Detection and tracking of ships in the Canadian Arctic

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Detection and tracking of ships in the Canadian Arctic

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Abstract The Canadian Arctic is becoming increasingly important as climate change and economic pressures stimulate increasing activity in the region. The number of transits, cruise ships, and adventurer expeditions in this area is on the rise. Ensuring environmental, economic, archeological, defence, safety and security responsibilities in this challenging area has resulted in many recent investments including the Arctic Offshore Patrol Vessels and the RADARSAT Constellation Mission. This chapter will explore the challenges in detection and tracking of ships in the Arctic from perspectives including: ship-ice discrimination in remote sensing, sparse data tracking, effects of constrained navigation, and operational decision aids.

Keywords Arctic, surveillance, situational awareness, detection, sparse data

1 Introduction

The Canadian Arctic is a vast and remote area which is becoming increasingly accessible due to changing environmental conditions. There is currently a wave of investment in new immediate and future capabilities for the Canadian Arctic on land, in sea and in space (Canada's Northern Strategy 2013). New facilities are being constructed, new ships are being built, and satellites are being launched. The responsibility for the North spans across many Canadian government departments. The Canadian Coast Guard provides a significant service to the Arctic through the provision of icebreakers, monitoring, regulation, and search and rescue. The Department of National Defence (DND) also plays an important role in the defence of the Arctic, and will be receiving a new fleet of Arctic Offshore Patrol Ships (AOPS) to patrol the north. Furthermore, remote sensing capabilities, like the privately-owned RADARSAT-2 satellite that is used to detect ships opera-

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tionally by DND's Polar Epsilon project, and the future RADARSAT Constellation Mission (RCM), in addition to increasing commercial satellite sources, provides a potential means to monitor vessel activity, environmental impact, and ice within Canadian Arctic waters. Much of this northern development is being supported by new facilities such as the Nanisivik Naval Facility on Baffin Island to refuel ships, and the Canadian High Arctic Research Station (CHARS).

The Arctic is also an important economic resource for Canada. Industries in fishing, natural resources, and tourism in the Arctic are some examples of this economic value. All of this activity also carries a risk and responsibility, such as providing search and rescue. For example, Arctic adventurers navigate the Arctic waters in various pleasure craft which are at risk from the environmental conditions and can lead to a search and rescue event.

Monitoring the activity in the Canadian Arctic is an important maritime safety and security challenge. The increasing seasonal accessibility of the Arctic opens up this northern approach for potential criminal or adversarial exploitation. To address these threats, whether through prevention or deterrence, two integral components are situational awareness in the Arctic and subsequent response capability.

This chapter focuses discussion on the situational awareness challenges and capabilities vice response capabilities. Section 2 presents some of the Canadian surveillance capabilities in the Arctic, and section 3 presents some examples of Arctic situational awareness achieved through these capabilities, as well as some future avenues of research for analysis and operational decision support.

2 Present and Future Capabilities

Sources of ship position information in the Arctic include the Northern Canada Vessel Traffic Services Zone Regulations (NORDREG), Space-based Automatic Identification System (S-AIS) and to a lesser extent a few Terrestrial AIS stations, Long Range Identification and Tracking (LRIT), Space-based Synthetic Aperture Radar (SAR), and open source reporting.

Managed by the Canadian Coast Guard, NORDREG is a regulation requiring vessels greater than 300 gross tonnes, vessels towing or pushing with a combined 500 gross tonnes or more, or vessels with pollutants or dangerous goods to periodically report their position and status (Canadian Coast Guard 2013). This regulatory reporting provides information which helps to ensure the safety and security of Arctic vessels, and also serves as a means to protect the Arctic environment.

