Improved SOVE Algorithm for Full Velocity Vector Estimation of Ships using Amplitude Data

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Abstract — **We propose a novel methodology for ship detection and their full velocity vector extraction from SAR data, using only the amplitude information. The algorithm is based on the Radon Transform to detect the ships and to retrieve the two components of the velocity vector, using the information from the wake orientation and from the azimuth displacement. To increase the robustness to noisy environments a dedicated filter, which operates in the spatial frequency domain, is proposed. The main advantages are that the algorithm does not need any *a priori* information and is very light from the computational point of view.**

I. INTRODUCTION

The SAR plays a very important role in the monitoring of the Earth surface. This instrument is particularly useful for moving target detection in commercial, surveillance and strategic context.

Ship monitoring is an application particularly fit for the SAR capability, due to its global monitoring capability and the strong interaction between SAR signal and this kind of targets. The main steps in monitoring the ship traffic are the detection, the classification and the velocity estimation, that is difficult to derive in a complex environment as the sea.

The SAR capability to derive the dynamic characteristics of ships is well known since the eighties [1]. Many techniques were developed, mainly based on the knowledge of the effects of the moving target in SAR images and on the analysis of the geometric characteristics present on the scene, depending on the data type ([1]-[6]).

If SAR raw data is available, there are many techniques for velocity estimation. The most used technique to estimate the along and across track velocity of a moving target are, respectively, the ATI/DPCA for the range velocity and an azimuth filter bank for the azimuth component. A combination of these techniques is also used in [7] to monitor the road traffic, integrating *a priori* information (represented by the knowledge of the road position, their width, maximum velocity, etc.). The *a priori* knowledge allows the correction of the azimuth displacement and the association of the moving target to the statistically more probable road. Using the information from a data-base, the method can estimate the full velocity vector of the vehicles.

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Due to the difficulty to obtain raw data for moving target processing (especially for the new SAR platforms), an algorithm which uses only the amplitude data is highly desirable.

For the ship detection the most common technique is based on CFAR detectors [2], where the setting of the decision threshold is critical. Other methodologies use the reflectivity coherence to detect the targets, considering that the sea has a strongly incoherent behavior, opposite to that of the ships [3].

For the velocity estimation, several techniques were developed, and depend of the data type. The main principle used to estimate the velocity is the localization and the form of the wake of the ship [4]. In fact, the azimuth shift of the ship from the wake is directly proportional to the radial velocity, and the absolute value of the ship is correlated to the internal wave speed or to the internal wake opening angle [5].

The problem is that in most situations only the turbulence of the wake, that appears dark, is visible, so it is not possible to estimate the velocity vector. It is clear that the wake detection is the fundamental key to estimate the ship velocity from amplitude SAR images.

An interesting method, very efficient to detect the wake on *quicklook* images [2] proposes to integrate the intensity over lines scanning the full 360º from the ship position, with the aim to detect the wake and its orientation. The limitation of this method is that only the radial component is estimated.

Recently the Radon transform was proposed to estimate the orientation of the wake. Since the Radon transform is able to detect the linear structures in an image, this tool is the main support of some works recently published to estimate the orientation of the wake [5].

The estimation of the full velocity vector is proposed in [6], using *a priori* information. The radial velocity is estimated from the distance between ship and wake, and the approach used to calculate the along track component is to derive the speed from the estimated radial velocity, the estimated aspect angle and the calculated incidence angle. The aspect angle is derived by using a data-base with the information of known ships for the identification.

II. PROPOSED METHODOLOGY

Typical limitations of the proposed techniques are the incapability to estimate the full velocity vector of the ships without a priori knowledge and some assumptions that limit their applicability in real contexts.

Herein we propose an improved version of the SOVE algorithm [8] to detect the ships and estimate their full velocity vector without using any a priori knowledge. It uses only amplitude SAR data and is simple, robust and fast, when compared with other recently proposed algorithms. The basic principle of the estimation is the consideration of the ship orientation, from which the wake turbulence direction is derived, using the Radon transform.

The method is structured in three steps, which allow to detect the ships present in the scene and to estimate their full velocity vector. The main steps of the methodology are the following:

1. Ship detection;
2. Focusing of each detected ship and pre-processing;
3. Full velocity vector estimation for each ship.

