processing (for example speckle reduction) of the SAR images. How the incidence angle, orientation of the iceberg relative to the radar look direction, and the season of data acquisition influence the radar intensity backscatter from the icebergs have been analyzed. The sensitivity to incidence angle was largest compared to the other parameters, indicating that ice volume or a very rough surface dominate the backscattering. Iceberg detection in the open ocean and in low concentration sea ice depends on the sea state, meteorological conditions, wind conditions (speed, direction), and the ocean wave field. Sea ice and icebergs can be black when they are melting towards a lighter background (rough ocean). The variations of radar intensity of icebergs, sea ice, and open water fit well with the K-distribution. They did not find a robust difference between the values of sea ice and icebergs. When Lee filter is used, the classification accuracy is improved for icebergs in sea ice. Except for the speckle filters, they found no optimal general filtering procedure. Strong deformation patterns and other adverse sea ice conditions have great influence on the detection results. Low wind speed and freezing conditions are best for optimal iceberg detection. More robust methods can be developed for iceberg detection in open water with well-known model simulations of ocean radar signatures. It is also easier to detect icebergs in smooth new and first-year ice. Backscatter from sea ice may vary significantly with the complex surface structures on the sea ice, so a manual verification step is necessary after automatic iceberg detection. A two-step analysis may be required. First, an analysis of the regional sea ice conditions should be done and then the iceberg detection is done. Different frequencies and polarizations may help in unfavorable conditions.

Dierking and Wesche [15] used polarimetric RADARSAT-2 C-band SAR images to investigate the improvements of detecting icebergs in sea ice using radar polarimetry. In many cases the cross-polarization ratios, correlation coefficients between the HH- and VV-polarization channels, as well as the entropy/alpha parameters contribute significantly to the volume scattering. Radar backscatter from the weathered surface of the icebergs should be taken into account for small incidence angles. If the icebergs have flipped over, surface scattering is dominant, and the radar signatures are very similar to sea ice.

There are different properties and conditions that decide which backscattering mechanism that contributes: how the ice is, firm properties, environmental conditions, geometrical shape of iceberg, polarimetry, frequency of the radar, radar parameters, and imaging geometry [15]. Thus, an iceberg can look very different from image to image.

Hughes and Wadhams [34] studied dual-polarization SAR images in the western Fram Strait to do sea ice type classification and iceberg detection with sea ice background using a CFAR technique. Previously the CFAR technique has only been used for single-polarization, but now it was tested for the first time on both polarization channels to see if the false alarm rate could be reduced. To maximize the probability of detection, the CFAR threshold was lowered. 7 % of the detected targets were manually classified as icebergs, while the method did not detect 50 % of the icebergs that were manually classified as icebergs. The manual inspections are done in RADARSAT-2 quad-polarization data and limited field observations. Further investigations should be done to see if the icebergs can be identified by using their shape and velocity.