Automatic Identification System (AIS) technology is an International Maritime Organization (IMO) mandated vessel safety system which is mandatory for vessels with passengers or greater than 300 gross tonnage, mandated by the International Convention for the Safety of Life at Sea (SOLAS), however, AIS can also be voluntarily used by others. AIS operates via Very High Frequency (VHF) radio transmissions at 161.975 MHz and 162.025 MHz and there are also two classes of AIS transceivers: class A (with a minimum 12 Watts transmission power), and class B (with a maximum of 2 Watts transmission power). Class B transmitters are intentionally limited in their transmission power to prevent saturation of the available radio bandwidth, and are used by non-mandated vessels for the primary purposes of safety and navigation. Class A transmitters provide position updates every three minutes or up to every two seconds when maneuvering while class B transmitters typically transmit every 30 seconds. Notably, many Arctic adventurers carry either class B transponders and/or other satellite transponder systems despite not being required to do so.

In order to receive these AIS radio messages, only an antenna and decoder are required. While initially envisioned to be used for local area communication of ship positions, coastal AIS receiving antenna networks provide a means to monitor traffic within radio range of antennas effectively in real time. By placing receiving antennas on aircraft or satellites, the area of coverage for AIS monitoring is greatly increased. While satellite-based AIS receivers provide a wide area of coverage, two drawbacks are in the reduced persistence of sensing as the satellite orbits out of a monitoring area (this drawback is being addressed by increasing the number of satellites in orbit), and a drawback in the degradation of detection performance due to the nature of the AIS protocols (Cervera and Ginesi 2008).

The nature of the detection performance degradation in S-AIS has been estimated as a geospatial function (Papa 2012), and as a function of the number of ships in the satellite field of view (Tunaley 2011). However, even with the suboptimal detection capabilities, the availability and relatively low cost of an AIS transceiver means that many non-mandated vessels can also provide their positions via AIS. Specifically, the use of class B AIS means that small participating vessels can be tracked via S-AIS.

The LRIT system is an IMO global vessel monitoring system for SOLAS mandated vessels, which provides periodic updates of participating vessel positions and status when within 1000 nautical miles of a nation's coastline. The LRIT system is different from the AIS system in the sense that it uses real-time satellite communications to provide the positions of vessels. Every LRIT participating ship provides position updates every six hours, but more frequent updates are possible by request of a nation. In the Polar Regions, many satellite communication systems are not as readily available since most communication satellites focus on serving regions at range from the equator, and so LRIT tracking is typically achieved via the Iridium constellation, which provides service in the Arctic region.

Active sensing is defined here as a capability which can detect non-cooperative or non-emitting vessels. Active sensing therefore provides a benefit over the aforementioned voluntary, regulatory, and passive capabilities. This enhances maritime security by being able to detect vessels which are either difficult to track passively, or may be attempting to evade detection for illicit purposes. Specifically, the RADARSAT-2 satellite, and the future RCM provide a means to achieve active sensing. These satellites have a sun-synchronous polar orbit, which means that they have frequent access to the Arctic region as access is constrained by the satellite duty cycle (Canada Space Agency 2015).

While SAR satellites provide a tantalizing opportunity to detect ships in the Arctic, there are also some significant challenges to overcome in order to exploit SAR ship detection in this environment. The primary challenge is the discrimination of ships from icebergs. Other related challenges, not discussed in this chapter, include ship detection performance (missed detections), and false detections. In order to achieve ship-ice discrimination, there are multiple techniques which can be used. The most basic of which is the association of SAR imagery with information from other systems such as AIS. Vachon, Kabatoff and Quinn (2014) describe the SAR-AIS Association System (SAAS), developed by Defence Research and Development Canada (DRDC) which achieves this association. In this way, SAR detections which are truly ships can be readily identified. The RADARSAT-2 satellite does not have an on-board AIS receiver therefore SAAS requires alternate sources of AIS ship detections. The RCM, however, will include on-board AIS receivers. In the case that a ship is not providing its position via AIS or other reporting means, other image processing techniques for ship-ice discrimination in the SAR imagery must be used.

