SYNTHETIC APERTURE RADAR FOR MARITIME DOMAIN AWARNESS: SHIP DETECTION IN A SOUTH AFRICAN CONTEXT

Colin Schwegmann[1,2], Waldo Kleynhans[1,2]

1. Council of Scientific and Industrial Research, South Africa, Colin Schwegman
cschwegmann@csir.co.za
2. University of Pretoria, South Africa

ABSTRACT

Maritime Domain Awareness is an initiative started to help each sea-bordering country improve its understanding of its Exclusive Economic Zone. A country that improves its Maritime Domain Awareness ensures that activities such as piracy and Illegal, Unreported and Unregulated fishing are identified more quickly and the appropriate actions for each are taken. For instance, having better awareness of the ships entering and leaving a country’s Exclusive Economic Zone could prevent illegal fishing that, in some cases, accounts for up to a 40% loss of legal catches. Various sources of data can be used to keep track of ships at sea including ship transponders (such as the Automatic Identification System and Long Range Identification and Tracking systems) and active radar sensor systems such as Synthetic Aperture Radar satellites. With the advent of new, freely available Synthetic Aperture Radar imagery from Sentinel-1, the observation of large coastal areas is becoming more and more feasible for countries such as South Africa. Synthetic Aperture Radar satellites are able to monitor large tracts of the Earth, day or night, in any weather condition. This allows for the tracking of hundreds of square kilometres of sea area in a single image. By combining and processing imagery from these satellites and ship transponders, a better picture of a country’s maritime domain can be captured thereby allowing countries to respond to environmental, commercial or security threats at sea. Furthermore, if South Africa can implement its own SAR asset, Maritime Domain Awareness for the entire country would be improved tremendously. This paper aims to give an overview of the research being done to detect ships in Synthetic Aperture Radar imagery within a South African context. It presents the current and future of Synthetic Aperture Radar satellites, how methods such as the Constant False Alarm Rate and Wavelet Transform are used to detect ships at sea and how techniques such as Simulated Annealing and Cascade Classifiers are currently being used to further improve ship detection accuracies.

INTRODUCTION

This paper is intended to give an overview of the work that is presently being done in the area of ship detection using Synthetic Aperture Radar (SAR) satellites and imagery. This introduction will provide motivation for why ship detection is necessary in terms of maritime awareness as well as give a short introduction to ship transponders, SAR and how the two can supplement one another to improve the detection of ships at sea. The paper is structured as follows: following the introduction, an overview of each of the steps in a ship detection system is given. Next, a look at some of the future advances in the field of ship detection and SAR imagery is shown followed by a conclusion on the state of the detection of ships for the improvement of maritime awareness.

Maritime Domain Awareness

Maritime Domain Awareness (MDA) is a termed used to describe all factors relating to the maritime including a "all areas and things of, on, under, relating to, adjacent to, or bordering on a sea, ocean, or other navigable waterway, including all maritime-related activities, infrastructure, people, cargo, and vessels and other conveyances," (DoD 2005). Each country is required to monitor its own Exclusive Economic Zone (EEZ) for actions that may negatively affect the country's environment, commerce or security such as Illegal, Unreported and Unregulated (IUU) fishing. This task is impractical on a global scale and as such the purpose of the MDA initiative is to allow various parties to participate in improving their own and other's MDA through collaboration. Some key MDA participants include the United States of America, Canada, Norway, and the Artic Council. South Africa is becoming an increasingly important MDA participant due to its large coast and unique positioning. South Africa's EEZ covers a larger area than its land and it is positioned at a maritime choke point in that it is surrounded by three oceans – the Indian, South Atlantic and Southern Ocean. In this way the improvement of South Africa's own MDA is important to ensure that the country can police its coast. Various technologies have been introduced that allow for improved monitoring of ships at sea and these include ship transponders and synthetic aperture radar.

Ship Transponders

Ship transponders are devices installed on ships that transmit ship details to a ground or space-based receiver. There exists a number of ship transponder technologies including Automatic Identification System (AIS), Satellite AIS (Sat-AIS), Long Range Identification and Tracking (LRIT) and Vessel Monitoring System (VMS) (IMO, 2011). Despite the simplicity of the ship transponder system one inherent problem exists: it is a collaborative tracking method. In order to effectively track ships, the transponder on-board needs to be on and transmitting. If it is damaged or switched off then the ships cannot be tracked in this manner. Ships that have their transponders turned off are known as "dark" targets. To track dark targets, especially those not covered by coastal radar, ship transponder based tracking can be supplemented using a remote sensing technique known as Synthetic Aperture Radar.

