Orbital Single-pass interferometry for vessel detection and classification

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Abstract

This manuscript tackles the possible usage of Polarimetric SAR interferometry in vessel classification. It presents a simple technique that combines the retrieved height information with a Pauli analysis of polarimetric data to build a tri-dimensional map of scattering centers. By comparing this output with a vessel pattern database generated from previous scattering studies, a decision on vessel identification can then be provided. The performances of this method have been preliminary tested with simulated data obtained from the UPC’s Orbital SAR Simulator, GRECOSAR, for a sensor inspired in the incoming TerraSAR-X. The obtained results show the tri-dimensional map is highly related with the observed geometry and it could allow vessel identification almost independently of the sea state.

I. INTRODUCTION

In the last two decades, SAR imagery has allowed to improve a lot of applications, mainly related with the inferring of physical parameters from Earth surface. Along this period, the addition of polarimetry and interferometry has been essential to extend the research to other areas oriented to global monitoring as biomass estimation and ice studies. Despite most of the work done with polarimetric SAR interferometry (POLInSAR) deal with distributed targets, there are other applications as vessel classification where this imagery mode could play an important role. Nowadays, some governments and institutions have a great interest on develop a global and independent ship monitoring system using SAR sensors, but unfortunately there is not yet an efficient classification method to base it. The generation of tri-dimensional maps of ships’ scattering centers via POLInSAR could be the solution for this application.

Recent studies in vessel classification have been focused on the polarimetric analysis of the scattering matrix S via Coherent Target Decompositions (CTD) [1], [2]. Such theorems have great potentialities in this field as they express the complex polarimetric behavior of each pixel of SAR images in a mixture of elemental mechanisms related to specific physical structures. The degree of significance of those mechanisms allows building a polarimetric signature from which guidelines of target’s geometry can be retrieved. CTD decompose the matrix S of each resolution cell as the coherent sum of the scattering matrices related to the simple mechanisms but assuming all share the same centre of phase. This issue causes a notably worsening of CTD performances in those images where some cells have scatters with diverse polarimetric mechanisms and phase centers. The main consequence is important changes in the polarimetric signature even for slight modifications on the observations conditions. Unfortunately, this happens normally in vessel SAR data due to the reduced resolution of the sensor compared with the complex geometry of the target making useless this approach for vessel classification. Unfortunately, this happens normally in vessel SAR data due to the reduced resolution of the sensor compared with the geometry of complex targets making very difficult the development of an algorithm [2]. Additionally, the azimuth distortions due to vessel motions during image acquisition [3] [4] can also worsen data interpretation. A first solution for this CTD limitation would be increasing the sensor’s resolution, but in such case unaffordable values would be required for achieving notable performances. Another way, in a first instance more efficient, would be the usage of single-pass interferometry as it provides an additional information channel from which a quantitative measure of the detected geometry could be inferred.

In this sense, this paper describes a simple technique oriented to classify vessels from the measured height. It analyzes the polarimetric data via the Pauli theorem to generate interferograms for each single channel. The final output is a global map built with the height information of the main scattering centers for each Pauli mechanism. This method is based on scattering studies carried out with simulated ISAR images [5] obtained from the Orbital SAR Simulator of complex targets, GRECOSAR, developed at UPC [6]. The simulations with different vessel models shown the most significant scattering mechanisms retrieved were just the elements of the Pauli basis. Preliminary tests of this technique have been made with simulated orbital POLInSAR data and they have shown reasonable performances even when the azimuth distortions due to ocean waves are noticeable. This paper presents the most interesting results for a hypothetic sensor based on the incoming TerraSAR-X.

II. THE CLASSIFICATION APPROACH

The scheme of the proposed vessel classification technique is shown in Fig. It consists on applying the Pauli theorem to both master and slave polarimetric datasets and isolate the three mechanisms of the Pauli basis. This analysis allows the
Fig. 1. Scheme of the proposed classification technique.

generation of three interferograms from which the height information of each channel is retrieved. The final output is a global tri-dimensional map of the most significant scatters built with their location, height and polarimetric information. A decision on ship identification can be provided by comparing this map with a classification pattern database derived from ISAR studies.