Lane et al [37] (2001) presented results from analyses of 40 SAR scenes collected during spring 2000. Iceberg detections in RADARSAT-1 Fine mode (8 m resolution), Wide mode (30 m resolution), and ScanSAR Narrow mode using target detection software were presented. 106 confirmed icebergs were within the images, and 104 of these were seen in the image visually. The target detection software presented pixel statistics for 35 of the iceberg targets, while the rest were under the land mask. The target detection software is developed by C-Core, and performs detection and discrimination. The software uses the CFAR technique, and gives a list of iceberg detections with pixel characteristics. Lane et al [38] (2002) presented further results using RADARSAT-1 Wide mode and ScanSAR Narrow B data. In different wind conditions for small, medium, and large sized icebergs, threshold and detection curves were generated. The CMOD4 wind model was used to model the cross section values of the ocean clutter. The values were verified with point source wind measurements. Iceberg detection is possible where the icebergs are at least of the size of the radar resolution cell, even though the wind is strong. Lane et al [39] (2003) used ENVISAT ASAR Image mode (HH) and Alternating Polarization (HH and HV) mode data for iceberg detection. Ground truth data were made by doing aerial reconnaissance. Data from RADARSAT-1 and ENVISAT was compared to show that the data are similar enough to make a combined sensor performance. Probability of Detection (POD) curves were made for different iceberg sizes and wind conditions. The RCS (Radar Cross Section) for the background ocean clutter was modelled using the CMOD4 wind model, and the calculations were verified using point source wind measurements. Both wind and incidence angle have effect on iceberg detection. The POD curves show a detection probability of 70 % for small, 85 % for medium, and 75 % for large icebergs at an incidence angle of 39°. For 45 degrees the numbers are 95 % for small, 95 % for medium, and 80 % for large icebergs. It is harder to detect icebergs for smaller incidence angles (31° - 39°). The probable reason why it is harder to detect large icebergs is because large icebergs have higher probability of being tabular shaped, and thus have lower backscatter. Lane et al [40] (2004) wanted to quantify the iceberg detection capability in sea ice using both RADARSAT-1 and ENVISAT ASAR images. Probability of detection curves for small, medium, and large sized icebergs in different ice type backgrounds were made based on sea ice backscatter values and iceberg data information. It was shown that it is easier to detect icebergs in sea ice for higher incidence angles (39 – 45 degrees) than for smaller incidence angles (31 – 39 degrees). It is harder to detect icebergs in sea ice than over ocean areas. Better detection rates can be achieved if sea ice segmentation is applied to the image. Larger icebergs are possible to detect, especially in leads in the ice and where there is differential drift [1].

Gill (2001) [20] used RADARSAT-1 ScanSAR Wide data from the marginal ice zones around Greenland to investigate ways to detect icebergs and sea ice edges operationally. Investigations of first-order statistics prior to the paper lead to the use of Power-to-Mean Ratio (PMR), which has been used to discriminate between different sea ice types and for iceberg detections. To supplement the PMR parameter, this paper investigated two new products: 1) the Gamma PDF to discriminate between open water and sea ice and 2) the CFAR product to detect icebergs. The CFAR method to detect vessels and icebergs has already been shown to be useful by Rey et al. [52] (1996), Vachon et al. [56] (1997), and Henschel et al. [26] (1997). There is one difference between the mentioned papers and the study done by Gill. The Gamma distribution is used to approximate the K-distribution to describe the background statistics, and a threshold for false alarms is used to remove targets that are not icebergs. By using the Gamma distribution you get a simple analytical expression for the probability for false alarm. In addition to reduce the speckle noise and then improving the target detection rate, incoherent averaging can be done on the image data. Validation with aircraft data showed promising results. They used a test to see if the products were helpful to operators in operational services to evaluate the products. Positive feedback from the analyst and promising results from the study made a conclusion to use the product developed for routine operations. The product doesn’t meet all the needs of the analyst, but it can be helpful to the analyst when the results are considered to be confident.

Frost et al [18] (2015), [19] (2016) proposed a novel algorithm to detect icebergs in SAR images. TerraSAR-X StripMap HH-polarization images from 2012 to 2015 are used to test the algorithm. It is based on Iterative Censoring CFAR (IC-CFAR) detector, which has shown good results for target detection. In addition to the traditional estimation of the statistical properties of open water backscatter (expressed by a PDF), the proposed algorithm analyzes recurring patterns (a novel filter) for example waves. Earlier studies on how to retrieve wind and sea state are used. Two small modifications on the CFAR detector are done to improve the results. In the first iteration step, gradient information is used to be able to see the difference between iceberg pixels and open water. In the second iteration step a merging process to merge iceberg pixels that belong to one iceberg by a front side driven region growing is done. The algorithm was tested with wind speeds up to 16.7 m/s and with incidence angles between 24.0° and 39.7°. False alarms due to rough sea and strong winds can be removed using this approach, and the false alarm rate was shown to be reduced with a factor three by the wave filter alone. The algorithm presented in the two papers produced a detection rate of 90-93 % and a false alarm rate of 0.002-0.003 false alarms per km^2. The proposed method optimizes the false alarm rate and the detection rate.