A. Radon Transform

The Radon Transform (RT) is a powerful mathematical instrument for line parameter extraction in images even in presence of noise [9].

Given an image g in the coordinate system (*x,y*), the RT is defined as [9]:

$$\hat{g}(\rho,\theta)=\int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty}g(x,y)\delta(\rho-x\cos\theta-y\sin\theta)dxdy \quad (1)$$

where δ is the Dirac delta function; the integral line through the image $g(x,y)$ is defined by the coordinate θ and ρ, that correspond respectively to the orientation and to the smallest distance to the origin of the coordinate system. So the RT computes the projection of an image along the direction given by (ρ,θ). Note that θ is unambiguous in $[0,\pi]$.

B. Ship Detection

A sea scene is considered, by masking the land. The scene is divided in sub-images and for each sub-image its histogram is generated. The algorithm estimates the parameters of the gamma distribution that better fit the histogram and the threshold of the cumulative distribution function is evaluated for ship detection, by selecting the value that includes 99% of the values.

The ship detection technique used in the algorithm is the CFAR method [1], based on the selection of the threshold estimated from the histogram analysis. Only the pixels that have higher value than the threshold are classified as ship. The generated ship map is composed by pixels with a binary 1 if the pixel is classified as a ship, 0 otherwise.

A ship is a complex object, in which some strong scatterers are distributed. If the distribution is not homogeneous, it can lead to more than single ship detection. To avoid this, for each pixel classified as a ship, the algorithm sets to 1 the adjacent pixels. From the ship map the algorithm finds the ships, their coordinate and their length.

C. Ship Focusing and pre-processing

The algorithm isolates the targets from the context and focuses a small scene with a single ship. The window dimensions of the scene must be large enough to contain the ship wake.

Firstly, the ship is masked to improve the wake sensitivity of the RT, because a strong scatterer can interfere with the estimation. To stress the low values and to saturate the high levels the logarithm of the image is computed.

Finally, the values on the matrix are linearly inverted (image negative), with the purpose to brighten the ship wake for the RT detection.

D. SOVE algorithm for velocity vector estimation

The basic principle of the algorithm is the detection of the wake turbulence direction, from which the motion parameters are derived.

In many cases, the ship wake is not always visible on the SAR images, depending on the sea state, the wind sea, the ship size and the ship velocity. This makes very difficult the detection of the wake.

Because generally the ship has a high SCR (Signal to Clutter Ratio) and presents a preferential orientation, the method estimates the ship orientation to derive the motion parameters. We named this algorithm as SOVE, acronym formed from Ship Orientation to Velocity Estimate.

We start by focusing the ship at a known azimuth distance from the center. Because the ship has an extended form, it can be considered, approximately, as a line segment. With the RT we estimate the orientation θ, taking the maximum of the image in the Radon domain. Note that θ is unambiguous only on a π interval.

To reduce the influence that the pseudo-structures in the image can have in the wake detection step, we use the SOVE filter in the frequency domain to select only the frequencies relative to the linear structures with an angle of $[\theta+\pi/2-\beta, \theta+\pi/2+\beta]$. This filter, illustrated in Fig. 1, is the big improvement on the original SOVE algorithm. To avoid strong distortions in the images, the filter does not cut the low frequencies. For the filter we chose the angle β=30° and the radius of the low pass filter R=20% of the image size. In fact, values of R lower than the 15% of the image size destroy the informative content of the scene. Note that all the pixels of the contour to the filter are set to 0.5, giving more continuity to the transition between the frequencies to pass and to filter.

Finally, the ship is focused at the center of the scene and the RT is applied to the image for the estimated angle θ, to scan the space in the right direction. To accommodate small errors on the orientation estimation, the RT is applied in the space $[\theta-\varepsilon, \theta+\varepsilon]$. The distance from the ship is derived taking the maximum value of the vector generated from the RT. To solve the ambiguity of the orientation estimate we scan all the space separately in the interval $[0,\pi]$ and $[\pi,2\pi]$.

