Ship Detection in Synthetic Aperture Radar Imagery

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ABSTRACT

Ship detection in synthetic aperture radar (SAR) ocean imagery is now being employed operationally based upon RADARSAT-1 and Envisat imagery and by using automated ship detection software. Several ship detection topics that focus on constraints, opportunities, and research activities are briefly reviewed. Examples based upon work carried out at Defence R&D Canada – Ottawa are presented.

Keywords: Synthetic aperture radar, SAR, RADARSAT, Envisat, ship, detection, AIS.

1 INTRODUCTION

Ship and ship wake signatures have been observed in synthetic aperture radar (SAR) imagery since such images of the ocean surface first became available. Operational ship detection systems are now being implemented based upon SAR imagery from the RADARSAT-1 and Envisat sensors. The challenge is to quantify the detection capability and to design new SAR sensors and software systems to better detect ship signatures, and to use these signatures to classify the ship targets of interest. Ship and ship wake detection has been reviewed extensively in recent years, *e.g.*, [1], [2], [3], so will not be reviewed in detail here. Furthermore, an international collaborative project known as DECLIMS [4] was recently active in this area and served to identify and advance the ship detection state-of-the-art.

In this paper, we focus on a number of current topics in SAR imaging of ships. Some of these topics, such as ship detectability and ship detection software, are at the heart of operational capabilities, an example of which will be implemented in Canada through the Polar Epsilon Project. Other topics, such as polarimetry, wind retrieval, inter-look coherence, and maritime automatic target recognition (ATR) remain research topics. Automatic Identification System (AIS), a VHF-based self identification system intended to improve maritime safety, is becoming a critical capability for corroboration of SAR signatures and to gather data for maritime ATR studies.

These topics of current interest in ship detection in SAR imagery are briefly discussed. Representative examples, mostly derived from work that has been carried out at Defence R&D Canada – Ottawa (DRDC Ottawa), are presented.

2 SHIP DETECTION TOPICS

2.1 Ship Detectability

Ship detection in synthetic aperture radar ocean imagery amounts to the detection of bright targets against the ocean clutter background. The potential for ship detection depends upon many factors including the local wind and wave conditions, the observation geometry, the radar frequency and polarization, and the ship size and type. Based upon these factors, simple models have been developed to predict the potential for ship detection [5]. The models include the wind-driven clutter against which ship signatures are detected, the probability density function of the clutter, the radar cross section of the ship (usually modelled as a simple function of the ship length), the radar geometry, and the spatial and radiometric resolutions of the radar. Models such as these have contributed to understanding the ship detection performance of current SAR systems, to comparing the ship detection performance of different radars and/or processors, and to the design of future SAR systems.

Figure 1 shows calculations of the minimum detectable ship length for the ERS (C-band, VV polarization), RADARSAT-1 (C-band, HH polarization with single beam and wider swath ScanSAR modes), and Envisat (C-band, with selectable polarization and alternating polarization modes) SARs. Specific parameters used include: a wind speed of 12 m/s blowing towards the radar ($\varphi = 0°$) and across the radar look direction ($\varphi = 90°$); *K*-distributed clutter with an order parameter of $\nu = 4$; and a constant false alarm rate (CFAR) of $2.5(10)^{-9}$.

The plots show how the size of the ship that can be detected improves (*i.e.*, decreases) as the incidence angle increases for a given resolution (*e.g.*, Standard or Fine beam modes) since the clutter level decreases with increasing incidence angle, and how HH polarization provides better detection since the clutter level is lower than that of VV polarization. A higher value for the wind speed shifts the curves upwards (*i.e.*, it becomes more difficult to detect smaller ships), while a lower value for the wind speed shifts the curves downwards (*i.e.*, better able to detect smaller ships).

2.2 Ship Detection Software

Considerable effort has gone into the development and validation of ship detection software. A common approach is to set a pixel-based threshold according to the clutter statistics and the desired constant false alarm rate, *e.g.*, [6], [7], [8], [9]. The detection process is closely related to the ship detectability calculations discussed in the previous section. Of course, excellent ship detection performance is required, especially if the detections are to be used to make decisions concerning the deployment of other assets such as surveillance aircraft. As such, pre- and post-processing steps are often employed to reduce false alarms. These steps could include clustering of above-threshold pixels into single detections, specifying minimum and maximum ship sizes of interest, specifying minimum or maximum proximity to the shoreline or other ships, searching for associated ship wake signatures, and use of the measured radar cross section of the ship relative to the ship signature length. Also, fusion of SAR detections with other surveillance information, such as may be derived from contemporaneous reception of AIS signals, helps to improve confidence in the SAR image detections.

