Detecting small ships in TerraSAR-X/TanDEM-X acquisitions at large grazing angle and moderate metocean conditions

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Abstract

The feasibility of detection of small ships in open sea using space-borne Synthetic Aperture Radar (SAR) techniques has been a hot research topic in the latest years. The increasing interest is justified by the large availability of Very High Resolution (VHR) civil SAR satellite missions, such as TerraSAR-X/TanDEM-X, COSMO-SkyMed and RADARSAT-2. In parallel, much attention has been paid to predict the minimum detectable ship size depending on the radar settings, e.g. resolution, transmitting and receiving polarization, radar angle of incidence, and metocean conditions, e.g. sea surface wind speed, sea surface wave height. Both, the simulated ship detectability model and data-driven approach show that at large radar grazing angle and starting with moderate metocean conditions, the probability of detecting small ships in single polarization (HH or VV) SAR data is drastically reduced. This paper investigates the potential of the coherent dual polarimetric phase information and additional polarimetric features in detecting small ships in this challenging environment. The goals are achieved with the help of dual co-pol (HH and VV) TerraSAR-X/TanDEM-X data acquired in the Mediterranean Sea in the framework of a large data collection campaign, where ships ground truth information is given by self-reporting messaging system.

1 Introduction

Remotely sensed data provide a simple possibility for the monitoring of ships position and their activities in the open sea and costal area. In this sense, Synthetic Aperture Radar (SAR) data have the unique capabilities to be almost weather independent and to operate at day and night, in addition SAR is very powerful in detecting metallic targets.

The monitoring of small ships in open ocean has a strong interest in the maritime surveillance domain because of the large number of unlawful maritime activities that involve small boats [1]. The detection of small ships in SAR imagery is however challenging and the success depends on a large number of factors, e.g. construction material of the ship, radar resolution etc. The Joint Research Center (JRC) of the European Commission (EC) has presented the key findings of the SAR satellite imagery small boat detection campaign in the report [1], where Very High Resolution (VHR) SAR imagery have been collected over pre-defined test sites where ground truth was provided by deployed boats. Although drawing final conclusions was not possible due to the reduced amount of data collected during the dedicated campaign, a detection score of 30-50% is indicated when calm sea conditions and optimal SAR settings apply.

This paper investigates the potential of the coherent dual polarimetric phase information and additional polarimetric features in detecting small ships in the challenging case of moderate metocean conditions and data acquisition at large grazing angle. The goals are achieved with the help of dual co-pol (HH and VV) TerraSAR-X/TanDEM-X data where ships ground truth information is given by self-reporting messaging system.

2 Motivation

With the increasing number of civil SAR missions operating with different working frequencies in the recent years, much attention has been paid to predict the minimum detectable ship size depending on the radar settings, e.g. resolution, transmitting and receiving polarization, radar angle of incidence, and metocean conditions like sea surface wind speed or sea surface wave height. Previous studies (see [2]-[4]) have approached the topic by building a prediction model which takes into account the underlying statistic of the ocean clutter radar backscatter distribution and relating the ship length to the highest measured Radar Cross Section (RCS) value of the ship itself. In [5] real TerraSAR-X Multilook Ground Range (MGD) Radiometrically Enhanced (RE) single-pol SAR data, have been used to develop a data-driven ship detectability model. Over 150 StripMap images have been processed with a highly optimized Constant False Alarm Rate (CFAR) ship detector setting a false alarm rate $<10^{-13}$. A detected ship is declared when to the SAR detection valid Automatic Identification System (AIS) ship report could be unambiguously assigned. On the contrary a valid AIS message without SAR detection represents a non-detected ship. These two classes are the base of a binary classifi-

