Study of Sea Clutter Influence in Ship Classification Algorithms based on Polarimetric SAR Inteferometry

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Abstract

This paper is focused to evaluate the influence of sea clutter in the performance of ship classification algorithms based on single-pass Polarimetric SAR Interferometry (PolInSAR). For such purpose, series of numerical simulations have been carried out with GRECOSAR, the SAR simulator of complex targets developed by UPC. There, different types of vessels have been considered for a TerraSAR-X like sensor and a sea surface following the two-scale wave approach. The quality of ship discrimination has been quantitatively evaluated with a novel identification method that exploits the particular scattering properties of ships. The results show that the presence of clutter does not notably drop identification performance, despite negative matches can be observed in some particular situations. But the requirement of single-pass interferometric capabilities is not achieved by any of the existing orbital system. This drawback can difficult the validation of what has been observed in simulation environments and can be one of the most limiting factors for the practical implementation of these techniques. Ideas and possible solutions to relax the system requirements are preliminary discussed.

1 Introduction

Nowadays, a new generation of SAR sensors with improved capabilities are ready to be used by the scientific community. They provide more resolution and polarimetric channels so that a new range of applications may be considered. Example is ship classification.

In the last years, RSLab has devoted a lot of efforts to further investigate this research line. In a first step, an accurate and efficient SAR simulator of complex targets GRECOSAR has been developed [1]. This tool has allowed to build controlled databases of PolInSAR images for different types of ships taking diverse operating bands and image resolutions into account. The analysis of such data has leaded to a phenomenological evaluation of ship scattering where the measured polarimetric mechanisms have been accurately related with specific geometrical structures [2]. This information has appeared to be essential for improving SAR image interpretation and characterizing the environment influence in ship geometry scattering.

In a second step, the gained knowledge has been used to develop a novel Vessel Classification Algorithm (VCA) [2]. This method applies a proper polarimetric and interferometric processing so that 3D scattering maps can be generated. These maps schematize the ship geometry appearing to be suitable for basing a classification rule. Different tests in GRECOSAR have shown that ship discrimination is possible in single-pass PolInSAR systems with a robust behavior against vessel motions and sea-ship interaction.

But despite of this performance, the reliability of VCA (and, in general, of PolInSAR imagery) for classifying ships in real scenarios is not still clear. One important problem is the lack of clutter in the performed simulations due to the limitations of the adopted sea model. In this paper, this problem is tackled by presenting the new two-scale surface approach adopted by GRECOSAR [3] [4]. This model has appeared to be suitable for simulation applications, specially when the main interest lies on sea-ship interaction [5]. It generates a clutter surrounding ship signature with a realistic probabilistic behavior. This new feature has been exploited in series of numerical simulations dealing with an X band sensor inspired in TerraSAR-X. They account for diverse clutter conditions and types of ships of different sizes. The analysis of these data have shown that moderate sea clutter does not excessively modify VCA performance. Only for some particular cases, erroneous identification is provided. In the current configuration, VCA needs from restrictive systems designs, which would probably need from alternative and smart proposals.

The paper is structured as follows. Section 2 and 3 describe the simulation environment and datasets used in this work. Section 4 evaluates the performance of VCA under clutter conditions whereas Section 5 provides guidelines about the potentiality of alternative modes for reducing system requirements.

2 Simulation Environment

GRECOSAR is a numerical tool capable to reproduce in simple PCs the SAR signatures of complex targets that any user-defined SAR sensor would provide in real scenarios [1]. It is based on the UPC's GRECO® solver that

estimates, for each single frequency, the RCS of 3D targets via high-frequency methods. The targets are modeled with facets via the CAD package GiD® of the International Center of Numerical Methods for Engineering.
GRECOSAR accounts high scenario flexibility. Any PolInSAR sensor and 3D ship model can be evaluated in a scenario considering target bearing, speed and motions over a dynamic sea. Sea surface is modeled by considering a limited flat plane surrounding the ship. This plane is discretized with dielectric facets (complex dielectric permittivity of $\epsilon = 70 + j \cdot 30$ for a 35 psu of salinity and $25^o C$ of temperature [6]) and has a hole in the middle where ships are embedded. In order to reach a perfect matching between the two targets, hole contour is defined by the buoyancy line where ship models are truncated. The result is a realistic scene that is processed at the same time ensuring a correct modeling of sea-ship interactions. Before integrating both targets, GRECOSAR applies the proper rotations to ship model and modifies sea height profile at each synthetic position. This is done with a simpler version of the two-scale model approach [4] [7] for which a small scale wave modulates the surface of a meso-scale one by