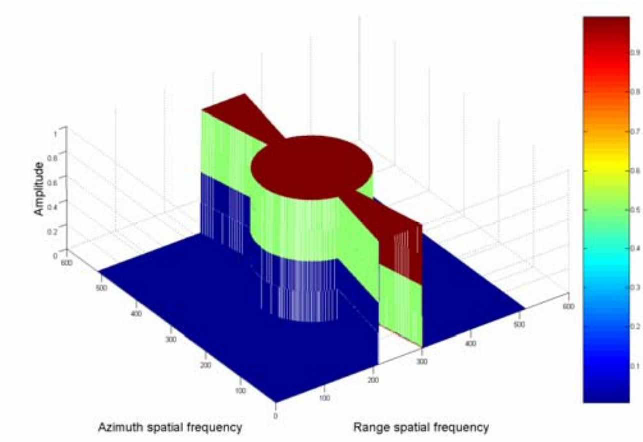

Fig. 1. The SOVE filter

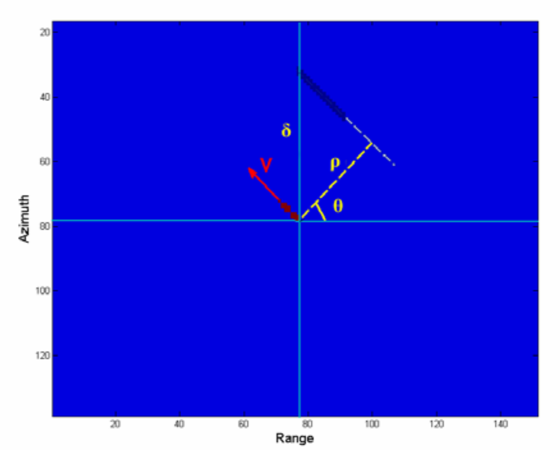

Fig. 2. SAR geometry of a ship and its wake.

The RT determines the couple (ρ,θ), that is related to the velocity vector, as shown in Fig. 2.

These parameters are related to the azimuth shift by

$$\rho = \delta \sin\theta \Rightarrow \delta = \rho / \sin\theta$$

From the couple (ρ,θ) we derive the range and azimuth velocity. In fact, the azimuth temporal shift of the moving target along the slant range is [7]:

$$\eta_{shift} = 2v_{sr} / \lambda \cdot f_R$$

where v_{sr} is the slant range velocity and f_R the Doppler rate. The spatial azimuth shift results:

$$\delta = v_B \cdot \eta_{shift}$$

where v_B is the ground beam velocity.

The ground range velocity is related to the shift:

$$v_{gr} = \lambda f_R \delta / 2v_B \sin\phi$$

where Φ is the incidence angle of the SAR.

The azimuth velocity results:

$$v_{az} = v_{gr} \tan\theta$$

Note that the azimuth and the range velocities are simultaneously obtained by using all the information of the RT.

The proposed methodology works well provided the ship has a minimal length (some pixels) on the focused SAR image.

III. RESULTS

The algorithm was tested with simulated and real data to characterize its advantages and disadvantages.

A. Simulation results

To test the velocity estimation algorithm we simulated a scene, in which there is a ship and its wake. Table I shows the parameters used to simulate the scene.

The characteristics of the ships are the length, the orientation, and the range and azimuth velocities. Table II presents the values used in the simulation.

Table I

Parameter	Symbol	Value
Dimension of range pixel	Δrg	12,5 m
Dimension of azimuth pixel	Δaz	12,5 m
Doppler rate	f_R	-2156 Hz/s
Signal to Clutter Ratio	SCR	23 dB

Table II

Parameter	Symbol	Value
Ship length	L	124 m
Orientation ship	θ	135°
Range velocity	v_{sr}	-5.8 m/s
Azimuth velocity	v_{az}	-5.8 m/s

To simulate a realistic scenario we considered the noise, modeled as a gamma function [10].

To analyze the sensitivity of the methodology to the wake visibility we varied the ratio between wake level and sea mean level (Wake-Sea Ratio, WSR) and the variance σ of the gamma function, related to the sea wind. Considering the typical values in a real scenario, the variance is varied in the interval [1000,10000] and the WSR in the interval [-5 dB,-1 dB], as shown in Fig. 3.