An example of a problem that does arise is that azimuth ambiguities are sometimes visible in the image, especially in the case of low background clutter, and may be detected by automated software as candidate ship targets. Azimuth ambiguities could arise from a ship signature or from bright targets on land. The azimuth ambiguity location is deterministic relative to a specific target location (including both azimuth and range offsets), so the expected location may be calculated from the radar parameters. In Figure 2 we show an example from an azimuth ambiguity marking tool that has been developed at DRDC Ottawa that is available in interactive target validation software. The azimuth ambiguity marking process could be automated to reduce this type of false alarm, especially in high density shipping regions and close to shore.

2.3 DECLIMS

The recently completed Detection and Classification of Marine Traffic from Space (DECLIMS) project [4] was lead by the Joint Research Center (JRC) and united 24 international partners involved in ship detection using remote sensing imagery. Although both radar and optical sensors were considered, the majority of the participants were concerned with radar imagery. The project goals included establishing the state of the art, carrying out benchmark tests for SAR detection and classification, and fostering improvements to capabilities, tools, products, and services.

DECLIMS focussed on automatic detection for SAR images and noted that this is now considered an operational capability, although it has not yet been perfected. There are already several dozen system and/or service providers that are active in this sector. All base their detection systems on CFAR, pixel-based algorithms, with little or no use of wake detection. Some service providers can deliver detected ship positions to users within a few minutes of target illumination.

A noteworthy example in the Canadian context of an operational ship detection system is the fisheries enforcement capability that has been deployed in the Southern Indian Ocean to combat illegal fishing of the Patagonian Toothfish [10]. The Sentry transportable groundstation [7] that was developed by Iosat Inc. of Halifax, Nova Scotia was upgraded and deployed on Kerguelen Island where it autonomously acquires, processes, and analyses SAR images from the RADARSAT-1 and Envisat sensors. The ship detection reports are combined with vessel monitoring system (VMS) positions reported via Argos for legal ships, to identify and locate illegal ships and re-direct patrol assets. The station has been in successful operation since 2004 and has demonstrably contributed to the repression of illegal fishing activities.

A major DECLIMS activity was the comparison of detection systems through benchmark testing [10], in which 8 different ship detection systems were intercompared using a set of common SAR images. Although it was noted that the overall detection rates depended strongly upon the ship size, radar resolution, and sea state, in most cases the systems performed quite similarly to one another; no single system outperformed all the others. It was noted that the vessel signatures were variable and unpredictable and problems were often encountered in the case of an inhomogeneous clutter background. Furthermore, false alarms were caused by target sidelobes, azimuth ambiguities, and inaccurate coastline masks, to name a few. It was suggested that detection could be improved by retaining an image analyst in the loop to verify candidate ship detections provided by operational software.

A key conclusion of the DECLIMS project is that the value of ship detection from remote sensing imagery is maximized when the resulting detections are fused with vessel traffic data from other sources such as VMS or AIS.

2.4 Polar Epsilon Project

In Canada, the Department of National Defence has initiated the Polar Epsilon Project, which will implement spacebased, wide area surveillance in support of sovereignty, continental security, and joint operations at home and abroad [11]. The primary objective of Polar Epsilon is to provide surveillance of Arctic land areas and the vast maritime approaches to Canada (Figure 3), focussing on the RADARSAT-2 sensor, scheduled for launch in 2007, with new ground stations that will be installed on the east and west coasts of Canada.

Polar Epsilon will deliver near-real time ship detection as a key capability. However, domain awareness requires detection, classification, identification, tracking, and determination of intent; no single sensor can meet all of these requirements. Nevertheless, RADARSAT-2 imagery will be used to provide first sensor detections that could be used to cue other surveillance assets such as maritime patrol aircraft, uninhabited aerial vehicles, or ships. Given the large data volumes that will be involved, automated processing that suppresses false alarms to the greatest extent possible will be required. The OceanWorks software has been developed to address this requirement [12]; it uses a fuzzy logic rule set based upon target size, shape, and radar cross section to reduce false alarms.