$$h(x, y, t) = h_l \cos\{\kappa_l x' - \sqrt{g\kappa_l} t\} + h_s \cos\{\kappa_s x' - \sqrt{g\kappa_s} t\} \quad (1)$$

where surface dynamics are fixed by $\sqrt{g\kappa_i}$ with g being the acceleration of gravity and $\kappa_i = 2\pi/\lambda_i$ the wavenumber vectors of the large ($i = l$) and small ($i = s$) scale waves. $x' = [x, y]^\dagger$ is the transpose vector of the original set $[x, y]$ accomplishing $\kappa_l x' = |\kappa_l| \cdot |x'| \cos\theta_i$ where θ_l is the wave course. For simulation purposes, this model appears to be good enough, specially when the main interest lies on evaluating vessel-sea scattering [5] (see Figure 1).
The reliability of the model has been assessed with probabilistic tests. Sea scenes of limited dimensions have been simulated with GRECOSAR for a discretizing accuracy fixed by the operating frequency. The reflectivity information has been used to estimate the Probability Density Function (PDF), which is compared with typical distributions associated with real seas. For sake of simplicity, sea swell has not been considered in the tests and, under such conditions, the Rayleigh PDF appears to be the most efficient quality descriptor. It provides a good measure of the degree of realism of simulated seas [8] and, in contrast to other proposals as refined Rayleigh PDF or k distribution, characterizes sea statistics in a more general way.
In this context, S band simulations have been carried out for a sea scenario of 60x60 square meters. PDF has been derived via histogram and the resulting fitted line is drawn in Fig. 2 for HH / VV channel. Graphics comparisons with the reference Rayleigh plot show a notable matching following the behavior predicted in [8]. The VV PDF is closer to Rayleigh graph with higher RCS whereas the HH one has a fixed offset. As a result, it can be considered that GRECOSAR's sea model generates reliable clutter.

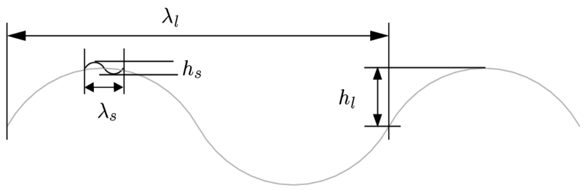

Figure 1: Scheme of the two-scale sea surface model.

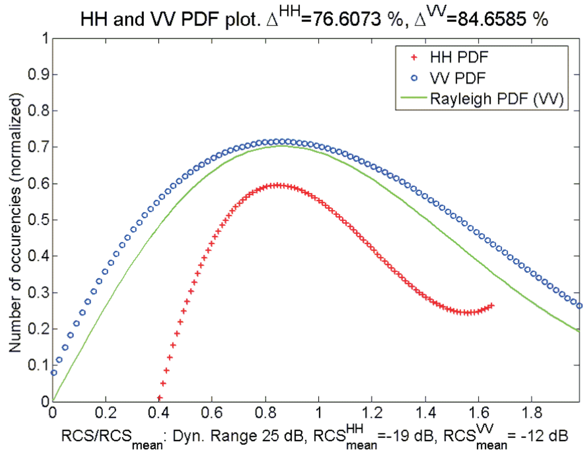

Figure 2: HH and VV PDF distributions estimated for the S band simulation of an open sea scenario. The facet length is four times lower than the operating wavelength.

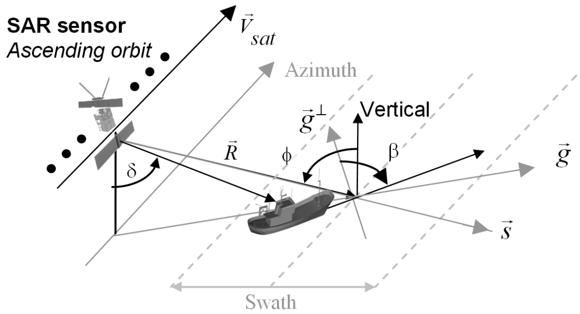

Figure 3: SAR geometry of GRECOSAR.

Table 1: X-band SAR sensor used in GRECOSAR.