Ship-ice discrimination can be enhanced through increased imagery resolution, and the configuration of transmitted and received radar polarizations (Howell et al. 2004; Howell et al. 2008). Ice and ships have different sensitivities to the radar polarizations and result in different polarizations on the reflected radiation. Transmission and reception polarization can be varied to transmit in horizontal (H) and/or vertical (V) polarization, and receive in H and/or V polarization. In quad polarization modes, the radar transmits both H and V polarized radiation and receives both H and V polarized returns. The combinations of these signals can be used to implement detectors that can better discriminate between ice and ships. Howell et al. 2004 and Howell et al. 2008, for example, report ship-iceberg discrimination performance accuracy using HV and HH polarizations on the order of 92% to 96% for large vessels in images with 30m resolution and swath widths between 56 km and 105 km.

Other enhancements to ship detection in SAR are also achieved via special maritime surveillance beam modes. Vachon et al. (2014) presents two RADARSAT-2 beam modes tuned for maritime surveillance, under the title Maritime Satellite Surveillance Radar (MSSR). The Detection of Vessels, Wide swath, Far incidence angle (DVWF) mode is specially designed for vessel detection, and the Ocean Surveillance, Very wide swath, Near incidence angle (OSVN) mode is tuned for general ocean surveillance, including ice detection and oil spill detection. The DVWF mode operates using a single polarization, and the OSVN using dual polarization.

To fully address the issue of maritime security, it is not sufficient to just develop and employ additional sensing capabilities. Future maritime Command and Control (C2) systems will have to support the processing and exploitation of greater quantities, varieties, and more complex information. For example, due to the non-persistent nature of the space-based SAR detections, and the vast area of surveillance with relatively few ships to detect in comparison to other parts of the world, any ship detections are spatially sparse in their nature. Generating effective situational awareness from this temporally and spatially sparse data presents an interesting research challenge. By fusing the available information, a clearer picture of maritime activities can be generated. Nonetheless, use of RADARSAT-2 in the Arctic for ship detection remains a practical challenge in terms of performance constraints due to the relatively low densities of traffic and high clutter due to land and ice.

The DRDC project for the next generation maritime C2 systems has as one component focusing on support for maritime and coastal Intelligence, Surveillance and Reconnaissance (ISR). To deliver a holistic Canadian solution for C2, one must consider the unique Canadian Arctic aspects in the ability to achieve maritime ISR in the Arctic which includes consideration of the types of information and data currently available in the existing C2 systems, and consideration for unique requirements to enhance and exploit Arctic situational awareness.

3 Situational Awareness

While navigable accessibility in the Arctic is increasing, in-situ sensing and communications remains a challenge due to the harsh environmental conditions. Satellite based transponder systems (e.g. LRIT and S-AIS) are the primary sources of information to track ships and active remote sensing capabilities (e.g. RADARSAT-2) are contributing to an increasing extent.

Fig. 1 shows all of the open-source and unclassified ship position reports captured in the Royal Canadian Navy's (RCN) Global Position Warehouse (GPW) from May 1, 2011 to July 1, 2015. GPW is a database which archives ship position reports which were processed by the Navy command and control system. There is no guarantee of correctness in this dataset, but it does record reported (as received) position, time, and any available identifying information. Shown also is the ice extent for the week of September 17, 2014, which represents the minimum ice extent for 2014. This ice data was retrieved from the United States National Oceanic and Atmospheric Administration (NOAA) Optimum Interpolation (OI) Sea Surface Temperature (SST) V2 dataset (method of Reynolds et al. 2002) and was retrieved via the National Centers for Environmental Information.