Ressel et al [51] (2015) used TerraSAR-X HH imagery, including both icebergs and sea ice, during spring season in the Baffin Bay outside the western Greenland coast. A processor for both sea ice classification and iceberg detection is presented. To do the classification texture features are extracted from the SAR images and a neural network is used to find areas of low sea ice concentration and different ice types. An adapted iterative CFAR detector is used to detect icebergs in the open water regions identified by the neural network. The outputs of the processor are sea ice boundary and iceberg positions. This comprehensive ice processor where additional information is also used is an example of a Near Real Time service that can be used in ice infested waters.

3.2 Iceberg detection in quad-polarimetry data

Kim et al [36] used fully polarimetric RADARSAT-2 SAR data to do polarimetric decompositions to be able to detect icebergs broken off from a glacier.

Marino and Hajnsek [43] used polarimetric data to do iceberg detection based on polarimetric perturbation analysis. It is a negative filter, focusing on the sea, and then all targets with features different than the sea are detected. In this paper the Notch filter is used for detection of icebergs using TerraSAR-X quad-polarization data. The results are promising, but ice ridges were also detected as icebergs.

Denbina et al [14] used pseudo quad-polarization data reconstruction from compact polarimetry to do iceberg detection.

3.3 Iceberg detection in compact-polarimetry data

Compact polarimetry will soon be available on the Canadian RADARSAT Constellation Mission (RCM). This will be a good compromise between dual-polarization and quad-polarization. Compact polarization images will give similar information content as quad-polarization images and similar swath width as dual-polarized images [47]. RCM will give improved iceberg detection capabilities. Denbina and Collins performed iceberg detection in simulated RCM data in [12].

4 Ship and iceberg discrimination

It is efficient to use SAR data for ship detection in the large ocean areas. Ship and iceberg discrimination is as important as ship detection in ice infested waters to avoid misuse of resources for investigation of possible vessels. Quad-polarization data, low noise floor, and high resolution are best to be able to detect vessels and icebergs and to be able to discriminate between them. Since wider swaths widths often are desirable, algorithms to discriminate vessels and ice are needed for lower resolution and fewer available polarization channels. It is easier to discriminate vessels and icebergs with increased resolution and decreased NESZ levels. Quad-polarization gives better performance than dual-polarization and dual-polarization gives better performance than single-polarization data. Compact polarimetry will probably give increased discrimination performance compared to dual-polarized data. The goal is to maximize the detection and classify most of the targets as vessels, icebergs, or other.

Ship and iceberg discrimination is well established, and the method used is adaptive threshold techniques. Most often a target feature identification and extraction is done followed by a feature selection, and last by a Quadratic Discriminant classification.

4.1 Ship and iceberg discrimination in dual-polarimetry data

The detection methods used to detect bright targets at sea cannot identify the targets, and therefore an algorithm that can discriminate between ice and vessels is needed [47]. The C-Core ICE-SAIS (Space-based Automatic Identification System) project used SAR and AIS data together to collect ground truth data to improve existing ship and ice discrimination methods [16]. C-Core has through several projects started in 1997 refined their ship and iceberg discrimination algorithm. Discrimination has been successfully demonstrated using a method described in [30], [29], [28], and [27]. The method uses the Bayesian-based maximum likelihood-quadratic discriminant function, which often is used in supervised pattern recognition. Howell’s goal in his master thesis [27] was to build the quadratic discriminant functions to build up class models of known ship and iceberg targets. Brightness, texture, and shape are features that describe the targets that are used to build each class model. When analyzing SAR images unknown targets can be compared with the class model to find the best fit. Howell has implemented and compared sequential forward selection and variants of exhaustive search algorithms (to find the best feature combination): exhaustive search and exhaustive ranked search. RADARSAT-1, ENVISAT AP dual-polarization HH/HV, and

EMISAR SAR data were used. Howell performed feature selection, algorithm training, and performance estimation, and achieved 90 % or better discrimination accuracy.

