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AN EFFICIENT HYBRID HIGH-FREQUENCY SOLUTION FOR THE COMPOSITE SCATTERING OF THE SHIP ON VERY LARGE TWO-DIMENSIONAL SEA SURFACE

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Abstract—A hybrid high-frequency solution is proposed to analyze the bistatic electromagnetic scattering of the ship target on very large two-dimensional randomly rough sea surface in this paper. The comprehensive geometrical model of the ship and sea surface is designed by CAD tools and the sea power spectrum, and its electromagnetic scattering characteristic is evaluated with the method of equivalent currents (MEC). Since the electromagnetic interaction between the ship hull and the sea surface in the vicinity of the broadside is similar to the scattering mechanism of the dihedral reflector, the iterative physical optics method (IPO) is utilized to study the electromagnetic coupling effects. The shadowing correction based on the Z-Buffer technology is introduced to eliminate the effects of the irrelevant scattering resources. At last, the validity of the hybrid method is confirmed by the SAR image of the ship on the very large two-dimensional sea surface, and the numerical results are presented to analyze the composite scattering characteristics of the ship on the sea surface.

1. INTRODUCTION

The study on the electromagnetic composite scattering from the electrically large target on the sea surface is of great significance for the marine surveillance, target detection and marine remote sensing. The experience and theories indicate that the electromagnetic scattering

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from the comprehensive model of the ship and sea surface should be treated as a whole.

Since the analytical method can not be applied to the randomly rough sea surface and complex targets, the solutions to the composite scattering of the ship on the surface are mainly distinguished as numerical methods and high-frequency asymptotic method. Method of moment (MOM), which involves the coupling interaction of every part of the target of interest, is a basic solution to the composite scattering [1, 2]. Many fast algorithms, such as the Generalized Forward-Backward Method (GFBM) in [3], the Mode-Expansion Method (MEM) in [4] and the Multiple Sweep Method of Moments (MSMM) in [5], are developed based on MOM to improve the calculational efficiency. The finite-difference time-domain method (FDTD) which is based on the differential forms of the Maxwell equations has also been used in this field [6]. Though the numerical methods can reach high accuracy, they are limited by the computer performance. The current numerical methods are mainly aiming at the two-dimensional models and can not calculate the electrically large target. Therefore the solution to the scattering problem of three-dimensional comprehensive ship-sea model is necessitated.

Another tractable means is the high frequency asymptotic method on the assumption that the scattering resources on the scatterer are independent to each other in high frequency band. The four-path method [7] ignores the high order coupling scattering and simplifies the composite scattering into four major scattering mechanisms. The key point of this method is the accuracy of the solution of every path. Concerning the strong interaction between the hull and the sea surface, reference [8] regards the complex structure as a dihedral reflector and studies it with the physical optics method (PO).

This paper proposes a new kind of hybrid high-frequency method to analyze the scattering of the ship on the two-dimensional randomly rough sea surface. In Section 2, the method of equivalent currents (MEC) is extended to analyze the composite scattering from the comprehensive ship-sea model. Particular emphasis is placed on the interaction between the hull and the sea surface with the iterative physical optics method (IPO) in Section 3. The shadowing correction is introduced for the complex scatterer to promote the calculation accuracy in Section 4. Finally, the SAR image is simulated for the ship on the large sea surface, and the influencing factors of the composite scattering are discussed based on the numerical results.

2. MODELING OF COMPOSITE SCATTERING

The composite scattering field of the ship on sea surface is often simplified into the direct scattering field and the coupling field from the scatterers in GHz band with high frequency asymptotic method. The high frequency asymptotic method could solve the realistic composite scattering problem successfully, if the accuracy of the solutions to the two scattering field is guaranteed.

The conventional high frequency solution to the sea surface scattering is used to calculate the sea surface scattering coefficient with the surface power spectrum. The scattering coefficient, which is usually defined as normalized radar cross section for rough surface (NRCS), just depends on the parameters of the sea spectrum, such as wind speed, wind direction and so on, while the incident wave keeps invariant. In order to calculate the composite scattering field, the scattering field other than the scattering coefficient is necessary. Then, the geometrical model of the sea surface is needed.