2.5 Polarimetry

Polarimetry and dual-polarization image acquisition present opportunities to improve ship detection and provide additional information for ship classification, including the possibility of ship/iceberg discrimination, which would reduce false alarms in iceberg-prone areas. Furthermore, these modes could offer the opportunity to provide good ship detection performance in concert with other maritime surveillance activities that require a large clutter signature, as is the case for ship wake and oil spill detection.

A polarimetric SAR system provides simultaneous observations of the scattering matrix at all possible linear polarization combinations. Ship detection is essentially a binary decision problem. The fundamental algorithms of polarimetric SAR ship detection apply statistical decision theory to the components of the scattering matrix to obtain a decision variable. Liu et al. [13] applied a likelihood ratio test with the Neyman-Pearson criterion to define a pixel-based detection criterion. Gaussian distributions for the scattering matrix components were assumed in order to derive an approximate decision variable, while measured data from an airborne polarimetric SAR were used to calculate the detection probabilities.

An example of receiver operating characteristics derived using this method is shown in Figure 4 for the 76 m long CFAV *Quest*. In this case, all possible radar polarization configurations were tested in order to evaluate their relative performance, all else held equal. We see that polarimetry performs best, but dual co-polarization with phase is also a useful choice.

Polarimetric decomposition techniques can provide information on constituent elemental scatterers in a target of interest. These could act as features for automatic target recognition algorithms. Research on this topic is complicated by motion-induced smearing that is not compensated by the SAR processor.

Unfortunately, the polarimetric modes for RADARSAT-2 will only be available for rather narrow swath widths as compared to the ScanSAR modes that will be used operationally for ship detection by projects such as Polar Epsilon. Nevertheless, there is strong evidence that significant benefits could be realized through use of polarimetric modes. Surveillance of spatially constrained areas of interest such as straits, channels, confined waterways, specific fishery zones, ports, and the Arctic Archipelago could be undertaken using polarimetric modes.

2.6 Wind Retrieval

The success of ship detection varies within an image according to the local wind and wave conditions. The wind speed and direction characterize the mean clutter level. High resolution wind fields are now routinely retrieved from SAR ocean images, *e.g.*, [14]. Similar to calculations of ship detectability, the retrieved wind speed can be used to guide expectation as to the scale of ship that should be detectable within an image. More precisely, the observed clutter-to-noise ratio and clutter statistics may be used to derive a spatially variable minimum detectable ship length index. An example of a high-resolution wind field (*i.e.*, on a 2 km grid) derived from a RADARSAT-1 ScanSAR image is shown in Figure 5.

2.7 Inter-look Coherence

It has been proposed that inter-look coherence techniques could help with the detection of smaller ships [15]. The premise is that each "look", which arises from bandpass filtering of the Doppler spectrum, corresponds to a different observation time. In the "split-look" ship detection technique, two sub-apertures are used. Ship targets of interest should be correlated between looks, while the background clutter remains uncorrelated. It has been proposed that this method should be beneficial for the detection of small targets. However, the concept has been difficult to verify and quantify [16], probably due to target decorrelation caused by target motion and changes in the target aspect angle between the two looks.

2.8 Automatic Identification System (AIS)

Automatic Identification System (AIS), a VHF transponder system intended for collision avoidance, is proving to be a valuable asset to identify ships in SAR imagery, especially as we move into the era of spaceborne AIS reception. Mandated by the International Maritime Organisation (IMO) and the Safety of Life at Sea (SOLAS) convention, AIS must be implemented on passenger vessels and on ships that are larger than 300 gross tons. Transmitted AIS information includes ship identification, position, and velocity. Of course, ships may have non-compliant AIS installations and could purposefully transmit incorrect data. Such occurrences could be identified through verification with SAR detections and signatures.

AIS data is already being used to improve the maritime picture through reception at fixed coastal stations and on aircraft and ships. In the near future, we are moving towards spaceborne reception, and there is currently discussion of including spaceborne AIS reception in operational ship detection systems. Spaceborne AIS reception presents challenges since thousands of AIS transmitters could be visible from a satellite for certain regions on the planet.

