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SAR Imagery Simulation of Ship Based on Electromagnetic Calculations and Sea Clutter Modelling for Classification Applications

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Abstract Ship detection and classification with space-borne SAR has many potential applications within the maritime surveillance, fishery activity management, monitoring ship traffic, and military security. While ship detection techniques with SAR imagery are well established, ship classification is still an open issue. One of the main reasons may be ascribed to the difficulties on acquiring the required quantities of real data of vessels under different observation and environmental conditions with precise ground truth. Therefore, simulation of SAR images with high scenario flexibility and reasonable computation costs is compulsory for ship classification algorithms development. However, the simulation of SAR imagery of ship over sea surface is challenging. Though great efforts have been devoted to tackle this difficult problem, it is far from being conquered. This paper proposes a novel scheme for SAR imagery simulation of ship over sea surface. The simulation is implemented based on high frequency electromagnetic calculations methods of PO, MEC, PTD and GO. SAR imagery of sea clutter is modelled by the representative K-distribution clutter model. Then, the simulated SAR imagery of ship can be produced by inserting the simulated SAR imagery chips of ship into the SAR imagery of sea clutter. The proposed scheme has been validated with canonical and complex ship targets over a typical sea scene.

Keywords synthetic aperture radar, SAR imagery simulation, electromagnetic calculation, ship classification

1. Introduction

Ship detection and classification with space-borne SAR has been widely used in many applications within the commercial fishery, vessel traffic management, and military sectors. Ship detection algorithms have been developed fast, and most of them could achieve good performance. On the contrary, ship classification is still an open issue. Considering the difficulties on acquiring the required quantities of real data of vessels under different observation and environmental conditions with precise ground truth, the researches on ship classification face more challenges. Simulation of SAR imagery of ship over sea surface is of great usefulness for it, and to simulate with high scenario flexibility and reasonable computation costs is compulsory for the development of ship classification algorithms. Through the simulation, not only the template database for SAR ship targets recognition could be
constructed, but also the simulation technology itself can facilitate the understanding of the scattering mechanisms of ship targets in the SAR imaging procedure. So it would effectively improve the researches on ship classification using SAR imagery.

Though lots of researches have been done on the SAR imagery simulation of ship targets (e.g., Baussard et.al [1] studied simulated SAR system for maritime target imaging using a PO-based approach, Chen et.al [2] presented an efficient slope-deterministic facet model for SAR imagery simulation of marine scene, etc.), it is still challenging. The total scattering field of ship on sea surface is very complex. It is a superimposition of the contributions from sea, ship target and interactions. Few theories can describe the electromagnetic wave scattering configurations accurately and practicably for realistic scattering from the electrically very large sea surface [2]. The sea surface is always dynamic, the scattering mechanisms and coupling effect of them are very complicated. Furthermore, the computation cost is comparatively large.

This paper proposes a novel scheme for SAR imagery simulation of ship over sea surface. The flowchart is shown in figure 1. It includes three sections: SAR image chip simulation of ship, SAR image simulation of sea surface and SAR image simulation of ship over sea surface. The scheme is inspired from the study of the conventional simulation methods and the analyses of the effect of the simulation accuracy especially the sea-ship interactions on ship classification performance. Wherein, an important fact is validated that within a specific incidence window, the sea-induced mechanisms do not excessively interfere with the scattering response of ships, moreover, although the presence of the sea indeed adds some mechanisms at the base of the hull, it does not prevent one from discriminating it from others during classification. So, it is intuitive to simplify and speed up the simulation of SAR imagery of ship over sea surface by omitting the sea-ship interactions for classification applications under certain conditions.

2. The Scattering Mechanisms of Simplified Ship Targets
The analysis of scattering mechanisms of ship targets is significant to the SAR imagery simulation. To illustrate the theory briefly, the scattering mechanisms of a simplified ship model is investigated firstly in this section. Then, the simulation methods of Radar Cross Sections (RCS) are analyzed and the simulated results are presented.

2.1. Scattering Mechanisms Analysis
There exist multiple complex scattering mechanisms contributing to the radar echoes of the ship target. Theoretically, the coupling between the ship and the ocean should be considered. For the sake of simplification, it is not taken into account in this paper and will be considered in the future work. As illustrated above, only the main factors influencing ship classification are considered. The sea-ship interactions on ship classification performance can be omitted under certain conditions. Figure 2 illustrates the electromagnetic scattering phenomenon of a simplified ship model. According to [1], the scattering from the ship mainly contains eight kinds of scattering. For weak computational burdens, not all of them are to be modelled and suitable approximations are adopted.
2.2. Electromagnetic Modelling of Ship Targets

Electromagnetic modelling of ship targets is actually the estimation of RCS or the computation of complex scattering field. According to the definition of the RCS:

\[ \sigma = \lim_{R \to \infty} 4\pi R^2 \left| \frac{E'}{E} \right| \]

where \( E' \) and \( E \) are the electric field strengths of incident and echo magnetic wave respectively, and \( R \) is the distance. The estimation of RCS in optical region is to calculate the electromagnetic field induced by the interactions between the target and incident wave. This paper uses the high-frequency approximation methods [3,4], which include geometrical optics (GO), physical optics (PO), geometrical theory of diffraction (GTD), physical theory of diffraction (PTD), etc. This paper uses the GO/PO hybrid method to calculate the scattering field approximately, and PTD method to calculate the diffraction of edges. In detail, the incidence angle \( \theta \), the azimuth \( \phi \) and the frequency of incidence wave \( f \) are firstly calculated using the parameters of SAR platform and system. Then, according to the ship 3D model, the electromagnetic scattering data in the two dimension frequency domain can be acquired using GO/PO hybrid and PTD methods.

