Automated ship detection on Synthetic Aperture Radar (SAR) images from Ocean wakes

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Abstract

In this study, we employ image processing techniques to detect ships from ocean wakes as seen on Synthetic Aperture Radar (SAR) image of the West Philippine Sea. Confronted with the inherent noise in SAR images, we employ contrast enhancement to highlight line features and apply the Radon transform to pinpoint ocean wakes trailing behind ships. Our method achieves a precision of 76% and a recall of 81%, despite the challenges posed by noise. These results demonstrate the potential of our approach in effectively identifying maritime vessels, paving the way for more accurate and reliable maritime surveillance in this strategically significant region.

Keywords: Ship Detection, Synthetic Aperture Radar, Radon Transform

1 Introduction

Synthetic Aperture Radar (SAR) plays a critical role in maritime domain awareness (MDA) by providing all-weather, day-and-night imaging capabilities. Despite SAR's ability to penetrate cloud cover and offer high-resolution images, detecting ships in SAR images is challenging due to image quality, resolution, and severe weather conditions [1, 2]. Ship wake detection, which reveals ship presence, is a key focus area in SAR imagery [3].

Despite recent advancements in machine learning [4, 5], traditional methods using Radon transform remain relevant for wake detection in SAR imagery [6], particularly in challenging SAR image conditions and environmental factors that can obscure wake patterns. In some cases, it is difficult to identify any targets such as marine vessels in large-scale remote sensing, but the wake is apparent. Thus, another approach is to indirectly detect the target from the ocean wakes [7]. This highlights the need to refine ship detection approaches using all the available techniques in image processing, ensuring a robust ship detection algorithm in SAR-based systems for maritime responsiveness.

Illegal, unreported, and unregulated (IUU) fishing poses a significant global threat, particularly in the Philippines, where satellite imagery reveals an increasing trend in potential fishing vessels in the West Philippine Sea [8]. Given the Philippines' dependence on its waters for livelihood, effective maritime surveillance is critical for combating IUU fishing and conserving marine biodiversity [9].

This study aims to develop a robust image processing algorithm using Radon transform to detect ship wakes from SAR images and inventory ships within the West Philippine Sea.

2 Methodology

2.1 Data and Study Area

We analysed a Sentinel-1 SAR Level-1 Ground Range Detected (GRD) image downloaded from the Copernicus Data Space Ecosystem covering a certain area within the West Philippine Sea. The configuration of the image acquisition is described in Table 1.

Table 1: Acquisition parameters the image used

Date of acquisition	September 19, 2023
Acquisition Mode	Interferometric Wide (IW)
Resolution	$5m \times 20m$
Swath Width	$250km$
Orbit direction	Descending
Polarization	VV
Incidence angle	$29.1° - 46.0°$

After downloading, the image first undergoes radiometric calibration and terrain correction using the ESA Sentinel Application Platform (SNAP). This platform is specifically designed to process data products from various satellite missions of the EU's Copernicus program, such as Sentinel.

2.2 Contrast Enhancement

We applied a median filter of kernel size of 5×5 pixels to despeckle the image for further processing. After this, we applied Canny edge detection on the filtered image to highlight the linear features and further remove the noise. Figure 2 shows how the process reduces the speckles from Median Filtering (Figure 2b) to Canny edge detection (Figure 2c).

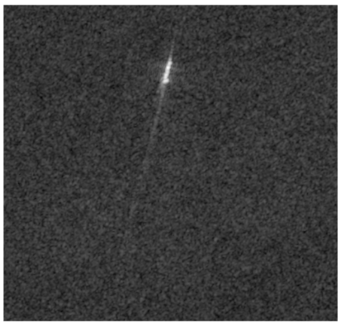
2.3 Wake Detection

After the image contrast has been enhanced, we implement Radon transform to detect wakes on the binary image. The Radon transform $R(\rho, \theta)$ of an image $I(x, y)$ is a function of the normal distance ρ from the origin and a line, and, θ is the angle of the normal to the line measured from the +x-axis expressed as