2.9 Automatic Target Recognition

Use of AIS data has permitted a heretofore unprecedented acquisition of known ship signatures in SAR imagery. DRDC Ottawa has carried out several experiments using AIS data from AISLive (http://www.aislive.com) to provide snapshots of AIS data at specific satellite pass times for high density shipping regions including Strait of Dover, Strait of Gibraltar, and Busan, South Korea. In one experiment, 32 matching RADARSAT-1 fine mode images along with AISLive snapshots were acquired [17]. The AIS signatures were projected into the satellite acquisition frame of reference by accounting for the time difference between the two observations and the azimuth shift associated with SAR imaging of moving targets. An example is shown in Figure 6. Access to the AIS data provides unprecedented insight to the nature of the ship target and its activities, in this example a tugboat towing a barge.

Based upon this data set, a SAR ship signature database has been developed that provides insight to the validity of the provided AIS data, to the accuracy of matching AIS data to a specific SAR signature, and to the nature of SAR signatures of ships. In Figure 7, the AIS-reported ship length is compared to the ship length in the authoritative Lloyd's registry (http://www.ships-register.com); an error rate of 9.4% was observed, mostly due to the occurrence of AIS-reported ship lengths of zero. Also in Figure 7, a histogram of the distance between the observed ship signature in the SAR image and the signature's predicted location from the AIS data (following dead reckoning and azimuth shifting operations) shows a mean difference of 173 m, suggesting that the two positions have been appropriately matched. Outliers in the histogram have been attributed to manoeuvring ships.

The ship signature database provides observations of the ship radar cross section as a function of the ship length. As shown in Figure 8, the ship radar cross section may be modelled roughly as $1.25L^2$, where L is the ship length in meters. Of course, this does not account for different classes of ships or their orientation, but it does provide a simple relationship that can be used for ship detection performance prediction. In the same figure, the histogram of the same ship radar cross section data for ships in the 100 m to 300 m length range shows that a Gamma probability density function describes the cross section variability. These sorts of empirical results could be used to reduce false alarms in automatic ship detection software.

Figure 9 shows representative ship signatures in RADARSAT-1 fine mode imagery. Along the top row, the ship signatures are well-formed, but along the bottom row, azimuthal ship motion has introduced azimuth-oriented smearing of the ship signatures. These uncompensated ship motion effects complicate automatic signature analysis, such as ship length estimation. In the same figure, the plot shows the ship length measured from the SAR signature as a function of the validated ship length. The agreement is generally good, with overestimates of the ship length attributed to the noted azimuth smearing events, and underestimates of the ship length attributed to errors in estimating the orientation of the ship axis along which the ship signature length is measured.

3 DISSCUSSION

In this paper we have reviewed some current topics in SAR imaging of ships. Ship detection performance prediction includes both clutter and ship cross section model elements. The latter, in particular, have recently improved with the availability of large validated ship signature data sets based upon AIS data.

AIS is one of the most important recent developments in SAR ship detection since it permits the opportunity to explicitly identify ship signatures detected in SAR imagery. Inconsistencies in the two data sources would serve to indicate ships of interest for additional surveillance. Spacebased AIS reception will open up the possibility of routine validation of SAR-observed ship signatures.

Further work on advanced ship detection techniques is still warranted. This could include further assessment of the inter-look coherence, as well as signal analysis that could lead to estimates of ship speed and heading. Such derived information could be useful to further verify the accuracy of reported AIS information.

SAR-derived wind speed provides characterization of the wind and wave environment in which the ships are being detected. This serves to adapt expectations as to the scale of ship that should be detectable in the imagery.

The next generation of SAR sensors will include polarimetric modes that offer improved ship detection and additional information for ship classification. To date, this is at the expense of a reduced acquisition swath, which is at odds with operational requirements through projects such as Polar Epsilon that will survey vast ocean regions. Nevertheless, polarimetry could be beneficial for monitoring of choke points or other spatially-constrained regions of interest.