Howell et al [30] investigated a multi-polarized area ratio and HV signal to clutter ratio (SCR) for target discrimination in ENVISAT ASAR data. It is suggested that if a target is detected in the HH-channel, but not the HV-channel, then it is an iceberg. In the test all iceberg targets were detected in the HH-channel, but only 20 % were detected in the HV-channel. The discrimination ratio when using the HV/HH area ratio was 92 % and 97 % for the multi-polarized HV SCR. The vessels used in this test were large vessels. More research should be done to investigate the possibility to discriminate between smaller vessels and icebergs, especially smaller fishing boats comparable to the SAR resolution.

Howell et al [29], [31] (2006) used Baye’s rule to maximize the posteriori probabilities to do target classification in ENVISAT ASAR HH/HV images. To model the probability if the target belonged to a ship or iceberg class, the maximum likelihood Gaussian classifier was used. To optimize the feature space dependent multivariate classifier, all of these three algorithms were evaluated: Sequential Forward Selection (SFS), Genetic Algorithm (GA), and Exhaustive Search (ES). By using the two-class maximum likelihood model, the discrimination accuracy was 93.5 %. An experienced user is required to do proper tuning of the parameters used in the GA method to get useful results. The SFS method is a simpler method, and requires less computational power, and performs almost as good as the other methods. With few targets, the ES method can be used. The method was effective to do the discrimination, and didn’t use too much computation time.

Howell et al used multi-polarization SAR data to discriminate between iceberg and ship targets [28] (2008). Convair-580 and ENVISAT ASAR HH/HV and HH/VV data were used to do the evaluation. Quadratic discriminant, based on Bayesian decision theory, was used in the analyses together with feature selection (based on SFS). Features are added to an empty feature set if these features give better classification results compared with the other features. Dual-polarized data performed almost as good as quad-polarized data. It is recommended to use HH/HV data since HH is best to use for target detection due to the increased backscatter from icebergs in HH, while HV is good to use for discriminating between icebergs and vessels.

Howell et al,[30] (2004) and Deepakumara et al [11] (2013) used ENVISAT and RADARSAT-2 data to perform discrimination between icebergs and ships. Deepakumara chose the best set of features for discrimination based on target features from image segments in the simulated pictures. C-Core has developed a classic pattern recognition based algorithm that is used for ship and iceberg discrimination. This approach is based on features (target morphology, polarimetric decompositions, radar cross section [16]) obtained from SAR data using ground truth to describe the unique characteristics of ships, icebergs and other classes [47]. The classification methods linear discriminant, quadratic discriminant, neural network, K-nearest neighbor, and support vector machines [47] have been investigated for ship and iceberg discrimination. There is not one method that outperforms the others. It depends on the image data that is going to be classified. With normally distributed data (based on the Bayesian minimum error rate), the quadratic discriminant method outperforms the other methods. The method with target feature optimization is done using the SFS algorithm. It is also run-time efficient, and it is possible to add new features to the feature set if necessary. This can be done by evaluating feature combinations to get a feature space, and then to improve the discrimination algorithm and class separability [73].

Work supported by DRDC presented in the C-Core report [73] analyzed the benefits of using multi-polarization data (Convair-580 quad-pol and ENVISAT dual-pol) for detection and discrimination of vessels and icebergs. 2207 targets were analyzed in the available data. ROC (Receiver Operator Characteristics) analysis was used to evaluate the detection rate and the false alarm rate and the trade-offs between the two as described by Liu et al [42]. A Constant False Alarm (CFAR) method was also used to evaluate the target detection capabilities in single- and dual-polarization data. The QD method was used for discrimination, and the rate varied with resolution and polarization between 93 % and 100 %, 93 % for simulated RADARSAT-2 Standard HH, 95 % for ASAR HH/HV, 97 % for ASAR HH/VV, and 100 % for full resolution VV/VH CV580 SAR data. At steeper incidence angles, HH/HV is preferred over HH/VV. This result may also hold for icebergs and small vessels, but this has not been tested properly. Dual-polarization is preferred over single-polarization, while quad-polarization gives only marginally better results than dual-polarization HH/HV and VV/VH using CV580 SAR data [73].