If the sea surface of which the spectrum parameters keep invariant is regarded as an isotropy, stationary and ergodicity stochastic process, the concrete sea surface models are the realizations of the random process. The ensemble average over many scattering fields from the statistically independent realizations of sea surface is approximately equal to the realistic scattering field from the sea surface, while the number of the realizations is large enough. This is often alleged as Monte Carlo method.

According to the linear accumulative theory, the wind-driven sea surface is modeled based on the JONSWAP spectrum [9], and the ship model can be designed with CAD tools. Then the comprehensive ship-sea model is obtained as shown in Figure 1. The surface of the ship-sea model is subdivided with triangular facets. It is apparent that every two adjacent triangular facets form a wedge structure of which the scattering field can be calculated by the MEC [10]. According to the principle of the high frequency asymptotic method, the composite scattering of the ship-sea model is given as

$$\mathbf{E}_s^{\text{model}} = \frac{\exp(\mathrm{i}kR)}{R} \cdot \overline{\overline{S}}_1(\hat{s},\, \hat{i}) \cdot \mathbf{E}_{\text{inc}} = \sum_{i=1}^{N} \mathbf{E}_i^{\text{edge}}. \tag{1}$$

$\mathbf{E}_{\text{inc}}$ is the incident plane wave and $\overline{\overline{S}}_1(\hat{s},\, \hat{i})$ is the scattering amplitude matrix. $\mathbf{E}_i^{\text{edge}}$, which is the scattering field of the wedge i, is given by MEC

$$\mathbf{E}^{\text{edge}} = \mathrm{i}k_0 \int_c \left[\eta_0 I(\mathbf{r}')\hat{k}_s \times \left(\hat{k}_s \times \hat{t}\right) + M(\mathbf{r}')\left(\hat{k}_s \times \hat{t}\right)\right] \frac{\exp(-\mathrm{i}k_0 S)}{4\pi s} \mathrm{d}l. \tag{2}$$

I and M, which are the equivalent edge currents (EEC) flowing along the edge, have three major types [11]. The PTDEEC which involves the diffraction and reflection fields is chosen in this paper.

It is known that the reflection coefficient of planar surface illuminated by plane wave is

$$R_H(\phi) = \frac{\sin\phi - \sqrt{\varepsilon_r - \cos^2\phi}}{\sin\phi + \sqrt{\varepsilon_r - \cos^2\phi}} \tag{3}$$

where ϕ is the plane wave elevation angle, and ε_r is the complex relative dielectric constant of sea water. It is obvious that $R_H \to -1$ while the frequency of incident wave is in GHz band. As a result, the sea surface and ship are both regarded as perfectly electric conducting (PEC), and only the horizontal polarization case is considered in this paper. The dielectric sea surface and ship with coated material will be investigated in future.