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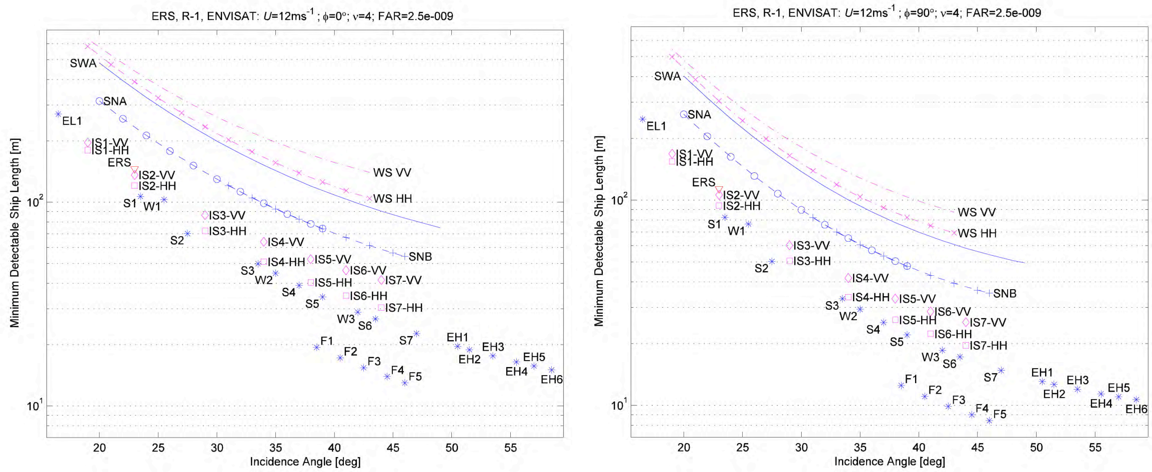

Figure 1. Minimum detectable ship length for the ERS, RADARSAT-1, and Envisat SAR sensors for a wind speed of 12 m/s blowing towards the radar (left) or across the radar look direction (right). The points correspond to the nominal centre of the single beam modes (for RADARSAT-1 EL=extended low, EH=extended high, S=standard, W=wide, F=fine; for Envisat IS=image mode represented by alternating polarization), while the lines represent the performance across ScanSAR modes (for RADARSAT-1 SWA=ScanSAR wide A, SNA=ScanSAR narrow A, SNB=ScanSAR narrow B; for Envisat WS=wide mode).