RADARSAT-1, ENVISAT ASAR, CV580 (airborne), TerraSAR-X, and COSMO SkyMed data has been used to test the algorithm. The discrimination capabilities have been analyzed as a function of iceberg size, wind speed, radar resolution, and radar geometry. When dual- and quad-polarization images became available, the new possibilities using multi-polarization have been evaluated [47].

The discrimination results are very accurate, especially for high resolution data (for example RADARSAT-2 Fine [16]). The algorithms are never 100 % accurate, and all extra information is valuable, for example the use of AIS data to identify which of the targets that are vessels. It has been shown that it is possible to discriminate between ships and icebergs for different resolutions and polarizations.

C-Core has done several studies and tests on ship and iceberg discrimination. They have tested their software on SAR data from several sensors, with different resolutions and polarizations. C-Core did a study for the Centre for Arctic Resource Development (CARD), and presented the results in a C-Core report in 2012 [7]. QD models and dual-polarized SAR data (RADARSAT-2 Wide and TerraSAR-X Stripmap SAR images) were used to detect icebergs in sea ice and to reduce the numerous false alarms from the sea ice backscatter. 134 icebergs were used to characterize the iceberg backscatter, and the QD model was used on 251 icebergs in 17 SAR images of the Labrador shelf and the west coast of Greenland. The QD model was used to reduce the number of false alarms. Sequential forward selection was used to determine the features (target area, HH mean backscatter, and HV maximum backscatter) needed to reduce the false alarms. 97 % of the false alarms were eliminated, keeping 97 % of the icebergs in the RADARSAT-2 images and 100 % of the icebergs in the TerraSAR-X images. This has been implemented in C-Core’s operational service for iceberg surveillance in the Iceberg Detection Software (IDS).

C-Core also did another study supported by the CSA (Canadian Space Agency) Earth Observation Application Development Program (EOADP) [9]. Data from RADARSAT-2 Fine and Fine Quad modes was used to simulate data from the RADARSAT-2 SCN (ScanSAR Narrow) and Maritime Satellite Surveillance RADAR (MSSR) modes. The classifiers had accuracies of 85 % and 95.6 % for SCN and MSSR, respectively. Recommendations for further work are to get a larger database and to test the MSSR classifier on real MSSR data.

C-Core now uses computer vision training (neural nets, state vector machines etc) for ship and iceberg discrimination in dual-polarization imagery, for example. A segmented target is used to extract target features, for example total RCS (for each channel), maximum pixel value (for each channel), target morphology, and channel ratio. C-Core is currently doing some work on the Sentinel-1 IW mode for ship and iceberg discrimination [46].

A large database of vessel and iceberg targets have been collected in a project presented in [10] and funded by CSA EOADP. AIS data has been used to identify the vessels. The goal is to develop robust classifier algorithms in SCW data. The classifiers have accuracies of 80-85 %.

Figure 4.1 Left: Container ship in a large pan of first-year ice. © Don Isaacs (CIS).

Flett et al [17] (2000) used RADARSAT-1 ScanSAR and Wide mode data off Newfoundland to test ship and iceberg discrimination.

Brekke and Anfinsen [5] discuss the possibilities to detect vessels in ice-infested waters (see an example in Figure 4.1) in Synthetic Aperture Radar images using local image statistics. The letter focuses on the detection stage where the usual approach is to detect vessels in all available polarization channels (HH/HV or VV/VH for dual-polarized images). The backscatter statistics of the sea ice clutter is modelled using the K-distribution. Different scenes have been evaluated: homogenous ice free from cracks and ridges, open water and ice-infested waters, ice edge, and open water. They investigated if the K-distribution is a good model for one look dual-polarization VV and VH data, and if it can be used to model sea ice clutter. The Kolmogorov-Smirnov and Anderson-Darling test statistics for both VV- and VH-polarizations are used to assess the goodness of fit of the K-distribution model. The authors have also tested the impact using the Method of Log Cumulant (MoLC) estimator to be able to find the shape parameter of the K-distribution. This method was compared to the Method of Moments (MoM) based on goodness-of fit testing of the model together with the observed data. The MoLC is a more advanced method than the MoM, and produces lower variance than the MoM method. Dual-polarized RADARSAT-2 SAR data have been used to evaluate a constant false-alarm rate ship detection algorithm, using the K-distribution with the MoLC estimator. The results from the tests show that the approach may work to do ship detection in ice-infested waters, and that automatic ship detection in ice-infested waters has a potential. The most promising results are shown in scenes with smooth ice, while for scenes with mixed sea ice and open water, many false alarms are being produced. All vessels were detected in the test.