ϕ [^{o}]	*20*	L_a [m]	*4*	PRF [Hz]	*3630*
f [GHz]	*9.65*	BW [MHz]	*135*	$\tau[\mu s]$	*25*

3 Data Description

GRECOSAR has been used in the following to generate a database of PolInSAR images for three types of vessels: 1) a Spanish fishing vessel (SPA) 27 m long and 10 m wide, 2) an Icelandic fishing vessel (ICE) 70 m long and 12 m wide and 3) a passenger ferry (FER) 200 m long and 30 m wide. The imaging geometry is depicted in Fig. 3. There, the adopted sensor is based on TerraSAR-X with an azimuth x range (AxR) resolution of 2.3 x 1.3 m (see Table 1). Single-pass Interferometry deal with a 30 m of orthogonal baseline. Three groups of simulations have been performed: 1) ship static with no sea, 2) ship in motion and 3) ship in motion over a sea surface ($\theta_l = 45^o$ (counterclockwise with respect to $\vec{g}^{\perp}$), $h_l = 1$ m, $h_s = 0.1$ m, $\lambda_l = 100$ m and $\lambda_s = 0.04$ m [1]. In both cases, seven bearings have been evaluated from 295^o to 355^o in steps of 10^o.

The images obtained with these simulations have been analyzed with VCA [2]. This method is based on previous scattering studies where the response of vessels has appeared to be dominated by a set of hot spots behaving as trihedral and dihedral. The analysis of diverse scattering images has allowed to build reference feature sets where the distribution of guide scatterers *(or Permanent Polarimetric Scatterers, PePS)* permits the discrimination among different ships. VCA exploits this knowledge by expressing the input PolInSAR data in terms of the quad-pol Pauli vector. The result is 3D scattering maps the spatial distribution of main scattering centers of which can be linked with the PePS distribution of the reference sets. The similarity between both groups of scatterers is evaluated with an Euclidean-based similarity parameter 0 < S < 1 that gives an error estimation about the 3D scatter distribution and polarimetric behavior. It has appeared to be a suitable quality descriptor for ship discrimination [2].

4 Analysis for Quad-pol mode

This section analyzes the images derived from previous simulations. Fig. 4 shows the most significant results for FER ship and bearings $\beta = 295^o$ and $\beta = 315^o$ (neither motions nor sea are simulated). There, the hot spots within ship geometry can be isolated so that VCA can provide the classification decision (discrimination with respect to the other models higher than 40 %). They correspond to the four PePS present in the FER reference feature set.

The same simulations than before have been generated for ship motions and sea plus ship motions. The results are presented in Fig. 5 and 6, and show two important effects, namely: 1) ship motions break with the spatial distribution of hot spots and 2) sea clutter contaminates the reflectivity information of ship signature according to sea model dimensions. Not only in these images but also in real data, both are the most disturbing effects for classification algorithms based on SAR imagery. They normally avoid to realize which ship is under observation by simple eye inspection. But with VCA this may be possible thanks to the proper combination of the advantages of polarimetry and interferometry.

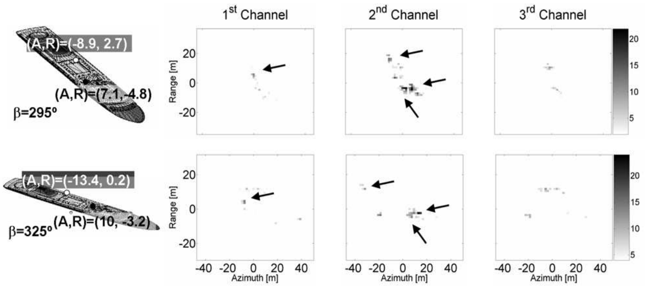

Figure 4: Magnitude of the Pauli channels for the FER ship with $\beta = 295^o$ and no sea surface. Arrows locate FER PePS.

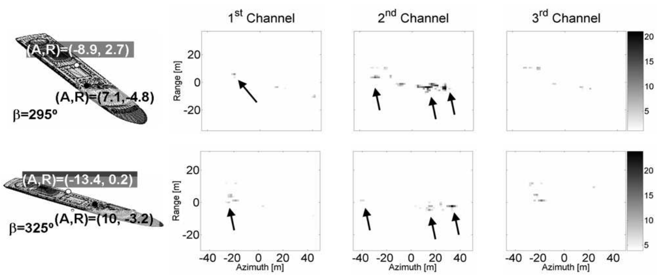

Figure 5: Magnitude of the Pauli channels for the FER ship with $\beta = 295^o$ with motions. Arrows locate FER PePS.