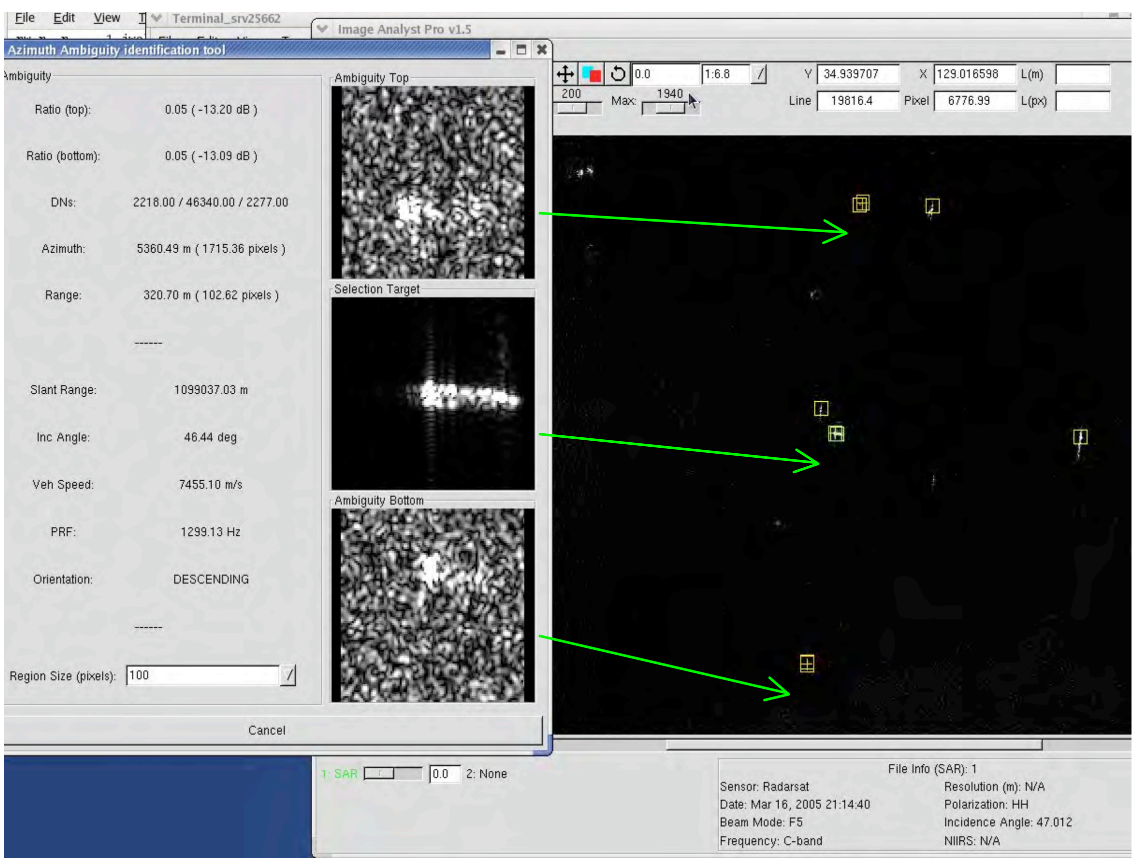

Figure 2. Example from an azimuth ambiguity marking tool that has been implemented in DRDC Ottawa interactive target validation software. Automatic target detections are shown as yellow squares. The analyst "clicks" on the target of interest (green square with + sign) and the azimuth ambiguity locations are indicated by the offset + signs and in the inset zoom windows. The azimuth ambiguities of a ship were detected as candidate ships.

Figure 3. Canadian Forces Areas of Interest for the vast maritime approaches to Canada.

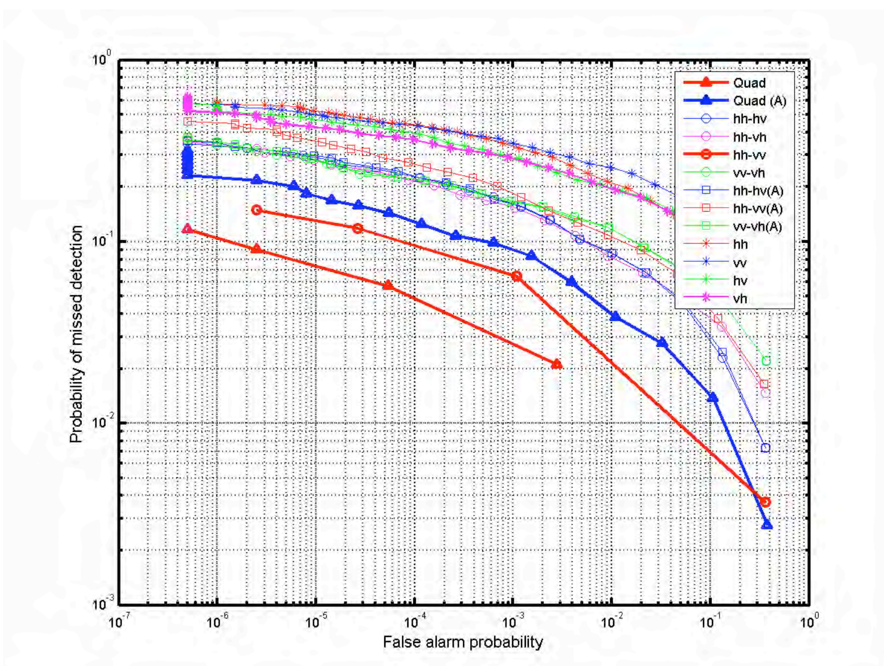

Figure 4. Detection performance using image statistics for various polarization combinations derived from airborne polarimetric SAR observation of CFAV *Quest*. Improved performance (that is lower probability of missed detection coupled with a lower probability of false alarm) occurs for the cases that are further to the lower left. In general, quad polarimetric mode offers the best ship detection performance, while single channel VV mode is the worst.