Mathematically, the Pauli vector for the \( i \)-th pixel is

\[
k^m_i = \frac{1}{\sqrt{2}} \begin{bmatrix} (S_{hh} + S_{vv})_i^m & (S_{hh} - S_{vv})_i^m & (2S_{hv})_i^m \end{bmatrix}^T
\]

(1)

where \( m \) stands for master (\( m=M \)) or slave (\( m=S \)) image, \([\ldots]^T\) means transpose operation and

\[
S_i^m = \begin{bmatrix} (S_{hh})_i^m & (S_{hv})_i^m & (S_{hv})_i^m & (S_{vv})_i^m \end{bmatrix}
\]

(2)

is the mono-static scattering matrix for that pixel. The first component of the Pauli vector refers to odd number of reflections clearly exemplified by trihedrals, the second to even number of reflections as observed in dihedrals with a null orientation and finally the third to anty-symmetric components represented by a dihedral oriented 45 degrees. From these mechanisms, three interferometric values can be derived for the \( i \)-th pixel

\[
I_{1\text{st}}^i = k_{1\text{st},M}^i (k_{1\text{st},S}^i)^* \\
I_{2\text{nd}}^i = k_{2\text{nd},M}^i (k_{2\text{nd},S}^i)^* \\
I_{3\text{rd}}^i = k_{3\text{rd},M}^i (k_{3\text{rd},S}^i)^*
\]

(3)

where \( k_{1\text{st},m}^i, k_{2\text{nd},m}^i, k_{3\text{rd},m}^i \) refer to the first, second and third Pauli mechanisms for the image \( m \) and \((\ldots)^*\) denotes complex conjugate. The usage of the previous formulation in each pixel of the image, before the proper coregistration and after applying height retrieval techniques, results on three height images \( H_{1\text{st}}, H_{2\text{nd}}, H_{3\text{rd}} \) each one related to a particular Pauli mechanism. The final global map integrates the heights of the local maximums present in the previous images. An important feature of the presented method is the possibility to isolate the height of different scatters within the same resolution cell if their mechanisms match Pauli ones [8]. This sub-pixel accuracy is not achieved for those scatters sharing the same mechanism, in such situation the relative height of their phase center is obtained instead.

The previous development is based on the assumption that the main mechanisms of the polarimetric signature of most vessels would be described with the Pauli ones. This asseveration is formulated according to scattering studies carried out by the authors with simulated Polarimetric ISAR images [5] obtained for different vessels and observation conditions from GRECOSAR [6]. The analysis of these datasets via CTD has shown each vessel has a particular polarimetric signature that it is preserved in a quite wide range of observation conditions and dominated by trihedral- and dihedral-like mechanisms. The first conclusion indicates that a particular vessel would have a specific distribution of scattering centers that could be observed under a reasonable range of views. On the other hand, the second conclusion outlines the phase contributions of these main scatters could be isolated by the Pauli theorem. Under these conditions, the previous approach provides an accurate tri-dimensional scatter discrimination, which would be used to base a classification algorithm. Despite any CTD theorem could be valid as the trihedral and dihedral elemental behaviors are always present, the Pauli one has been selected due to its orthogonality and simplicity.
In order to illustrate the kind of data used in the previous study and give an idea about the structures that could mainly contribute in the vessels’ response, two simulated polarimetric ISAR (POLISAR) image with centimetric resolution are presented in Fig. 2(a) and Fig. 2(b). These images are the output of the Pauli’s decomposition coded in RGB format (red → 1st mechanism, green → 2nd mechanism, blue → 3rd mechanism) for the vessel model shown in Fig. 2(c). This model corresponds to a Spanish fishing vessel with a length and width of 27 and 10 meters respectively. As it can be observed, two main groups of scatters are highlighted: the buttresses of the deck shape working as trihedrals and the base of the masts over the cabin with a dihedral-like behavior. These scatters show those vessels’ areas that could have more significance in a SAR image obtained from a similar point of view. With this information the height map the Pauli-POLInSAR method would provide for such SAR image can be predicted. If this analysis is extended to other views, it could be found a scatter distribution common to all height maps within a solid angle, which can be considered the classification pattern of the vessel. This process has been done for the ship presented in Fig. 2(c) to test the decision rule at the final step of the algorithm. This rule is based on the similarity value, e, computed by the algorithm. For each pattern of the database, the algorithm measures the difference of the three coordinates of each reference point respect the values retrieved in the analyzed data and expresses the result relative to the cell dimensions and a predefined height value (relative errors). This value is specific for each model and it fixes the maximum height error allowed in order to preserve height pattern. The inverse of the mean value of the different relative errors is the parameter e and the pattern with the highest similarity indicates the model identified.