Meyer and Hinz [44] used wavelet prescreening, filtering of the resulting objects, and adaptive thresholding for ship detection over inhomogeneous background. The method was tested on ALOS PALSAR and RADARSAT-1 ScanSAR images with sea ice, and detected valid ships “of better than” 70%, but with an extra 25 % false alarms.

4.2 Ship and iceberg discrimination in quad-polarimetry data

Hu et al [33] used quad-polarimetric SAR images and a coherent Time-Frequency (TF) decomposition to do ship detection. The polarimetric SAR data can first be decomposed in azimuth direction, in range direction, or in both directions. Transformation of the SAR data into the frequency domain was done, and then the spectral bands were split. Then the TF coherence indicator, which is a statistical descriptor, was used to do target detection in different backgrounds. The different polarimetric coherences over the sub bands for ships, icebergs, sea ice, and open water were used to separate the targets. The proposed method can effectively do ship detection in backgrounds as open sea with artifacts, sea ice areas etc. The method was successful in detecting a vessel in sea ice in three different SAR images. The method was also able to separate ships from image artifacts, such as range ambiguities and small islands. This technique might be used for dual- and compact-polarization.

RSI (2004) [53] and Power et al [48] (2012) showed that there are benefits of using quad-polarization SAR data to do ship and iceberg discrimination. But the benefits are not so great as to defend the use of the narrower swath widths that quad-polarization data gives.

Hannevik et al [24] used RADARSAT-2 SAR quad-polarization data. The different polarization channels were used to perform the polarimetric decomposition methods Pauli, circular, Krogager, and Yamaguchi, to better be able to discriminate between ships and ice. The

Yamaguchi decomposition method gave promising results to discriminate vessels from sea ice or ocean background. More research needs to be done to see the difference between icebergs and vessels.

Bentes et al [3] (2016) presented a study on ship and ice discrimination using Convolutional Neural Networks (CNN) for operational scenarios. High resolution TerraSAR-X StripMap quad-polarization images were used. The proposed CNN model was compared with a Support Vector Machine (SVM), and the CNN model used in this test indicated superior results and a better generalized model over the SVM method. 90 % of the data were used to train the CNN architecture, and the model is validated using the remaining 10 % of the data.

4.3 Ship and iceberg discrimination in compact-polarimetry data

Denbina et al [13] described ways to detect ships and icebergs (based on the likelihood ratio test of Liu and Meek [41]) and to discriminate between them in medium and low resolution circular polarization modes on the RADARSAT Constellation Mission. The compact polarization data were simulated using RADARSAT-2 Fine quad-pol data to achieve data with the same resolution and noise floor as planned on the RCM. The properties of the received polarization ellipse were used to adjust the false alarm rates from pixel to pixel when doing the target detection. The polarization ellipse orientation is given by the values mean ψ, mean χ, and mean m, which are the polarization ellipse orientation, polarization ellipse ellipticity, and degree of polarization. An SVM classifier was used to discriminate between ship and iceberg targets. The discrimination was done using a stratified 10-fold cross-validation, which means that the data were divided into ten different folds/groups where each group contained about the same number of ships and icebergs. The discrimination accuracy for CTLR (Circular Transmit Linear Receive) medium resolution data were 99.3 % and 96.5 % for HH/HV dual-polarization data. Simulated RADARSAT Constellation Mission data gave good results for target detection and ship and ice discrimination.