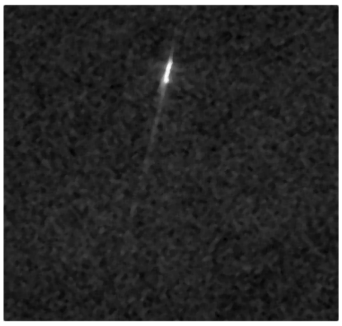
$$R(\rho, \theta) = \iint_D I(x, y)\delta(\rho - x\cos\theta - y\sin\theta)dxdy, \tag{1}$$

where D is the image domain with position (x, y) and δ is the Dirac delta function. This transform integrates the pixels within the image along each line which transforms lines into single points within the Radon space. This process effectively converts spatial domain information into the parameter space where edges and other linear features are transformed as points and thus become more prominent and easier to detect. This process not only helps suppress noise but also highlights linear features, such as ship wakes, as bright points in the Radon space (Figure 1d). By analyzing these bright points, we can effectively detect and characterize the ship wakes present in the SAR image.

After identifying the most prominent lines in the Radon domain, which are assumed to correspond to the ship wakes, the brightest object along this line is considered to indicate the ship's location (see Figure 1e). This processing is implemented on 512-by-512 pixel image tiles and the resulting points are aggregated for measuring detection performance.

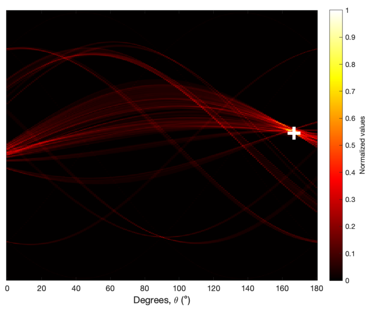


(a) SAR image

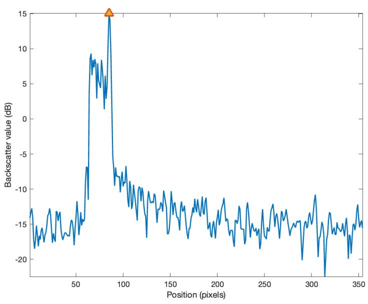


(b) After Median filtering

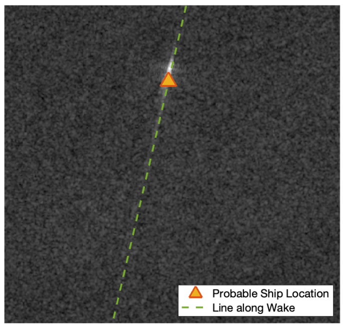
(c) After Canny edge detection



(d) Enhanced image in Radon space with the peak shown



(e) Intensity profile along the line feature from Radon transform



(f) Line along the wake with the ship location

Figure 1: Contrast enhancement (b-c) leaves only the prominent edges and linear features on the scene. After enhancement, Radon transform (d) is used to identify the wake and locate the ship.

2.4 Masking and Filtering

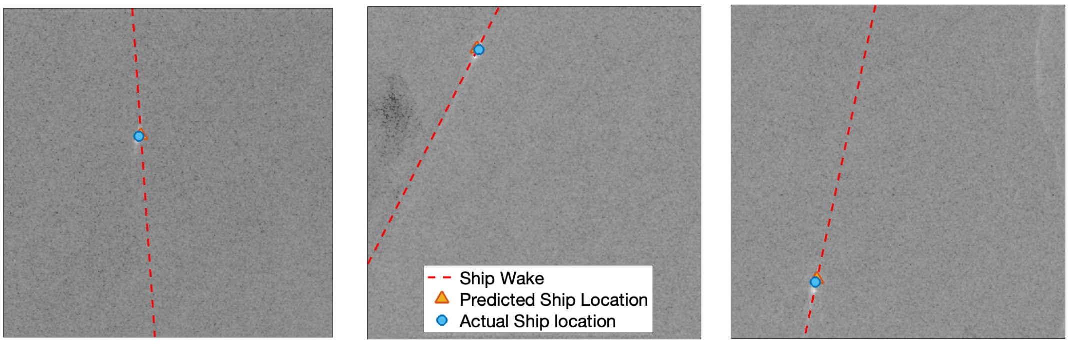
To exclude land masses from processing, we applied a mask using QGIS, an open-source GIS software. This ensured that only the sea parts were analyzed in the SAR images.