III. SIMULATION ENVIRONMENT

The described classification technique has been preliminary validated with GRECOSAR [6]. This numerical tool generates POLInSAR and POLISAR data for complex targets with notable accuracy, high scenario flexibility and reduced computational loads. The electromagnetic fields scattered by the input models are computed by the electromagnetic solver GRECOTM also developed at UPC [7]. This software works in the frequency domain with high-frequency methods, such as Physical Optics (PO) and the Physical Theory of Diffraction (PTD) that avoids the unrealistic computational requirements imposed by the discretization of Maxwell’s equations when applied to large models. It uses an original graphical processing approach for which a bitmap of the model is generated to isolate the visible surfaces from the ‘back-facing’ ones. This allows efficient and less consuming electromagnetic computations that reduce notably the hardware requirements of the simulator. Target models are defined via CAD packages with both parametric or facet-based surfaces. For instance, the model shown in Fig. 2(c) has around of 275,000 triangular facets.

The simulated orbital acquisition geometry is presented in Fig. 3. Besides the incidence angle $\varphi$, sensor attitude and target bearing $\delta$, the simulator can also deal with the cruising speed, and the rotational and translational motions experimented by the vessel due to ocean waves. A simple wave model, which considers waves as sinusoids, is used to derive the angular velocities from the user-defined sea state.

The angular span of the ISAR data is highlighted in Fig. 3 with a light grey shading. The simulator considers a kind of circular spotlight mode with the sensor at a constant the distance from the static target for a given incidence and angular aperture. This last parameter measures the angular excursion of the sensor (only the positions over the sea level are taken into account) around the point with the highest height over the horizon, C. With this imagery mode, it is possible to measure the same polarimetric information of simulated SAR datasets but with resolutions around centimeters. This results on extremely accurate scattering images that improve the interpretation of SAR images and allow the generation of the classification patterns.

All the data presented in this paper has been generated for the vessel model of Fig. 2(c) and the hypothetic stripmap orbital single-pass POLInSAR sensor summarized in Table I. This sensor is based on the TerraSAR-X configuration, but with a resolution of 2.3 meters in azimuth and 1.3 in range for an antenna dimensions of 4.3 meters length and 0.89 meters width.
Fig. 3. SAR acquisition geometry of GRECOSAR for ascending orbit. In spite of the simplified drawing, the simulator considers keplerian orbits and ellipsoidal Earth.

TABLE I

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta \omega_g$</td>
<td>7 km</td>
</tr>
<tr>
<td>$h$</td>
<td>514 km</td>
</tr>
<tr>
<td>$\varphi$</td>
<td>20°</td>
</tr>
<tr>
<td>$L_a, L_r$</td>
<td>4.3, 0.89 m</td>
</tr>
<tr>
<td>$f$</td>
<td>9.65 GHz</td>
</tr>
<tr>
<td>PRF</td>
<td>3630 Hz</td>
</tr>
<tr>
<td>BW</td>
<td>135 MHz</td>
</tr>
<tr>
<td>FS</td>
<td>150 MHz</td>
</tr>
<tr>
<td>$\tau$</td>
<td>25 $\mu$s</td>
</tr>
</tbody>
</table>

The effective perpendicular baseline is 30 meters (the real one is 60 meters as the ping-pong mode is used) leading to a height sensitivity of

$$\partial h = \frac{\lambda \sin \varphi r}{4\pi B_\perp} \partial \phi = 0.2685 \partial \phi$$

where $\partial \phi$ is the phase error expressed in degrees and $r = 544293$ m. the range to the center of the swath.