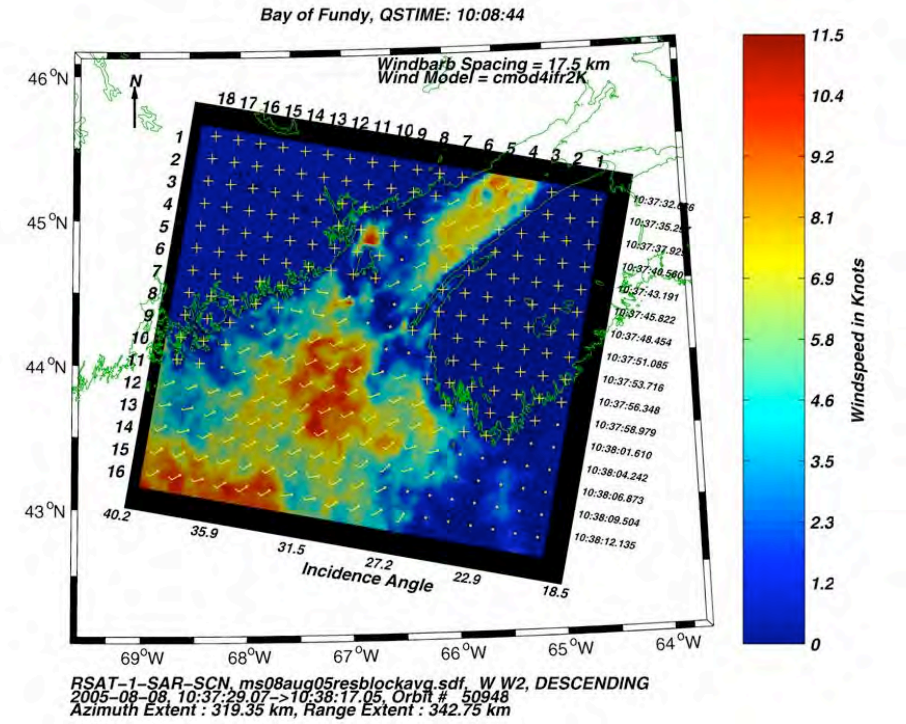

Figure 5. Spatially variable wind field derived from a RADARSAT-1 ScanSAR narrow image acquired off the east coast of Canada in August 2005. A scatterometer wind field was used to provide wind direction guidance for the retrieval operation.

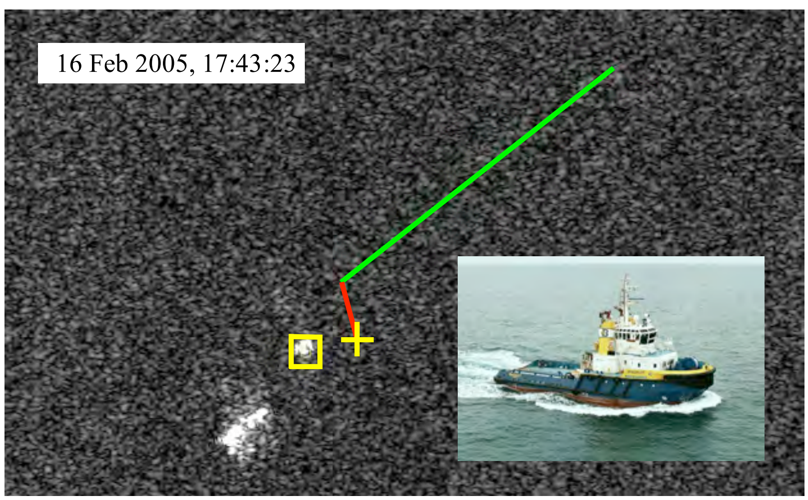

Figure 6. RADARSAT-1 fine mode image of a tug boat towing a barge in the Strait of Dover, confirmed by AIS data obtained from AISLive. The yellow square indicates the automatically detected target position. The + indicates the AIS-predicted SAR signature position, which uses the AIS velocity and the time difference between the SAR and AIS data acquisitions to dead reckon the AIS position along the green line, and the AIS velocity and the SAR geometry to azimuth shift the AIS position along the red line. Unique AIS identification of the ship permits retrieval of a photograph of the ship of interest.