5 Further work

Ship and iceberg detection, as well as ship and ice discrimination, can be difficult, especially if the background is heterogeneous. If the detection is going to be done in heterogeneous background clutter, as for example in ice-infested waters or where there is variable ocean background, other approaches than what have been described in the previous chapters are required. Multi-mode, sub-aperture and multi-polarization analyses, including SCM (Sub-aperture Cross-correlation Magnitude), polarimetric notch filters, and time-frequency polarimetric coherence analyses have shown potential to be used [47]. These techniques should be evaluated with the goal of improving already existing operational software.

False alarm algorithms to be able to discriminate between ships, icebergs, and false alarms as for example ocean features, sea ice, image artifacts, and environmental clutter are lacking. Possible techniques are sub-aperture and polarization coherence together with classic pattern recognition techniques. The compact polarization possibility on the upcoming RCM might reduce the false alarm rates. RCM has a relatively high noise floor, and thus it is necessary to study how it is possible to overcome the challenge with the NESZ shortcomings. No documentation is found on how to reduce false alarms when both icebergs and ships are present at the same time [47].

Further analysis should be done on iceberg detection and ship and iceberg discrimination [73]. Some analysis has been done on RADARSAT-2 Fine and ScanSAR Narrow modes by Canadian Ice Service (CIS). The results are promising and better than ASAR, even for ScanSAR resolutions, and good enough for operational iceberg surveillance. Further work has to be done on the other RADARSAT-2 modes: RADARSAT-2 ScanSAR Wide, Standard, and Maritime Satellite Surveillance Radar (MSSR) modes. Simulations and analysis should also be done on Sentinel-1 and RCM. Analysis on simulated data can be done since RADARSAT-2 Fine mode can be resampled and used.

The major weakness in ship and iceberg discrimination is the false alarm rejection. Discrimination is based on the unique sub-aperture, polarization coherence, and feature sets for the false alarm classes. The last one is included in C-Core’s QD algorithms [47].

Compact polarimetry on for example RCM will provide new possibilities for ship and ice discrimination, because it is expected to perform better than dual-polarization, but not as good as quad-polarization, and keep the large swath width as dual-polarization data has. Compact polarimetry may help deal with the issues of the higher noise floor on RCM compared to RADARSAT-2 [47]. More studies are needed to explore the benefits of using compact polarimetry for ship and iceberg discrimination.

C-CORE has proposed studies to investigate the RCM modes to study the compact polarization scattering and to develop detection and discrimination algorithms for compact polarization. The studies will concentrate on ship detection at different resolutions, low noise at 100 m resolution and medium resolution (30 m and 50 m) modes [47].

6 Conclusion and recommendations

There is still much work to be done in the field of ship detection, iceberg detection and ship and iceberg discrimination. Especially, there are challenges when doing these tasks in heterogeneous background.

Research has been done around the world on ship detection in sea and ice, iceberg detection in sea and ice, as well as ship and iceberg discrimination. There are many good automatic ship detectors. Ship and iceberg discrimination is more complicated. It seems like Canada and C-Core have the best ship and iceberg discrimination algorithm operational today. They are using several methods in computer vision training, for example neural nets and state vector machines.

FFI’s goal is to implement a ship and iceberg discriminator in the FFI developed ship detector Aegir [4], [23]. Since C-Core already has very good experience in this field, it is natural to look at what they have done and achieved. To classify if a target is a vessel or ice, we have to do some tests on our own since classification is location dependent [46]. The advice from C-Core is to build up one or more data bases over our interest areas (for example East Greenland, Barents Sea, and north of Spitsbergen). The images have to include in total several hundred validated vessels and icebergs. This can be done by collecting SAR images from different satellites and different modes. To verify if the targets are vessels or ice can be done by using AIS and possibly other sources as optical satellite imagery, Coast Guard vessels, air plane observations etc. The data base will be used to do the training. The results can be used to implement an algorithm in Aegir.

Right now C-Core is doing some work on Sentinel-1 IW (Interferometric Wide) mode [46]. That might be a place to start. RADARSAT-2 ScanSAR Wide and Narrow modes are also of interest for Norwegian operational users.