2.3. The RCS Simulation Results

In order to validate the method illustrated above, the RCS simulation of some canonical geometrical structure in optical region is performed firstly. A geometrical structure of a right dihedral with the width \( a = b = 50\text{cm} \) is shown in Figure 3. The angle between two planes is 90°. Theoretically, when \( \theta = 90° , f = 10\text{GHz} \), and \( \phi = 45° \), the maximum RCS is achieved by:

\[ \sigma_{\text{max}} = 8\pi a^2 b^2 / \lambda^2 \]

where \( \lambda \) is the wavelength of the carrier wave. The value is equivalent to 32.42dBsm. The RCS simulation result of the right dihedral is presented in Figure 4. It shows the corresponding simulated RCS curve versus azimuth. It is shown that the simulated peak value of RCS achieves 32.39dB when the azimuth equals to 45°, which agrees with the theoretical value well. The difference is only 0.03dB. So the adopted methods are valid.

Figure 5 shows a 3D ship model. Under the condition that the incidence angle is 75°, the frequency is 10GHz, and the azimuth ranges from 0° to 360°, the corresponding simulation result of its RCS is shown in Figure 6. The RCS peak values approximately appear at azimuth 0°, 90°, 180° and 270°, just the ship’s front, back, left and right direction.

![Figure 3. Geometrical structure of a right dihedral](image3.png)

![Figure 4. Simulated RCS curve of the right dihedral in Figure 3.](image4.png)
3. SAR Image Simulation of Ship Target

The RCS simulation prepares for SAR image simulation of ship target. For the intrinsic equivalence of the imaging principle of spotlight SAR to ISAR, the spotlight SAR imaging geometry is mainly considered in this paper and the SAR image simulation can be realized by turntable imaging.

3.1. SAR Imaging for Ship Target

Figure 7 shows the geometry of turntable imaging. The object on the turntable is radiated by the radar at look angle $\theta$. The target’s coordinate $xoy$ is fixed on the object and rotates along with the target’s rotation. The complex-valued measurements $F_{M,N}(f, \theta)$ is collected over a range of aspect angle and frequency, where $M$ and $N$ are the sample numbers in frequency and azimuth dimensions respectively. Figure 8 presents that the measurements lying in the sector grids of solid line in polar coordinate format. In order to get SAR image, these measurements must be re-sampled to a uniform grid on Cartesian coordinate with $f_x = f \cos \theta, f_y = f \sin \theta$. The re-sampled measurements are uniformly located in the rectangle grids of dot line. The flowchart of SAR imaging is shown in Figure 9.

3.2. SAR Image Simulation Results

Using the proposed imaging processing illustrated in Figure 9, SAR images of the ship model in section 2 are simulated under different polarization modes, resolutions, frequencies, incidence angles and azimuth. Four of them under the HH polarization are shown in Figure 10. Different incidence angle or azimuth leads to different result.
4. Modelling of SAR Image of Sea Clutter

Since the concept of K-distribution [5] was first introduced by E. Jakeman and P.N. Pusey in 1976, K distribution has attracted more attention for its advantages in modeling sea clutter [6]. This paper uses the ZMNL [7, 8] method to produce the correlated sequences with K distribution (see Figure 11). The basis of ZMNL is to produce correlated Gaussian random process firstly, and then to acquire correlated random sequences through non-linear transformations.

\[ H(\omega) = \text{ZMNL} \]

\[ g(t) \]

\[ s(t) \]

\[ H(\omega) \]

\[ g(t) \]

\[ s(t) \]

\[ H(\omega) \]

\[ g(t) \]

\[ s(t) \]

\[ H(\omega) \]

\[ g(t) \]

\[ s(t) \]

The steps of producing correlated clutter with K distribution can be summarized: 1) Sampling the power spectrum density function \( S(f) \) based on the proper choice of \( \Delta f \) to get the sampling sequence \( \{ \hat{S}_n \} \), where \( n = 1,2,\ldots,N \); 2) Perform IFFT on \( \{ \hat{S}_n \} \) to get the self-correlated function \( \{ S_n \} \) of the required random sequences; 3) Look up the curve table to calculate \( \{ r_n \} \); 4) Perform FFT on the \( \{ r_n \} \) to get the power spectrum density sequence \( \{ \hat{f}_n \} \) of the random sequences X and Y; 5) To produce the correlated Gaussian distribution sequence \( \{ u_{1,n} \} \) using the equation:

\[ X(\Delta f) = \sqrt{S(n\Delta f)} \Delta f \]

where \( \{ \xi_n \} \) is the sequence of independent random phase factor, with the mean of each member is zero and \( |\xi_n| = 1 \); 6) Perform the steps in Figure 12 to acquire correlated K distribution random sequence. The simulated result for sea clutter with K distribution is shown in Figure 13.

5. SAR Image Simulation of Ship over Sea Surface

The former work completes the SAR imagery simulation of ship and sea surface respectively. According to the flowchart of simulation in section 1, this section performs the final step (ship chips
inserting) to combine the simulation results of section 3 and 4. To insert the simulated ship chip into the simulated sea surface, the SAR imagery of ship over sea surface could be acquired. Using the four simulated results in section 3, the corresponding final results are shown in Figure 14.

![Figure 14. Simulated SAR Imagery of Ship over Sea Surface under Different Azimuths](image)

6. Conclusions
The SAR imagery simulation of ship over sea surface is significant to the ship classification applications. Though it is more challenging, to simulate SAR images with high scenario flexibility and reasonable computation costs is compulsory for ship classification algorithms development. Based on the method of electromagnetic modelling, the flowchart of SAR image simulation of ship over sea surface is presented and the detailed methods are investigated. In the future work, the proposed SAR images simulation methods will be improved and evaluated further.

References