Simulation Study of the Dynamic Sea Influence on SAR Imaging of Ships

Xiangrong Ding, Jianwu Zou, Minghao Sun and Kaixuan Zhang

ABSTRACT

The ship with sea background SAR imaging simulation technology has a great significance for the detection and identification of the ship with sea background target and the design and verification of the SAR system. In order to improve the fidelity of the ship with sea background SAR simulation image, this paper constructing a dynamic sea surface model, combined with the ship's three-dimensional model and electromagnetic scattering model, the signal-level SAR imaging simulation of the sea-ship composite scene is carried out, and the SAR simulation image with high fidelity is obtained, and compared with the simulated images in the static sea scene, it intuitively reflects the realistic degree of SAR simulation images in dynamic sea scenes and can provide help for ship target detection and recognition in sea clutter background.

1. INTRODUCTION

Because SAR imaging is restricted by a series of factors such as environmental conditions, target characteristics and system parameters, it is difficult to obtain SAR images under any conditions by means of measurement. The SAR image simulation technology for ships can obtain SAR images under any parameter conditions in a short time without restrictions, which has great significance for the establishment of ships target reference template library, detection and recognition of sea surface ships targets [1-2].

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The related literature shows that scholars at home and abroad study more about the sea imaging simulation without combining with the sea ships, and usually build a static model [3]. Actually, the sea keeps fluctuating, so in the process of ships SAR imaging simulation, the consideration should be given to the fluctuation status, that is to say, the sea should be changed constantly with the SAR transmitted pulse. But this method will inevitably make data and calculation amount sharply increase and make simulation time become too long. Therefore, the paper constructs a dynamic sea surface model, and carries out SAR imaging simulation of ships under dynamic sea surface scene on the basis of the SAR working process, and compares with the SAR images under static sea surface scene. Then the paper discusses the reasonable updating frequency of sea surface, and expects the future research direction according to the existing problems.

2. SIMULATION PROGRAM FLOW

This paper adopts a SAR imaging simulation scheme based on 3d modeling technology and computational electromagnetics. This simulation scheme carries out signal-level simulation on the basis of the SAR dynamic working process. The specific simulation program flow is shown in figure 1.
3. SCENE MODEL

3.1 Ship Model

In terms of modeling methods, this paper adopts the panel method to construct the target model. The panel method can meet the requirements of real-time and high-precision calculation, and can vividly describe the target model with fine appearance. Moreover, it can conveniently deal with the occlusion problem of the facets, which brings convenience to the construction of high-precision model and the calculation of target scattering field [4-5]. Specific steps are as follow: Consult the public information of the true size and detailed data of vessels. Use toolbox of 3D MAX, which includes a variety of tools such as polygons and 2D shape editing to cut, rotate, render the targets by the order of the main part (hull, superstructure, etc.) and the accessory part (naval gun, the anti-ship missile, dense array, etc.). Then, according to the resolution requirements, the ship model is divided into small facet model, which contains the position of facet, edge, normal vector and other information [6].

3.2 Sea Model

According to the two-scale sea spectrum model, the sea surface is composed of large-scale gravity waves \( S_1(k) \) and small-scale tension waves \( S_2(k) \) [7-8].

\[
S(k) = \begin{cases} 
S_1(k) & k < 0.04 \text{rad/cm} \\
S_2(k) & k > 0.04 \text{rad/cm}
\end{cases}
\]

(1)

\[
S_1(k) = \frac{\alpha}{2|k|} \exp \left[ -0.74 \frac{g_c^2}{k^2 U_{19.5}^4} \right]
\]

(2)

\[
S_2(k) = 0.875/(2\pi)^{n-1} \left( 1 + \frac{3k^2}{k_m^2} \right) g_c^{(1-p)/2} \left( k(1 + \frac{k^2}{k_m^2}) \right)^{-(p+1)/2}
\]

(3)

In the expression, \( \alpha \) is spectral correlation coefficient, and the value is \( 5.6 \times 10^{-3} \). \( U \) is the wind speed at 19.5m sea level. \( g_c \) is the acceleration of gravity, and the value is \( 9.81 \text{m/s}^2 \). \( g_c = 981 \text{cm/s}^2 \). \( k_m = 3.63 \text{rad/cm} \), \( p = 5 - \log(U_*) \). \( U_* \) is friction velocity, and the unit is cm/s. Using the Longue-Higgin model, the linear superposition method considers the fluctuation of sea surface as the superposition of infinite cosine waves with different frequencies, amplitudes, initial phases and propagation directions. The Sea surface wave height can be expressed as
\[ \zeta(x, y, t) = \sum_{i=1}^{\infty} \sum_{j=1}^{\infty} a_{ij} \cos[k_i(x \cos \theta_j + y \sin \theta_j) + \omega t + \varepsilon_{ij}] \] (4)

\( \zeta(x, y, t) \) is the sea surface height of coordinates \((x, y)\) at time \(t\). \(a_{ij}\) is amplitude. \(\theta_j\) is wave direction. \(k_i\) is wave number. \(\omega_i\) is angular frequency. \(\varepsilon_{ij}\) is initial phase. When \(t\) takes a specific value, the sea surface model is static. When \(t\) changes with the repetition cycle of SAR emission pulse, the sea surface model is a dynamic sea surface model. Import the constructed ship model into MATLAB, and combine with the sea surface model based on the displacement information. After reasonable combination transformation, the combined model of sea surface and ships can be obtained, as shown in figure 2. Update sea level information over time, then the dynamic sea surface ship 3d composite model is obtained.