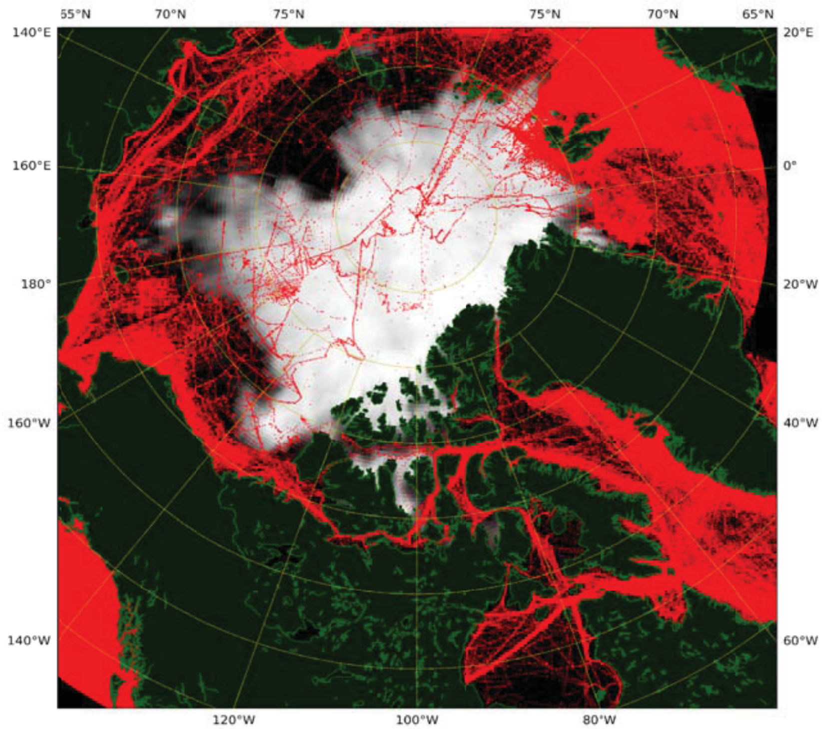

Fig. 1 All position contacts in GPW over five years from May 1, 2011 to July 1, 2015, inclusive, plotted as red dots. For spatial reference, the ice extent shown is from the week of September 17, 2014

It is clear from the spatial distribution of position contacts that there is a significant amount of activity in the Arctic, and one can begin to observe potential patterns and activities from just the basic positional observations shown in Fig. 1. Not shown in Fig. 1 is the number of transits and many of the position reports could be from a smaller subset of ships making repeated journeys. The density of these observations is presented in Fig. 2, which highlights the areas of higher density of position reports. In interpreting Fig. 2, one should be careful to consider the convolution of increased reporting frequency due to sensor locations, and increased reporting due to actual traffic density. This means that while the density in Fig. 2 is representative of the density of traffic, it should not be taken as an absolute value for traffic density (as it is conditioned also on sensor persistence and update rates).