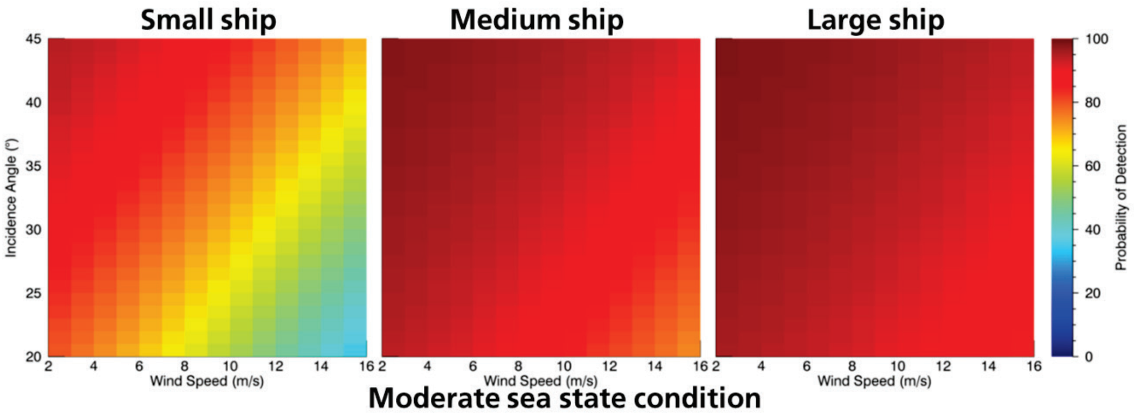

Figure 1: TerraSAR-X high resolution data-driven ship detectability model results for different ship sizes (from left to right: small, medium and large vessels) for the case of moderate sea state conditions. Each plot shows the probability of detection as a function of incidence angle and wind speed.

cation task solved by L2-regularized Logistic Regression. The features parameters space includes the ship length, incidence angle, wind speed and significant wave height. Ship length is extracted from AIS data. The incidence angle information is extracted from the SAR geometry metadata. The geophysical parameters are estimated by employing the in house algorithms for wind XMOD2, and waves XWAVE [5]. In order to ease the visualization of the resulting 4D space, the significant wave height is discretized in low and moderate and the ship samples are grouped according to their length L in 3 classes: small ($1 < L[m] \leq 25$); medium ($25 < L[m] \leq 150$); large ($150 < L[m]$). Once the model is trained with the given inputs, the hyperplane separating the two classes, detected and non-detected ship, can be used to provide the probability of detection as function of the features under investigation. In **Figure 1** are shown the results as 2D plots for the case of interest with moderate sea state condition, where wind speed is binned in steps of 1m/s and incidence angle is binned in steps of 1deg. As can be seen in **Figure 1**, the probability of detecting a ship belonging to the class "small" strongly decreases when wind speed and grazing angle increase (incidence angle decreases). Similar trends were shown also by the theoretical ship detectability models presented in [2]-[4], where the minimum ship length increases in such situation.

3 Approach and Data

The analysis conducted on single polarization high resolution TerraSAR-X images, shown in the previous section, suggests investigating the potential of the coherent dual polarimetric phase information and additional polarimetric features to solve the detection of small ships when the sea state condition is moderate and wind speed is high. In fact, in such situation the received sea surface backscatter starts to become specular with intensity values that can reach or overcome the radar backscatter of a small ship. Adopting standard detectors like CFAR applied on intensity backscatter values might either fail in the detection or generate too many false alarms. An example of trade-off between false alarms and detection of small ships in the situation described above is shown in **Figure 2**, where either the "small" ship, i.e. ship2, is not detected (left panel) or is detected but raising an unacceptable number of false alarms (right panel).