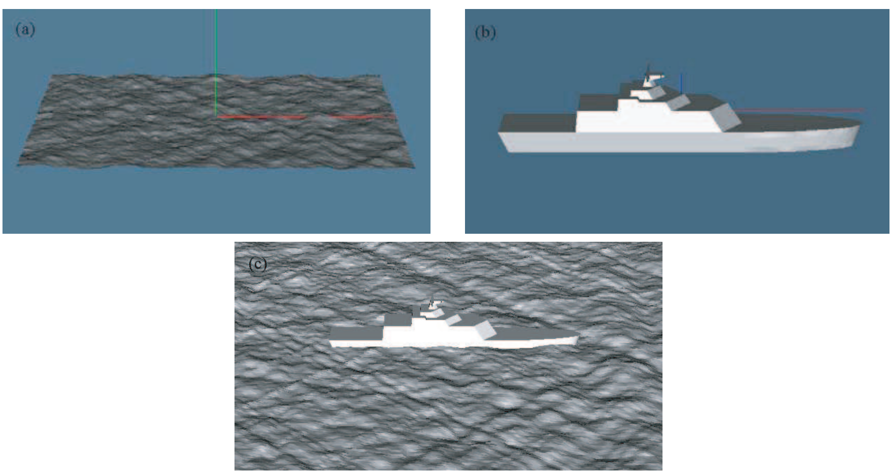

Figure 1. Geometrical models of the targets of interest. (a) The two-dimensional sea surface is modeled based on the JONSWAP spectrum. (b) The electrically large ship model is designed with CAD tools. (c) The comprehensive ship-sea model is the combination of the sea surface and ship.

3. MULTIPLE SCATTERING BETWEEN THE HULL AND SEA SURFACE

It is well known that the interaction between the hull and sea surface, which is similar to the scattering of dihedral reflector, has significant influence on the composite scattering of the ship-sea model. Because the sea surface is randomly rough, and the size of the broadside is large in terms of the electromagnetic wave length, the scattering of the hull-surface structure is more complicated than the general dihedral reflector. Considering the interference of other parts of the ship-sea model, the scattering field of the hull-surface structure is given as

$$\mathbf{E}_s^{\mathrm{cor}}(\mathbf{r}) = \frac{\exp(\mathrm{i}kR)}{R} \cdot \overline{\overline{S}}_2(\hat{s}, \hat{i}) \cdot (\mathbf{E}_{\mathrm{inc}} + \mathbf{E}_{\mathrm{cou}}). \tag{4}$$

$\mathbf{E}_{\mathrm{inc}}$ and $\mathbf{E}_{\mathrm{cou}}$ are the incident wave and the coupling field caused by the other parts respectively. Since the bistatic scattering intensity of the dihedral reflector is stronger in both the backward and forward directions than in other directions, the interference of the hull-surface structure on other parts of the ship-sea model is neglected in the paper.

Since the IPO [12] is suited to evaluate the multiple scattering from the complex structures by the introduction of the corrected currents, it is extended to the scattering problem of the dihedral reflector.

By using the Huygens principle, the magnetic field integral equation (MFIE) for the perfectly electric conducting dihedral reflector is given by

$$\mathbf{H}_s^{\mathrm{cor}}(r) = \oint_S \mathbf{J}(\mathbf{r}') \times \nabla' G(\mathbf{r}, \mathbf{r}') \mathrm{d}s'. \tag{5}$$

$\mathbf{J}(\mathbf{r}')$ and $G(\mathbf{r}, \mathbf{r}')$ are the electrical current on the scatterer and the scalar Green function in the free space respectively. The PO current can be determined as

$$\mathbf{J}_0(\mathbf{r}') = \begin{cases} 2\hat{n} \times (\mathbf{H}_{\mathrm{inc}}(\mathbf{r}') + \mathbf{H}_{\mathrm{cou}}(\mathbf{r}')) & \text{illuminated} \\ 0 & \text{unilluminated} \end{cases} \tag{6}$$

where $\mathbf{J}_0(\mathbf{r}')$ can be regarded as the zeroth order current for IPO. Based on the physical optics approximation, the corrected current $\mathbf{J}_N(\mathbf{r})$ is introduced by the iterative integral

$$\mathbf{J}_n(\mathbf{r}) = 2\hat{n} \times (\mathbf{H}^{\mathrm{inc}}(\mathbf{r}') + \mathbf{H}^{\mathrm{cou}}(\mathbf{r}')) + 2\hat{n} \times \oint_S \mathbf{J}_{n-1}(\mathbf{r}) \times \nabla' G(\mathbf{r}, \mathbf{r}') \mathrm{d}s' \qquad n = 1, 2, \ldots, N \tag{7}$$

where $\mathbf{J}_{n-1}(\mathbf{r})$ is the $(n-1)$th order current. The scattering electric field of the dihedral reflector $\mathbf{E}_s^{\rm cor}$ is obtained by the scattering magnetic field $\mathbf{H}_s^{\rm cor}$ which is calculated with (5) and (7).