IV. DATA ANALYSIS

A first POLInSAR simulation (simulation 1) was done for a bearing $\delta = 295^\circ$ and calm sea. The main results are summarized in Fig. 4 jointly with a set of intermediate results that illustrate the steps of the classification method scheme presented in Fig. 1. Figure 'A' shows the magnitude of each Pauli interferogram with a dynamic range of 20 dB. Figure 'B' presents the global height map by superimposing to a vessel snapshot the height values of the local maximums present in the images of Figure 'A'. Red triangles stands for trihedrals, green squares for dihedrals 0° and blue crosses for dihedrals 45°. To simplify the image, the threshold is fixed by the maximum value of all three interferograms minus the dynamic range and the point of view corresponds to the SAR simulation one.

On the other hand, Figure 'D' shows the RGB-Pauli image similar to that presented in Fig. 2(a) of a POLISAR dataset obtained for the same point of view than the SAR simulation. As commented in Section II the analysis of this image jointly with additional datasets obtained for diverse observation conditions has allowed the generation of a classification pattern for this particular vessel. It gathers the locations, the heights and the polarimetric mechanisms of the scattering centers common in all the images. Figure 'E' provides a representation where the blue circles locate the reference points which height is impressed in orange. For helping data interpretation, this pattern and the height map, Figure 'C', are provided with the point of view of the ISAR simulation.

At a glance, it can be observed a correlation between the ISAR image and the height map as in both the same scatters are highlighted with similar mechanisms. As in Fig. 2(a) these scatters are the buttresses of deck shape and the base of the cabin masts. By comparing the height map information with that included in the vessel’s pattern, a similarity value $e$ is provided. For this case, $e = 72\%$, a value that would allow the correct identification of the vessel.

In order to show the robustness of this method in front of the SAR image distortions induced by vessel motions [3] [4], the same simulation has been done but for a rough sea state causing a pitching with an angular velocity of 1.5°/s and a rolling of 0.26°/s (simulation 2). The obtained results are shown in Fig. 5. First of all, it can be noted the important azimuth distortions due to the non-uniform shifts of the different vessel’s scatters. These shifts are induced by the rotational motions that generate particular radial velocities for each scatter according to its location respect the center of rotation. The main effects observed are
an enlargement of azimuth’s vessel length in the SAR image and azimuth location errors in the scattering centers of the height map. It can be shown these displacements agree reasonably the expected values according to the simulated geometry and the theoretical formulas [4]. But despite of these distortions, the degree of similarity found is quite similar to the one retrieved with calm sea as height information has been preserved. Even more, the value is a little better. This is possibly due to the spread of the overall vessel response in azimuth that allows a better scatter isolation in the SAR images. In this situation the accuracy of height retrieving would increase. Therefore, it seems the azimuth distortions do not worsen the results provided by the presented method, in contrast of what would happen with approaches dealing only with the CTD analysis over Polariometric SAR data [2].

These two simulations have been repeated for two different bearings: $\delta = 315^\circ$ and $\delta = 325^\circ$. With the first value, the rough sea situation causes a pitching of $1.3^\circ/s$ and a rolling of $0.76^\circ/s$ whereas the other a pitching of $1.2^\circ/s$ and a rolling of $0.9^\circ/s$. The obtained results are gathered in Fig. 5 by means of the retrieved height map and the RGB-coded Pauli POLISAR image. The images of each pair of simulations with the same bearing are row-ordered via three columns. The central column contains the POLISAR image. As observed, the obtained results are similar to those presented in the previous case as the
buttresses and the masts of the cabin are also highlighted as main scatters. The similarity parameter $e$ for each case is high enough to allow a correct vessel identification even in presence of important azimuth distortions due to rough sea state (see the right column of Fig. 6). These results show that with the Pauli-POLInSAR method important improvements could be obtained respect others techniques that does not use interferometric information.

V. CONCLUSION

This paper has described a new technique for vessel classification based on single-pass orbital Polarimetric SAR Interferometry. The Pauli polarimetric data analysis has been combined with classical height retrieval techniques to generate a tri-dimensional image with scattering mechanisms information of the observed ship’s geometry. A preliminary study done with simulated images has shown the robustness of the proposed method even with rough sea states inducing important azimuth distortions, making feasible the development of vessel classification algorithms based on this technique. Anyway more work has to be carried out extending the study with more vessel models, considering the impact of the surrounding sea to the classification performances and evaluating the sensor requirements and limitations for the required polarimetric and interferometric capabilities.

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