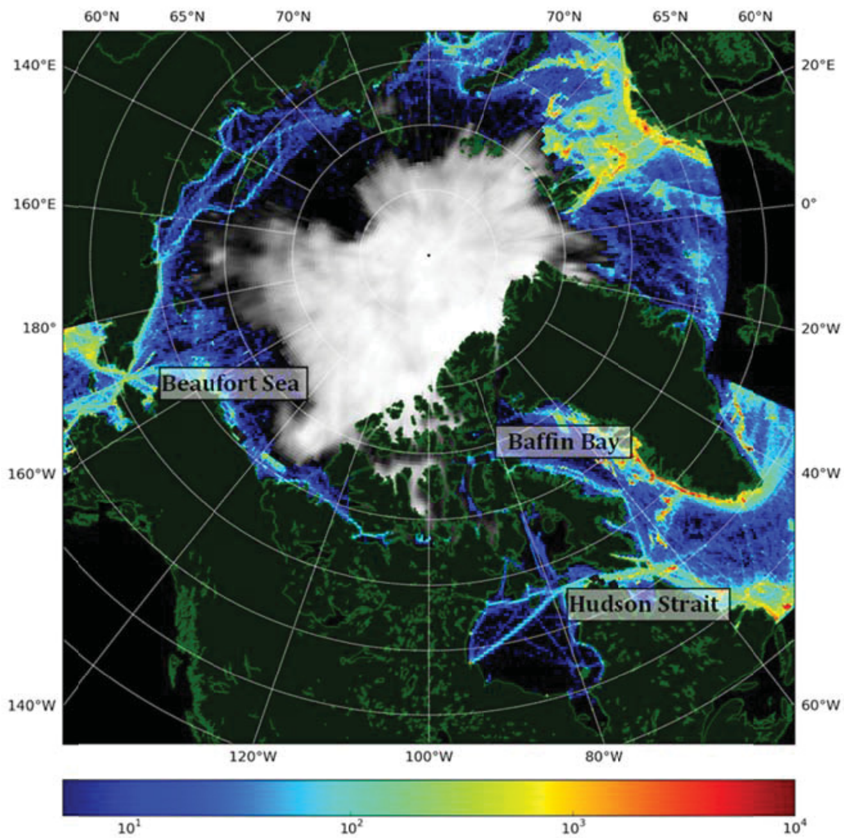

Fig. 2 Density map of position contacts with a grid size for the density layer of one degree latitude by one degree longitude, and logarithmic color scale. Each of the three major maritime approaches to the Canadian Arctic are labelled

In Fig. 2, three primary active maritime approaches to the Canadian Arctic are labelled: the western approach from the Beaufort Sea along the coast of Alaska into Canadian waters; the eastern approach south of Greenland through the Davis Strait and into Baffin Bay (and potentially the North West Passages); and the eastern approach through Hudson Strait into Hudson Bay or into the North West Passages via Fury and Hecla Strait The investigation of this dataset presented next will investigate the eastern Arctic approaches.

One of the labels captured by GPW is the category of ship in terms of merchant (commercial) vessels, government (i.e. Navy or Coast Guard) vessels, or fishing boats. Fig. 3 presents colour coded detections in the Baffin Bay area to illustrate the visible vessel patterns in the Arctic.

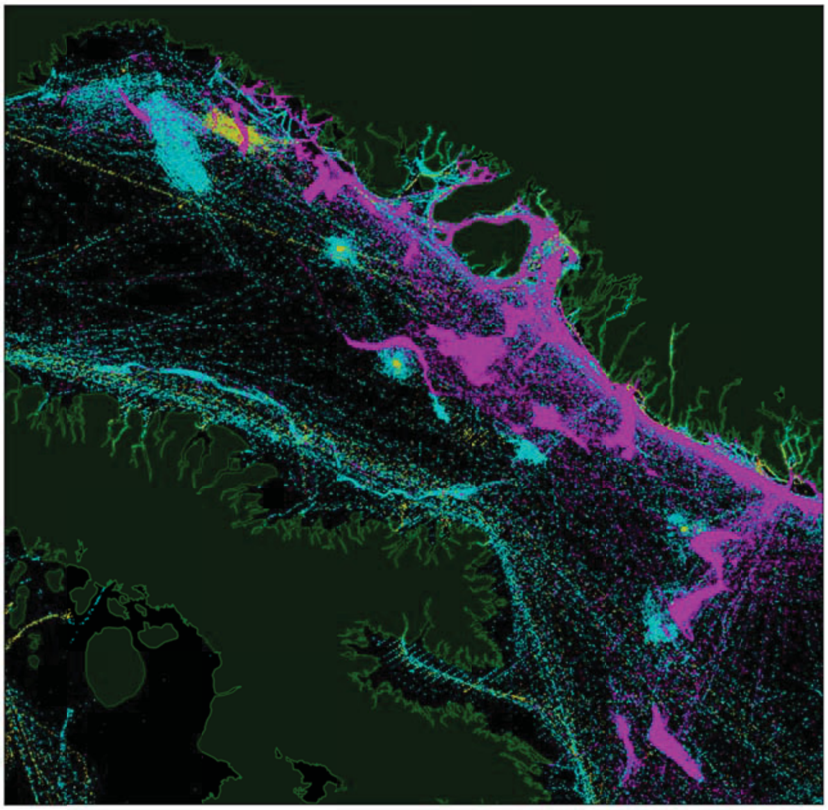

Fig. 3 Close-in plot of detections in Baffin Bay with reported fishing boats as magenta, commercial ships as cyan, and government ships as yellow