Synthetic Aperture Radar

Synthetic Aperture Radar (SAR) satellites observe large tracts of the Earth from space. SAR is an active sensor that utilises radar technology at specific electromagnetic (EM) frequencies to pierce cloud cover and other materials. This allows SAR satellites to observe areas remotely and can do so in any weather condition, day or night (Oliver, 2004). The extent of coastal area that two SAR images can cover is shown in Figure 1.

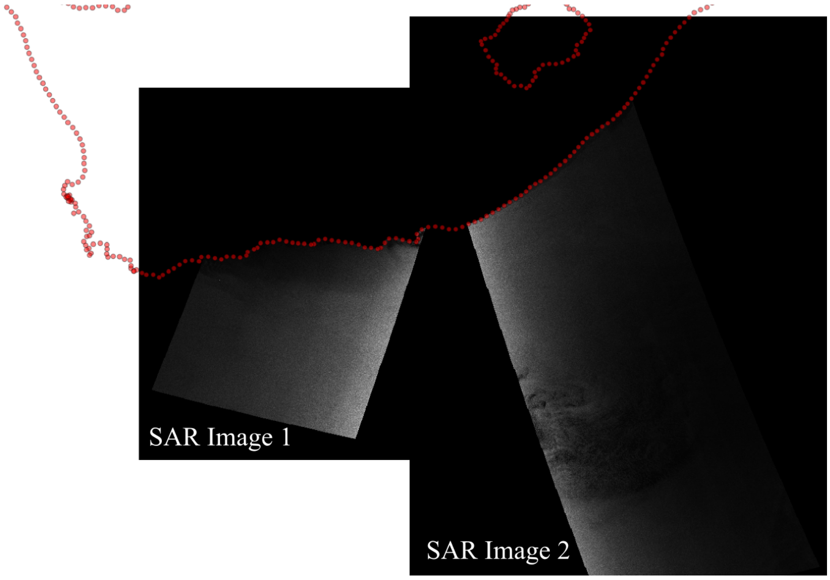

Figure 1. Two ENVISAT ASAR WSM images with the South African coastal border overlaid. It is clear that with only two images a large percentage of South Africa's Exclusive Economic Zone (EEZ) can be monitored.

Ocean water has a low backscatter because the EM signals disperse within the water whereas highly metallic objects such as ships and oil rigs will reflect the signals back to the SAR satellite. Ships appear as bright pixels and ocean as darker pixels within SAR imagery. An example of how ships look in SAR images as well as how SAR images can supplement ship transponder tracking is shown in Figure 2.

SAR Preprocessing

The SAR pre-processing step is the step that affects many basic attributes of the image and include techniques to geo-locate the image and filter speckle noise from the image. Geo-locating is an important step in that it ensures that results obtained from the processing of SAR images can be compared to real-world positions.

CURRENT METHODS

This section will discuss the basic flow of imagery through a ship detection system and will provide some insight into some of the most prominent systems used for the detection of ships at sea within SAR imagery. It should be noted that only a brief overview of the possibly methods used to detect ships is given.

Specific, detailed methodology for each of these methods can be found in the papers referenced (for instance much more detail about the Constant False Alarm Rate prescreening method can be found in (Crisp, 2004; Peterson, 2012; Kleynhans 2013; Schwegmann, 2014).

Ship Detection System

A ship detection system is typically composed of a number of steps that are used to process a SAR image (Crisp, 2004).

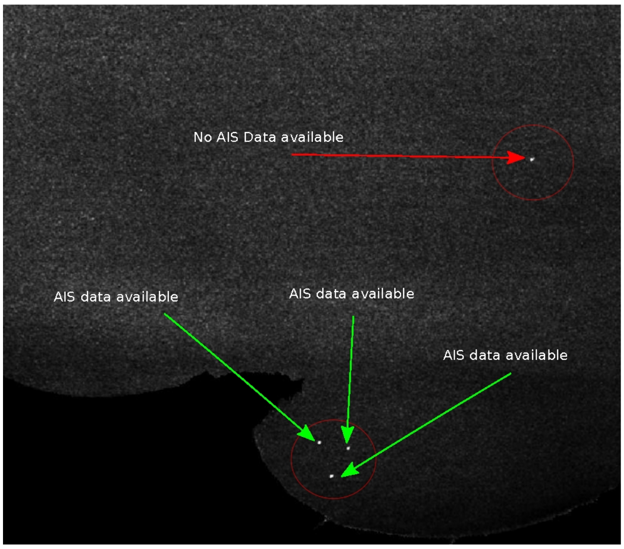

Figure 2. SAR intensity image with the bright spots indicating ships. In some cases SAR images can highlight "dark" targets which could typically not be tracked using ship transponder data only.