The recent progresses of radar polarimetry [6]-[7] and the Single-Look-Complex (SLC) SAR spectral analysis technique [8]-[9] for ship detection applications have shown an improved overall detection performance, but the studies conducted up to now do not take into account the ship size, meteorological conditions and radar observation geometry. In this study polarimetric features which have shown good clutter suppression powers are used. Polarimetric $SPAN$, degree of depolarization (DoD), co-pol correlation (ρ) and the Even-Odd bounce ratio (EOR) are all framed under the Kennaugh elements:

$$\begin{gathered} SPAN = 2 * K_0 \\ DoD = 1 - \frac{\sqrt{(K_3)^2 + (K_4)^2 + (K_7)^2}}{K_0} \\ \rho = \sqrt{(K_3)^2 + (K_7)^2} \\ EOR = K_4/K_0 \end{gathered} \tag{1}$$

where the Kennaugh elements are defined as:

$$\begin{gathered} K_0 = \frac{1}{2}\{|HH|^2 + |VV|^2\} \\ K_3 = -Re\{HH * conj(VV)\} \\ K_4 = \frac{1}{2}\{|HH|^2 - |VV|^2\} \\ K_7 = Im\{HH * conj(VV)\} \end{gathered} \tag{2}$$

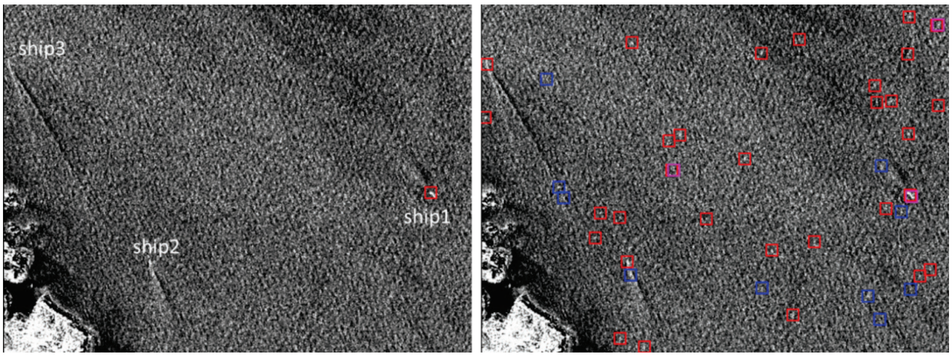

Figure 2: Trade-off between low false alarms and the detection of small ships. TerraSAR-X sub-image with 3 visible ships. Ship1 and ship2 could be further identified via AIS reported length into “medium” and “small”. On the left panel, the detections are marked with red squares as result of CFAR processing with 10^{-13} PFA. On the right panel, the detections are marked with red squares as result of CFAR processing with 10^{-6} PFA, the blue squares indicate possible azimuth ambiguities.

Twelve dual co-pol (HH and VV) TerraSAR-X/TanDEM-X images are selected among the planned acquisitions in the Mediterranean Sea. An overview of the amount of SAR data collected at large grazing angle is provided in **Figure 3**. The white frames indicate the geographical position of each image collection, while the background shows the ship density. Obviously the images selected contain at least one ship that could be classified via AIS as “small” ($L[m] \leq 40$) and met-ocean conditions in place are moderate (at least wind speed ≥7m/s). These boundary conditions has lead us to a total number of 38 small ships which have not been detected in the HH intensity channel processed with two parameters CFAR and PFA <10^{-13}. Region of Interest (ROI) containing the 38 ships are extracted from the full images and are used for the ROC analysis of different polarimetric features.

4 Discussion

The polarimetric features, which are expressed in (1), are evaluated via ROC curve analysis. The baseline detector is given by the intensity of the co-polarization channel HH, i.e HH^2. The baseline detector as well as $SPAN$, DoD, ρ and EOR are firstly multi-looked using a boxcar moving window of 5 x 5 pixels in range x azimuth. This boxcar window size is selected empirically as a good trade-off between resolution loss and speckle reduction. The summary of the ROC curves for the 5 detectors under investigation is provided in **Figure 4**.