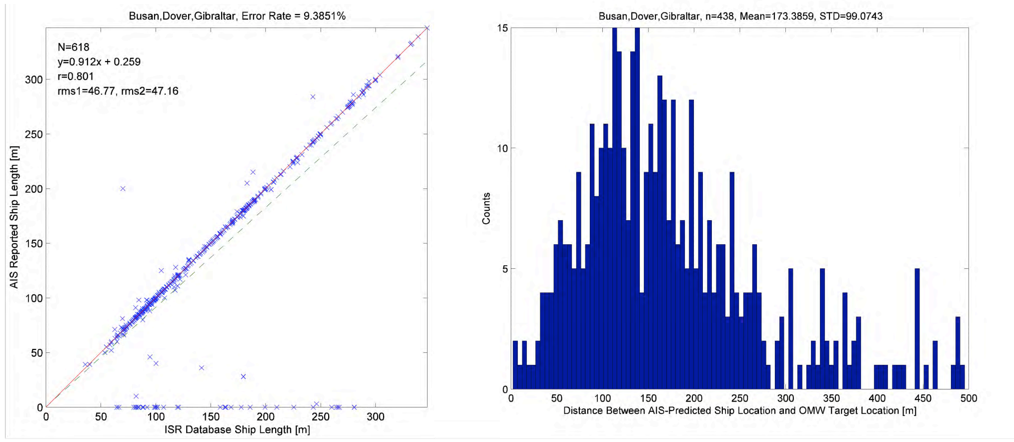

Figure 7. AIS-reported ship length obtained via AISLive versus validated ship length (left); histogram of the distance between the SAR ship signature location and the predicted location of the ship signature based upon AIS data (right).

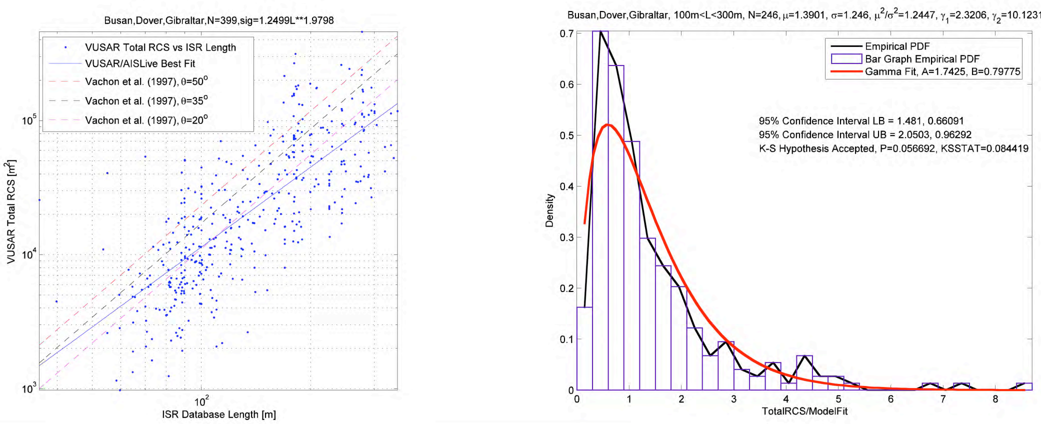

Figure 8. Ship radar cross section versus validated ship length (left). The solid blue line is the best fit to the observed data. The other lines represent other models [5]. Histograms of ship radar cross section with the best fit to a Gamma probability density function for ships in the 100 m to 300 m length scale range (right).

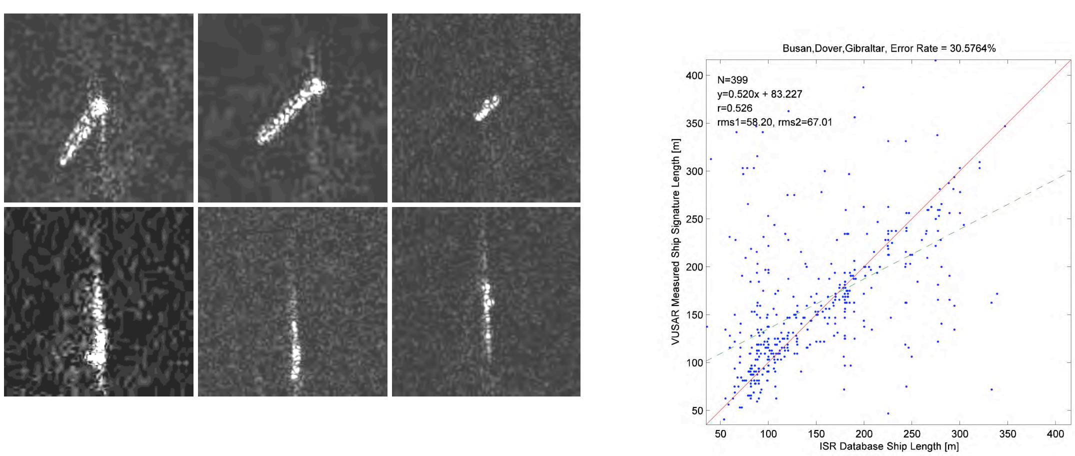

Figure 9. Representative RADARSAT-1 fine mode ship signatures (left), with well-defined ships (top row) and azimuth smeared ships (bottom row); measured ship length from the SAR image signature versus validated ship length (right).