Each of the steps plays an important role in the detection of ships at sea however some of the following steps are omitted because subsequent steps provide similar functionality. Figure 3 shows an example of a typical SAR ship detection system.

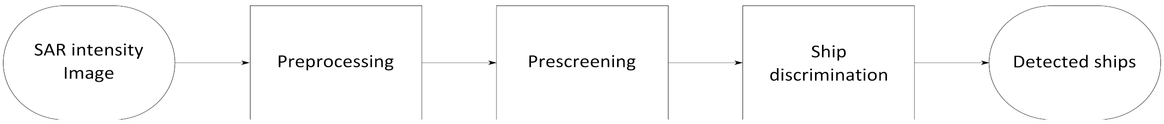

Figure 3. The typical flow diagram for a ship detection system using SAR imagery. Some steps are forgone in certain configurations as they are combined or compensated for in other steps.

SAR pre-processing

Speckle noise is a multiplicative noise that is often found in SAR images (Oliver, 2004). Speckle is usually dealt with using filters such as the Lee (Crisp, 2004) and Sigma (Zhong, 102) filters. Newer techniques to despeckle SAR images includes Wavelets (Peterson, 2012; Vijaykumar 2012), signal subspace techniques (Yahya, 2012), and maximum a posteriori (MAP) filters (Peng, 2014). Sometimes speckle filtering is forgone altogether because the pre-screening methods take the noise within the SAR images into account when detecting ships.

SAR pre-screening

Once the image has been pre-processed the next step in the ship detection system is known as pre-screening. Pre-screening of SAR images has been given the most attention in literature and is typically split into three distinct groups: Global, Local and Other methods.

Global: These pre-screening methods consider the whole SAR image at once. Each pixel is compared to a reference threshold to determine if the pixel under test is a ship or not (Crisp, 2004). Global methods are simple and highly efficient in terms of run-time but are not typically used anymore because one single threshold is often not descriptive enough to differentiate amongst the various pixel values within an image. The results for this group of methods tends to be very good for the number of correct detections but due to lack of proper discrimination many false alarms are generated by these methods.

Local or adaptive methods: These pre-screening methods consider pixels and their neighbours when determining whether a pixel is a ship or not. These methods allow for a more adaptive approach to ship detection by accounting for local variations in pixel intensity across a SAR image. The most widely-used of the local-based ship detection methods is a method known as Constant False Alarm Rate (CFAR). CFAR was designed to ensure an acceptable level of false alarms for a given threshold when detecting ships. The Cell-Averaging CFAR (CA-CFAR) method (Crisp 2004; Kleynhans, 2013; Lombardo, 2001) detects ships using the following

$$\text{Ship detected} = \begin{cases} true, & if \;\; x_t > \mu_b t \\ false, & if \;\; x_t < \mu_b t \end{cases} \tag{1}$$

Where μ_b is the mean pixel value for the neighbours around the test pixel x_t. The symbol *t* is known as the threshold and determines how many times larger the test pixel needs to be above the mean pixel value to be detected as a ship. The selection of *t* is a complex task and the computation of the threshold value using the K-distrubition (upon which the CFAR method is based) requires to be solved numerically (Crisp, 2004). As such CA-CFAR (a special case of the K-distributed CFAR method) allows for the selection of a single threshold value that creates a threshold plane against which the mean pixel neighbourhood value is compared. Adaptions to this concept is discussed in the chapter title “Future Methods”. Previously, noise within SAR images has been modelled using either the Gaussian, Rayleigh or K distributions. The first two were used in the early days of SAR processing but more recent research showed that sea noise would be better modelled using the K-distribution. Despite this, however, some authors argue that the K-distribution is not a sufficient distribution model for background pixel intensities and other distributions such as the alpha-stable (Ferrar, 1998) and Cauchy–Rayleigh (Peng, 2014). Adaptive methods typically have both excellent detection rates and low to very low false alarm rates. These methods are the ones most used in practice due to their real-world performance.