**Figure 2. Combination Model.**

4. ELECTROMAGNETIC SCATTERING MODEL

This paper uses the physical optical method, which belongs to high frequency approximation method, costs less memory consumption and has high computational efficiency, to calculate the backscattering coefficient of each small facet [9]. Physical optics method uses the far-field approximation method to calculate the integral of the target scattering field and obtain the backscattering coefficient of the facet. The scattering field is kept in a limited range due to the limitation of the induction field, so several problems can be overcome such as complicated calculation process and large amount of data caused by the large induction field, and consideration can be given to the calculation efficiency and accuracy [10]. The calculation formula of the ship composite scene facet is:
\[
\sigma_0 = \frac{4\pi}{\lambda^2} \int_{S} (\vec{n} \cdot \vec{s}) \cdot e^{2\pi j k Z} ds
\]

(5)

Inside the formula, \(\vec{n}\) is facet normal vector. \(\vec{s}\) is Radar electromagnetic wave incidence direction vector. \(Z\) is the distance between the facet \(ds\) and the observation point. \(ds\) is the proportion of the area in which the facet is illuminated.

5. ECHO MODEL

Based on the basis of the backscattering coefficients of each facet, the target echo is calculated by simulating the actual working process of radar. Set the minimum slant distance of the platform as \(R_0\), the platform velocity as \(V\), the radar incidence Angle as \(\theta\), and the azimuth accumulation time as \(T\). The pulse string transmitted by radar during operation is usually a linear frequency modulation pulse string in the form of:

\[
f(t) = \sum_{n=-\infty}^{\infty} P(t - n \cdot PRT) \exp \left\{ 2\pi j f_c (t - n \cdot PRT) + \pi k, (t - n \cdot PRT)^2 \right\}
\]

(6)

\(\text{rect}(\cdot)\) is the rectangle window function; \(f_c\) is carrier center frequency; \(K_r\) is the linear modulation frequency; \(PRT\) is pulse repetition period, and \(T_r\) is pulse duration. According to the Side-looking working process of SAR, the sampled two-dimensional echo can be expressed as follows:

\[
Sr(n, m) = \sum_{k=1}^{K} \sigma \cdot \exp \left\{ j \pi K_r [t(m) - \frac{2R(n;k)}{C}]^2 \right\} \cdot \exp \left[-j \frac{4\pi}{\lambda} R(n;k) \right]
\]

(7)

\(n = 1, 2, 3 \ldots N; m = 1, 2, 3 \ldots M\)

\(K\) is the number of point targets. \(M\) is the number of distance sampling. \(N\) is the number of azimuth sampling, and \(R(n;k)\) is the slant distance from facet to radar.

6. SIMULATION RESULTS AND ANALYSIS

The simulated SAR images of ships on the sea can be obtained by using the range-doppler (RD) imaging algorithm to process echoes [11], as shown in figure 3. Simulation parameters are shown in TABLE 1. In the simulation conducted in this paper, the operating system is Windows7 flagship 64bit, memory 8GB, Intel(R)
The simulation software platform is MATLAB R2014.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distance resolution $r$</td>
<td>1m</td>
</tr>
<tr>
<td>Azimuth resolution $\rho_z$</td>
<td>1m</td>
</tr>
<tr>
<td>Center frequency $f_0$</td>
<td>15GHz</td>
</tr>
<tr>
<td>Wavelength $\lambda$</td>
<td>2cm</td>
</tr>
<tr>
<td>Pulse frequency $f_r$</td>
<td>121Hz</td>
</tr>
<tr>
<td>Antenna aperture $D$</td>
<td>2m</td>
</tr>
<tr>
<td>FM signal bandwidth $B$</td>
<td>150MHz</td>
</tr>
<tr>
<td>Pulse width $\tau$</td>
<td>1us</td>
</tr>
<tr>
<td>Incident angle $\theta_0$</td>
<td>30°</td>
</tr>
<tr>
<td>Oblique viewing angle $\theta_c$</td>
<td>0°</td>
</tr>
<tr>
<td>Platform flight speed $v$</td>
<td>300m/s</td>
</tr>
<tr>
<td>Flight altitude $h$</td>
<td>2000m</td>
</tr>
</tbody>
</table>

(a) no sea surface influence       (b) fluctuating number: 8
(c) fluctuating number: 16         (d) fluctuating number: 32

Figure 3. Simulation results.
Contrast static sea scene in figure (a) with the dynamic sea scene in figure (b), (c), (d), it can be found that under the condition of 1m*1m resolution of dynamic water scene, the geometry of the sea in the simulated image does change because of the real-time fluctuation of the sea. The outline characteristics of ship can be clearly reflected, the simulated sea scene is more in line with the real scene and accord with the SAR image characteristics. But the simulation time increases with the increase of the sea update frequency. The time cost of figure (a) - (d) are 8056s and 57827s, 115829 s and 227762 s, and will increase with the speeding up of the update frequency. From the simulation image, the image does not change obviously because of the speeding up of sea update frequency, so the sea update frequency should consider the time-consuming problem, and combine image lifelikeness and real-time simulation.

7. COMPLIMENTARY CLOSE

Paper constructs the dynamic sea surface model, and combines with ship 3D model, the electromagnetic scattering model. Then the paper generates sea ships composite model based on the actual working process of the SAR echo signal, and compares static sea scene with dynamic sea scene under different frequency. The simulation image under dynamic sea scene is more in line with the actual situation and has higher fidelity, but costs more time. In addition, this paper only considers the fluctuation of the sea surface, but in the actual situation, most ships are in the motion state, so the next research focus is to consider the motion posture of ships and how to improve the calculation rate of simulation.

REFERENCES

4. Wenhua Ye. 2012.A Theory and Experiment Study of Composite Electromagnetic Scattering from Target over Different Scale Sea Surface Xidian University, Xi’an:2012