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Abbreviations

AIS	Automatic Identification System
ASAR	Advanced Synthetic Aperture Radar
CARD	Centre for Arctic Resource Development
CFAR	The Constant False Alarm
CIS	Canadian Ice Service
CNN	Convolutional Neural Networks
CSA	Canadian Space Agency
CTLR	Circular Transmit Linear Receive
EOADP	Earth Observation Application Development Program
ES	Exhaustive Search
FFI	Forsvarets Forskningsinstitutt
GA	Genetic Algorithm
H	Horizontal polarization
HH	Horizontal sent – Horizontal received
HV	Horizontal sent – Vertical received
IDS	Iceberg detection Software
IC-CFAR	Iterative Censoring CFAR
IW	Interferometric Wide
JRC	Joint Research Centre
LRT	Likelihood Ratio Test
MDA	Maritime Domain Awareness
MoLC	Method of Log Cumulant
MoM	Method of Moments
MSSR	Maritime Satellite Surveillance RADAR
NESZ	Noise Equivalent Sigma Zero
NRT	Near Real Time
PDF	Probability Density Function
PMR	Power-to-Mean Ratio
POD	Probability of Detection
PolSAR	Polarimetric SAR
PRI	Precision Image Product
PRNL	Petroleum Research Newfoundland
QD	Quadratic Discriminant
RCM	Radarsat Constellation Mission
RCS	Radar Cross Section
ROC	Receiver Operating Curves
S-AIS	Space-based Automatic Identification System
SAR	Synthetic Aperture Radar
SCM	Sub-aperture Cross-correlation Magnitude
SCN	ScanSAR Narrow
SCR	Signal to Clutter Ratio
SFS	Sequential Forward Algorithm
SLC	Single Look Complex
SVM	Support Vector Machine
TF	Time Frequency
USGS	U.S. Geological Survey
V	Vertical polarization

VH	Vertical sent – Horizontal received
VV	Vertical sent – Vertical received

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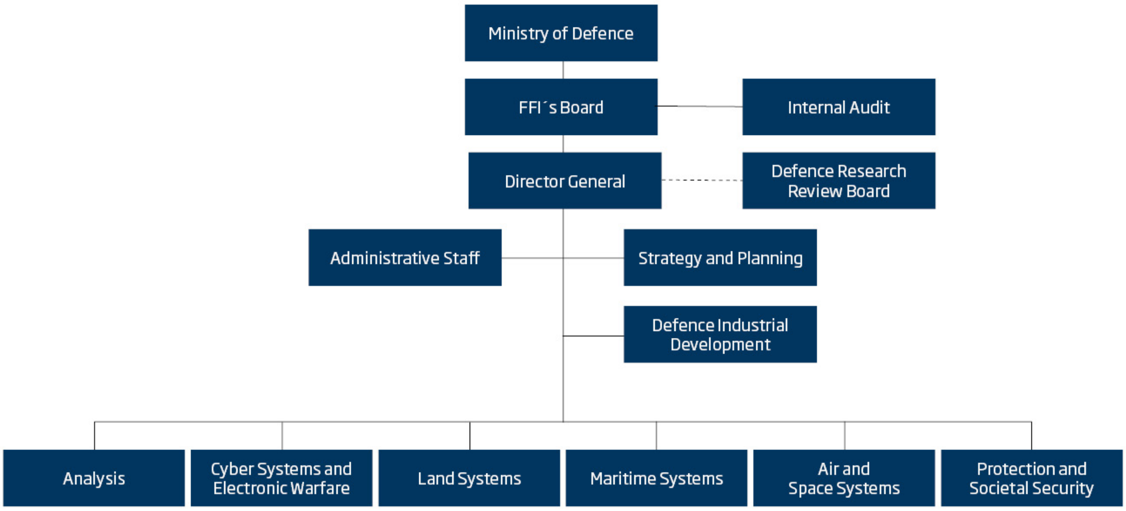

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