Other: These pre-screening methods do not specifically fall into one of the two previous categories. These methods typically use some form of machine learning to help discriminate sea pixels from ship pixels. Excellent examples of other pre-screening methods including Wavelet Transform (WT) ship detection (Gao, 2011), Genetic Algorithm Radial Basis Function (GA-RBF) Neural Network (Leung, 2002) and Ant Colony Optimization (Li, 2012). Ship detection using these methods are typically on par with that of adaptive methods.

SAR ship discrimination

A final step to improve detection results is that of the ship discrimination stage. This stage is sometimes omitted from the ship detection process because much of the discrimination is done in the pre-screening stage. The ship discrimination step is typically implemented to group similar pixels to form simpler representations of ship pixels or further filtering to improve detection accuracy or decrease false alarm rate. In some cases, ship discrimination can improve the results of previous steps by an order of magnitude (Crisp, 2004).

Ship discrimination can be performed using a variety of methods from simple filters to advanced machine learning systems. The simplest example of ship discrimination is that of a Butterworth filter (Eldhurst, 1988). More advanced methods of ship discrimination include: morphological filtering (Lin, 1997), using an additional two-parameter CFAR stage (Crisp, 2004; Ji, 2010), Resonance Agglomeration and Elimination of Local Noise (Schwartz, 2002) and Mean Shift Clustering (Comanicius, 2002). A novel usage of machine learning combines output from multiple classifiers in the pre-screening stage with a Support Vector Machine (SVM) in the discrimination stage to identify ships (Ji, 2013).

FUTURE METHODS AND SAR IMAGERY

This section is split into two parts: the first details some of the current and upcoming SAR imagery sources and the second details some future methods of ship detection.

Current and future SAR imagery

SAR imagery has been used for the detection of ships at sea as far back as 1979 (Evans, 1979). Since then a number of prominent SAR satellites have been utilised such as: European Remote-Sensing (ERS) 1 and 2 satellites, Environmental Satellite (ENVISAT) and the radar satellite (RADARSAT) 1 and 2 (Oliver, 2004). These have all played important roles in the development of ship detection systems that are available today.

Looking towards the future there are two SAR satellites will be providing modern SAR imagery. The first is the Spanish PAZ SAR satellite planned to launch in Q3 of 2014 (Kramer, 2014). The mission plans to provide over 200 SAR images daily. This level of observation will allow for a more up-to-date view of the Earth and oceans. Sentinel-1 is a two satellite constellation that is a follow up to the European Space Agency's (ESA) ERS-2 and ENVISAT missions. The first of the two satellites is a C-band SAR sensor and was launch on 3rd of April 2014 with one of its objectives to provide SAR imagery of the ocean (Earth Online, 2014). This mission will improve MDA of any country because the imagery will be freely available to use for any purpose.

Future SAR Ship detection methods

Many of the ship detection methods discussed above use SAR satellite imagery and very little auxiliary data to help detect ships. One of the important advancements of the field going forward is the integration of data such as ship transponder data with SAR imagery for the improvement of ship detection. Ship transponder can be used reliably as historical, ship positioning and movement data (Kleynhans 2013; Schwegmann, 2014). By gathering historical ship positions a ship distribution map of a given area can be created. A novel usage of this ship distribution map is using the map as a probability distribution and using it to decide when a CFAR threshold is too high. Two papers recently written employ the usage of the ship distribution map to select the threshold where the change average ship probability over a number of thresholds is greatest (Kleynhans 2013; Schwegmann, 2014). The first paper determines when a single threshold (flat plane) changes the average ship probability the most whereas the second paper expands this idea by trying to find the non-flat threshold plane.

Another ship detection method uses facial image features as descriptors for ships in images and then detects ships using these features and a cascade classifier (Schwegmann, 2014). Even though these image features are simple they are enough to describe complex objects such as faces and as such simpler objects such as ships in SAR imagery can be described with very few features. This means that the system can be trained to detect ships more quickly and with fewer errors.

CONCLUSION

Ship detection is becoming an increasingly important activity for countries wishing to improve their MDA. Usually, only countries with large military budgets could afford to focus on ship detection at sea. With the advent of freely accessible SAR imagery such as Sentinel-1, countries that were previously unable to research ship detection may do so now. The detection of ships within SAR imagery is a complicated procedure with a number of steps that need to be carefully considered before implementation. Newer methods use a variety of data sources to improve ship detection performance. Governements can improve their own maritime domain awareness by investing into various sources of maritime data. The integration of ship transponder data and SAR imagery, acquired either with various assets (international and/or South African owned satellites) will lead to more advanced ship detection systems and thus improved understanding and policing of South African Waters.

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