The data in Fig. 3 for fishing boats is further analyzed to learn about their pattern of life. The pattern of life in the Arctic is a valuable context when evaluating sparse data. One of the more recent methods available for generation of pattern of life from large datasets is by using automated machine learning algorithms. For example, by using the DBSCAN algorithm (Esther et al. 1996) on the fishing data in Fig. 3, historical fishing zones can be extracted (among other items of interest such as locations of ports and harbours, stopping areas, and even transit corridors). Fig. 4 shows the generation of clusters (reported speed between zero and one knots, minimum 10 observations, with a 20 km Euclidean neighbourhood threshold) for the fishing data using the DBSCAN algorithm. The clusters generated in Fig. 4 are also shown overlaid on bathymetry data obtained from the ETOPO1 dataset provided by NOAA (Amante and Eakins 2009). One can observe that the seemingly odd-shaped high-density regions of fishing activity are aligned to bathymetric features, which are no doubt linked to the occurrence of the resources being fished.

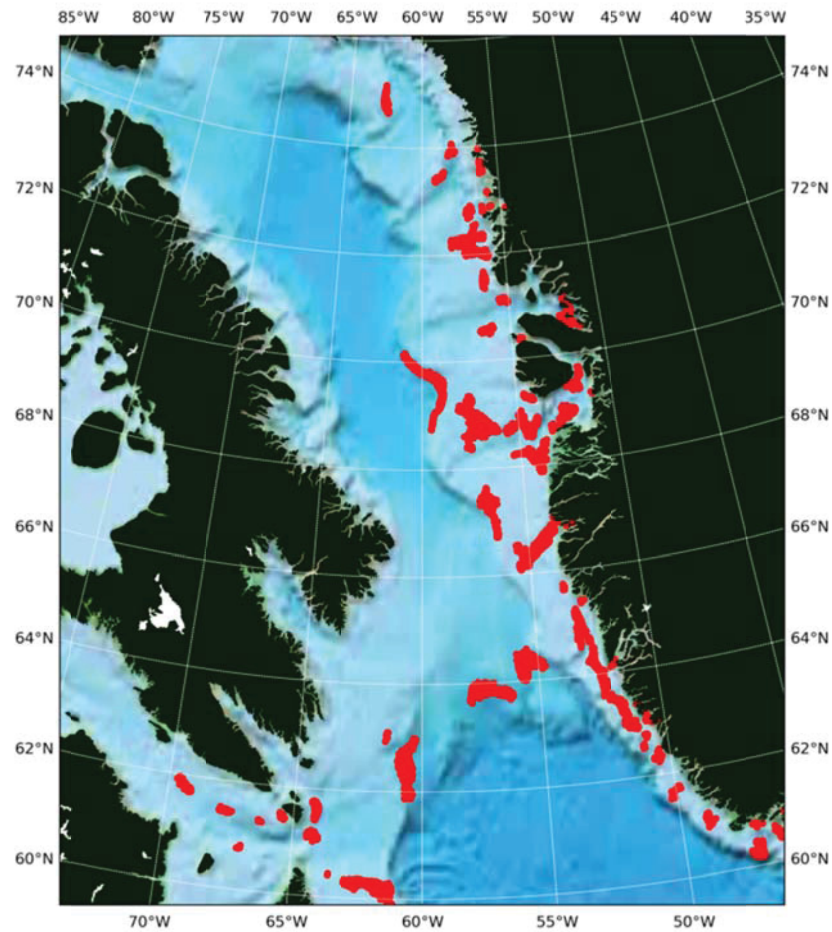

Fig. 4 Fishing vessel observations clustered on low speed are shown overlaid on bathymetry data

While the type of context generated by the analysis of this dataset is useful for general situational awareness, it is also a valuable piece for the enhancement to the detection and tracking of maritime threats or other vessels of interest. Pallotta et al. (2013) presents a powerful technique to automatically learn pattern of life activity from AIS observations using automated machine learning. Adapting their type of analysis to Arctic data would provide an atlas of "normal" pattern of life, which can then be used for threat analysis, anomaly detection, and decision making. Another application of pattern of life information has been shown by Mazzarella et al. (2015) where knowledge of normal shipping activities improves the ability to associate SAR detections with temporally asynchronous AIS detections. Improved association of SAR ship detections with pattern of life can help disambiguate the detection of ships from icebergs and improve the tracking of ships which is currently highly dependent on AIS.