Given the susceptibility of SAR images to environmental conditions, further filtering was necessary to eliminate false peaks caused by local maxima among noisy image tiles. We implemented a filtering technique with a criterion where a detected peak must be some several standard deviations above the mean of both the line profile and the entire image tile. This approach minimized the likelihood of falsely detecting ships based on the highest backscatter values along the wake.

3 Results and Discussion

For wake detection, we successfully identified numerous ships within the image. To validate our detections, we visually inspected and confirmed a total of forty-three (43) ships, which were saved in a shapefile for reference.

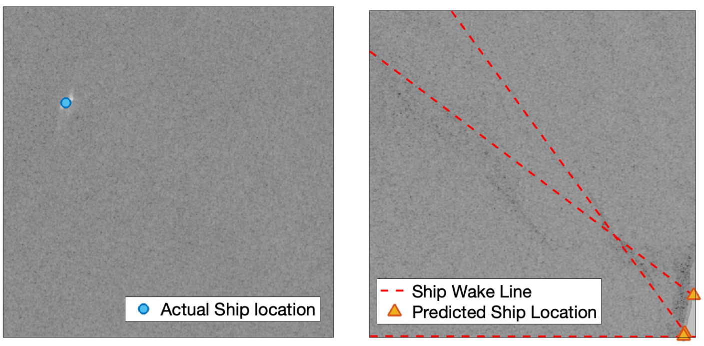
Figure 2 illustrates the detected ships across the entire SAR image. While we identified forty-three (43) vessels in total, our algorithm successfully detected only thirty-five (35) of them. The figure also shows the wake line, from which the line profile is extracted.



(a) (b) (c)

Figure 2: Detected ships on SAR image with the red line tracing the ocean wake and the predicted ship points (triangles) behind the actual ship locations (circles).

From our analysis, we utilized precision and recall as metrics to evaluate the algorithm's performance, resulting in a Precision of 76% and a Recall of 81% from our predictions. The persistent presence of noise in the image mainly contributes to the precision rate, amid our best efforts to eliminate it, generating false positives among our predictions. This is evident from Figure 3b, where image edges caused by noise led to false predictions. Meanwhile, recall could be affected by our stringent measures such as thresholding to eliminate noisy peaks among our predictions which compromises weak or less bright peaks in the image, as shown in Figure 3a.



(a) Missed ships (b) False predictions

Figure 3: Failed predictions from algorithm

The entire process of extracting line features from the image, from Canny edge detection to the Radon transform, has the drawback of also identifying prominent lines within the image, such as the pattern produced by the double-bounce of a SAR signal on corners. Detected instead are either the vessel hull or the pattern itself which aids in the integral transform, but fails to segment the ocean wakes on the image.

Also, our algorithm is only optimized for detecting wakes in straight lines, which is common in SAR images. On the other hand, it might struggle to recognize wakes with non-linear shapes resulting from directional changes in navigation. This limitation restricts the algorithm's ability to accurately detect ocean wakes with varied geometries.

4 Conclusions

SAR images are often affected by speckles due to external factors, but the accessibility of various noise reduction methods has helped mitigate this issue, particularly in object detection applications. In this study, we have demonstrated the effectiveness of image processing techniques in detecting ships based on ocean wakes. By using a combined approach in contrast enhancement, we were able to isolate linear features such as wakes in the image, enabling the determination of potential ship locations. However, continuous improvements are essential, and this will be implemented in the future to build a comprehensive inventory of ships in WPS for maritime domain awareness.

Aside from ship detection, the techniques used in this paper can be extended to detect other linear features in the ocean such as rogue waves, tsunami waves and other forms of wakes generated by different vessels at sea. SAR images can also capture ocean currents, tidal fronts, and oil spills, although these features are outside the current scope of our study and could be considered for future research.

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