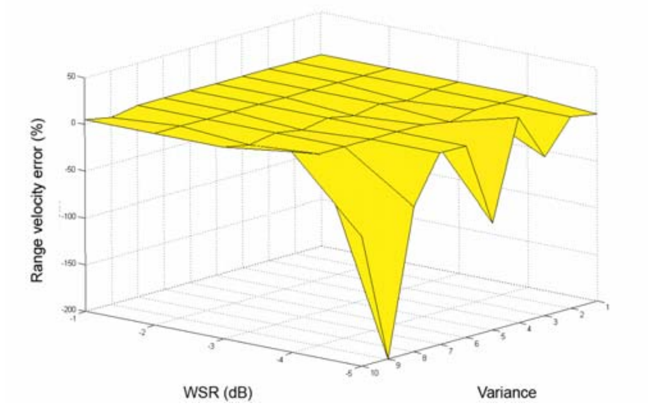

Fig. 3. Range velocity error on the σ-WSR plane.

Fig. 3 presents results, where the range velocity error for the estimation algorithms is plotted on the variance-WSR plane. The graphic of the azimuth velocity error is similar and, as such, is herein omitted due to the paper length reasons.

The SOVE algorithm results robust and accurate, producing good results for a WSR higher than -1 dB, as shown in Fig.2. In fact, for WSR>2 dB the mean error is 4.5% for the range and azimuth velocity.

For illustration purposes, we show in Fig. 4 a real SAR scene with variance of 5000 and WSR of -3 dB.

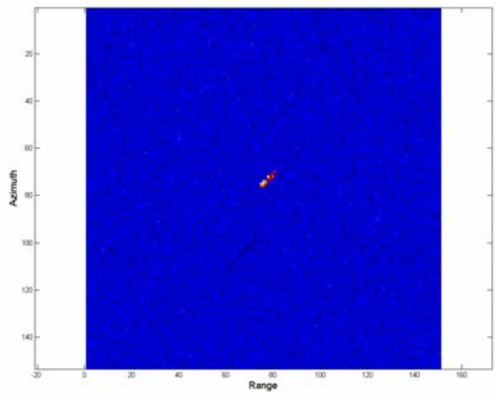

Fig. 4. Simulation with WSR=-3 dB and σ=5000.

B. Real data results

The algorithm was tested on the scene of ERS 2 “e2_16466_2763PRI”, where one ship with SCR of 30 dB is present (Fig. 5).

From Fig.5, we can note that the WSR is very low and the ship has a complex form. Under these conditions the velocity estimation results difficult for the algorithm, because the RT can’t identify well the wake as a linear structure. Nevertheless, the SOVE algorithm estimates the velocity vector with a small error.

Table III shows the results of the SOVE algorithm.

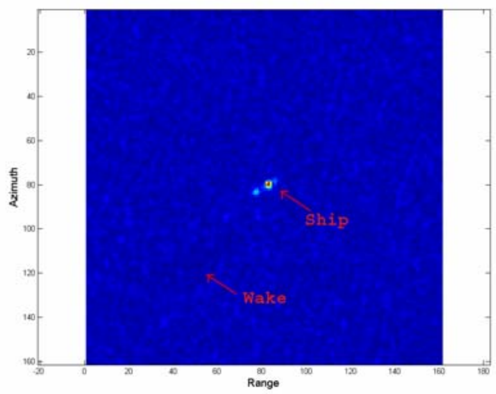

Fig. 5. Ship with its wake

Table III

Real velocity (m/s)		**Estimated velocity (m/s)**		**Error (%)**	
Range	*Azimuth*	*Range*	*Azimuth*	*Range*	*Azimuth*
4.1	-2.7	4.3	-2.7	4.9	0

IV. CONCLUSIONS

We propose the SOVE algorithm for ship detection and full velocity vector estimation from amplitude SAR data. The algorithm uses the RT to detect the ships and to derive the two components of the velocity vector at the same time. The main advantages are that the algorithm does not need any a priori information and it is computationally very light.

From the simulations, the SOVE algorithm is very accurate and robust, failing only in extreme conditions. To experiment the algorithm in a real context, we applied it in unfavorable scenes. Even under these conditions it produced very encouraging results.

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