Another application being explored to support decision making is the enhanced prediction of vessels of interest by using known transit activities (Pallotta et al. 2014). Here, the authors found that an Integrated Ornstein-Uhlenbeck model describes the growth of uncertainty in a predicted position for generally open-water transits. The Ornstein-Uhlenbeck model is a stochastic model where the statistics of state changes over a time series are described using normal distributions for the range of possibilities combined with a mean-reverting tendency. One can think of this as an approximation of a driver aiming to steer straight, but the actual path may have deviations to either side of the ideal line of transit. The driver is applying a mean reverting force.

While this Integrated Ornstein-Uhlenbeck model has been recently shown to work well for describing traffic in unrestricted open water, it is not certain whether this same model applies to ship predictions in the Arctic environment. It is arguably unlikely to be as effective in the Arctic due to the significant navigational constraints from land and ice. Therefore, for effective decision support in the Arctic, a prediction model for constrained or semi constrained navigation is required for vessel prediction in regions such as the Canadian Arctic. Hammond (2014) proposes one approach using graphs, however, additional work to reduce computational complexity, and validation against real data has yet to be achieved for this approach.

The foundations for a new paradigm of maritime ISR are being developed. Of relevant interest here is the use of large datasets to enhance the use of sparse or noisy sensor data. The Arctic trend in both the amount of traffic and information available in the Arctic is clear from the histogram of ship position reports over time, presented in Fig. 5. From May 2011 to July 2015, the seasonality of the traffic report quantities is evident in the periodic rise during the summer months and fall during the winter months. However, the trend to draw attention to in Fig. 5 is the ever-increasing quantity of reports over time. This increasing amount of data, in combination with automated machine learning algorithms and enhanced active remote sensing capabilities, enables new approaches to detect and track maritime threats in the Canadian Arctic.

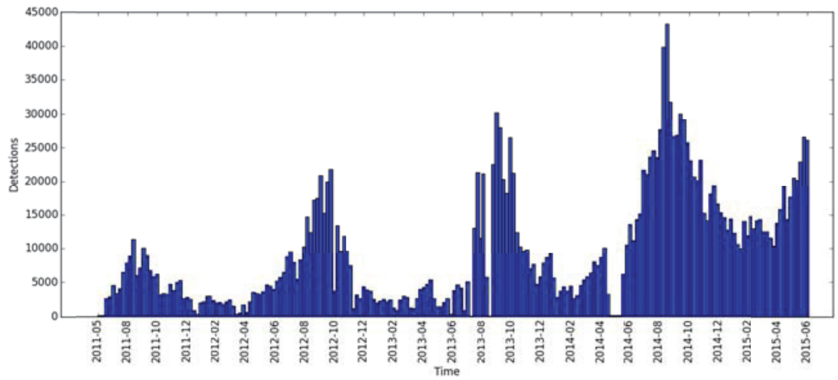

Fig. 5 Histogram of all ship detections in GPW north of 60 degrees latitude and between 170 West and 40 West degrees longitude with time in the x axis is indicated as year and month, and weekly histogram bins

4 Conclusions

The Government of Canada continues to invest in the Canadian Arctic, and the capability to detect and track vessels in the remote and challenging Canadian Arctic maritime environment is continuously increasing. The future RADARSAT Constellation Mission is one example capability which has the potential to enhance Arctic situational awareness and improve maritime security.

Future work by DRDC in developing the requirements for the next generation maritime C2 system will investigate the combination of unidentified ship detections (i.e. from RADARSAT-2 or RCM) against patterns of life in order to cross-cue surveillance capabilities. Furthermore, with the inclusion of the pattern of life data and navigational constraints, new and existing applications for operational decision support such as vessel of interest reconnaissance tools can be improved.

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