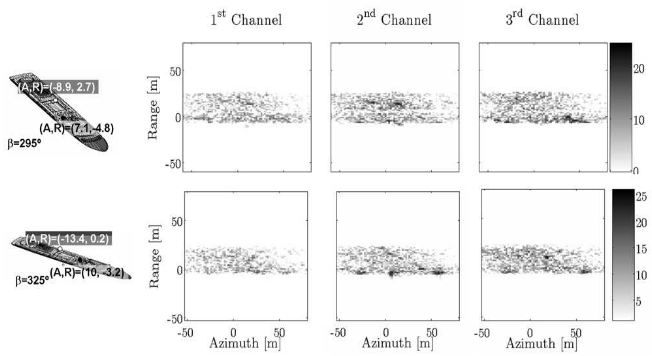

Figure 6: Magnitude of the Pauli channels for the FER ship with $\beta = 295^o$, motions and sea.

To confirm this, Table 2 and 3 gather respectively the similarity values provided by VCA when each of the three vessels is processed with no environment and with sea. The similarities correspond to the three available patterns. As observed, good identification performance is obtained in

[1] $\lambda_s = \lambda/2\sin\phi$ so that Bragg scattering phenomena becomes magnified [4]. Facet length is accordingly updated to properly model λ_s feature. Its value is four times lower than λ_s as this ratio has appeared to provide the best trade-off between data accuracy and processing load.

all the cases even when the clutter makes the identification of hot spots difficult. The reason is the decision criteria of VCA based on RCS and polarimetric mechanisms, which looks for those scatterers with the closest response to canonic targets. This assures the highest phase stability possible from which confident heights can be retrieved.

Table 2: Similarity values $0 < S < 1$ retrieved for the X band simulations with no environment in quad-pol mode.

$\beta = 295^o \mid \beta = 315^o$	SPA_{pat}	ICE_{pat}	FER_{pat}
Processing SPA	**0.82** | **0.8**	0.31 | 0.47	0.3 | 0.32
Processing ICE	0.08 | 0.0	**0.56** | **0.82**	0.08 | 0.28
Processing FER	0.1 | 0.11	0.19 | 0.0	**0.7** | **0.6**

Table 3: Similarity values $0 < S < 1$ retrieved for the X band simulations with clutter in quad-pol mode.

$\beta = 295^o \mid \beta = 315^o$	SPA_{pat}	ICE_{pat}	FER_{pat}
Processing SPA	**0.57** | **0.44**	0.15 | 0.0	0.0 | 0.25
Processing ICE	0.1 | **0.7**	**0.8** | 0.44	0.1 | 0.25
Processing FER	0.21 | 0.0	0.3 | 0.0	**0.69** | **0.56**

5 Alternative polarimetric modes

Previous section has suggested that ship classification with a robust behavior against clutter and ship motions can be possible. But this is only reachable if single-pass PolInSAR systems with resolutions lower than 3 m are considered [2]. These requirements are quite demanding because important restrictions in swath coverage can be observed as well as problems related with system design and the mechanical complexity of interferometric configuration. Swath limitations can be partially overcome with alternative polarimetric modes that reduces the number of polarimetric channels to measure. Example is the Alternate Polarimetric (AP) mode of ENVISAT where HH-VV and HH-HV combinations can be managed. The first case is the ideal one as allows the isolation of PePS mechanisms. The problem however is the fact that HH and VV are not obtained at the same time and this can lead to fatal decorrelation effects when evaluating Pauli mechanisms. HH-HV option does not appear to be very helpful as clutter response becomes magnified due to the cross-polar term.
Other options lay in dual-circular schemes that can discriminate, under low clutter conditions, trihedral-like from dihedral-like behaviors with one measurement. The problem here is dihedral-like behaviors that are not as pure as in the Pauli case (second channel) because they are contaminated with cross-polar terms. This means that, when clutter is high, dihedral mechanisms experiment errors in height isolation and proper mechanism identification.

6 Conclusions

This paper has studied the influence of sea clutter in ship classification based on PolInSAR. Different tests have shown that notable performance may be achieved with VCA under moderate clutter. But to reach this performance, single-pass PolInSAR systems with resolutions < 3 m are demanded. Two main problems arise with such design: 1) single-pass implies tandem missions or one single platform with a complex and fussy interferometric mast; 2) Quad-pol modes needs from various measures at each synthetic position reducing the available coverage. Both issues makes very difficult to find a system that would fulfill previous requirements. In this sense, future works should consider alternative polarimetric modes as an option to make possible the evaluation of VCA in real scenarios.

7 Acknowledgement

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