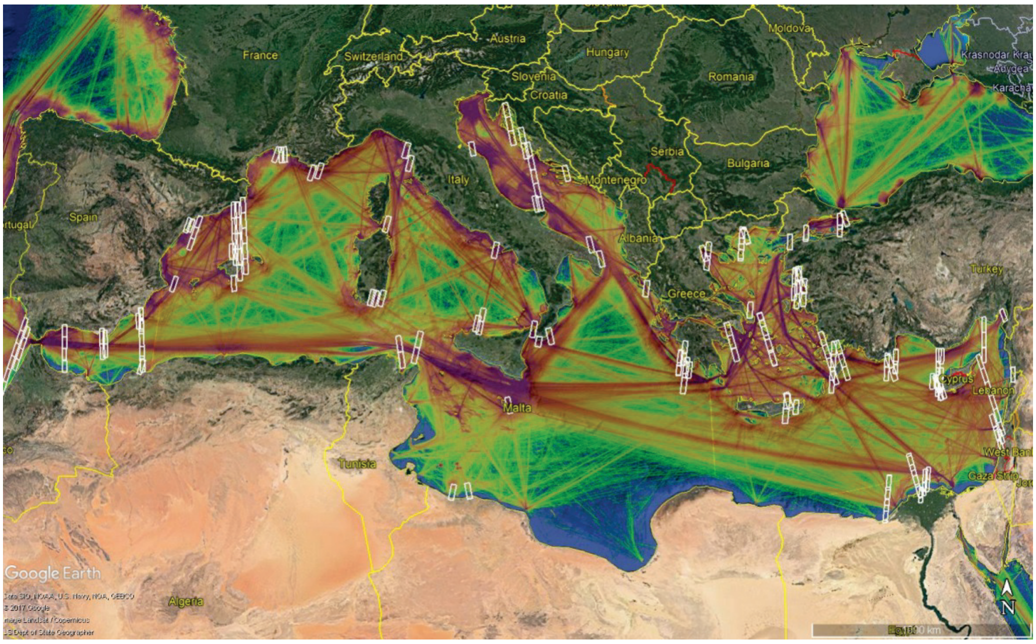

Figure 3: Mediterranean Sea data collection campaign. TerraSAR-X/TanDEM-X dual-pol HH-VV acquired scenes with large grazing angle (indicated by the white frames) overlaid on the color coded maritime traffic density in 2016 based on the ©MarineTraffic Automatic Identification System network.

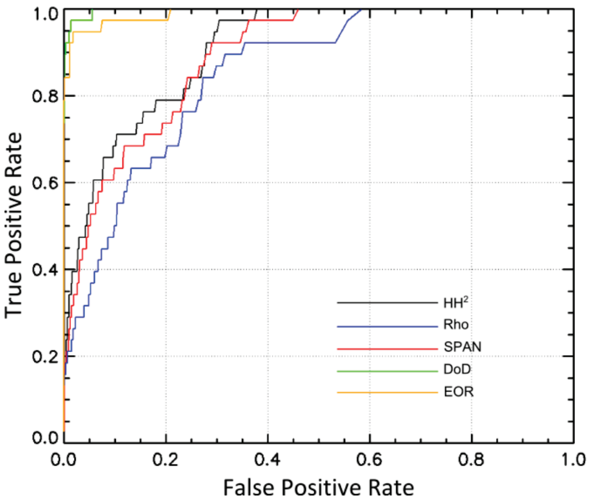

Figure 4:.

On the horizontal axis, the False Positive Rate (FPR) and on the vertical axis, the True Positive Rate (TPR) are indicated, both in normalized linear units. It can be seen that DoD and EOR perform better than the baseline detector HH^2, while $SPAN$ and ρ perform slightly worse than the baseline detector HH^2. This outcome demonstrates that the simple availability of multiple polarization channels does not always provide a gaining performance if not properly exploited. These positive trends shown by DoD and EOR in detecting small ships in such challenging situation should be verified also in respect to a large variety of metocean conditions, different radar angles of incidence and ship types and dimensions. Such analysis requires a large amount of SAR and ground truth data, which is currently ongoing processed.

Acknowledgment

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