The multiple scattering in the parts of the hull-surface structure is taken in account by the corrected current $\mathbf{J}_N(\mathbf{r})$. Thus, the accuracy of coupling field $\mathbf{E}_s^{\rm cor}$ depends on the order N of the IPO current $\mathbf{J}_N(\mathbf{r})$, which is actually the reflection times of the electromagnetic wave in the hull-surface structure. Generally speaking, if the internal angle of the dihedral reflector is larger than 60°, the triply scattering should be counted [13]. Since the angle formed by the hull and sea surface is 70° in this paper, $N = 3$ is necessary in the calculation. Then the total composite scattering field can be determined by (12), (14) and (18)

$$\begin{aligned}\mathbf{E}_s &= \mathbf{E}_s^{\rm model} + \mathbf{E}_s^{\rm cor}\\ &= \frac{\exp(\mathrm{i}kR)}{R}\cdot\left[\overline{\overline{S}}_1(\hat{s},\,\hat{i})\cdot\mathbf{E}_{\rm inc}+\overline{\overline{S}}_2(\hat{s},\,\hat{i})\cdot(\mathbf{E}_{\rm inc}+\mathbf{E}_{\rm cou})\right].\end{aligned}\quad(8)$$

4. SHADOWING CORRECTION

Theories for wave scattering from sea surface generally assume that all parts of the scattering surface are illuminated by the incident wave. In practice, some regions of the surface may be screened by parts of the surface for the high frequency limitation. Similarly, the self-shadowing phenomenon also exists for the ship-sea model. Some shadowing functions have been introduced in the former theories [14], which were actually kinds of corrections of the sea surface scattering coefficient.

In this paper, the shadowing correction of the comprehensive ship-sea model is realized based on the Z-Buffer technology which is a common algorithm for computer graphics. The principle of the correction process is given as follows.

The scatterer is located in the center of the Cartesian coordinate system. A new coordinate system is defined for the view direction $(\theta,\,\varphi)$. z' is along the view direction and pointing to the observer, and the plane $x'oy'$ is vertical to the view direction. y' is the projection of z on $x'oy'$. The conversion relation is given as

$$\left\{\begin{array}{l}\hat{x}' = -\sin\varphi\hat{x}+\cos\varphi\hat{y}\\ \hat{y}' = -\cos\theta\cos\varphi\hat{x}-\cos\theta\sin\varphi\hat{y}+\sin\theta\hat{z}.\\ \hat{z}' = \sin\theta\cos\varphi\hat{x}+\sin\theta\sin\varphi\hat{y}+\cos\theta\hat{z}\end{array}\right.\quad(9)$$

It is equivalent to project the ship-sea model on the plane $x'oy'$, and z' in the new coordinate system, which represents the distance from the facet to the observer. The z' value of the projections of the facets

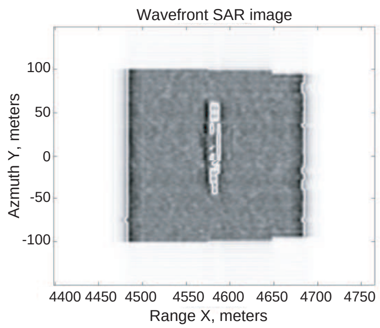

Figure 2. SAR images of the ship on sea surface. The operating frequency of the incident wave is 1 GHz, and the elevation angle is 30°.

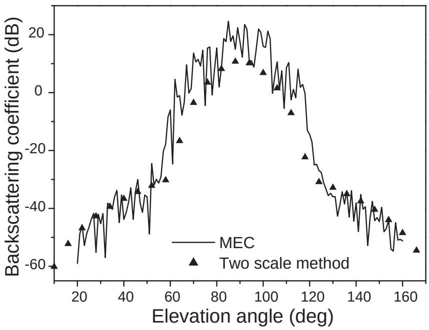

Figure 3. Backscattering coefficients of the sea surface with the MEC and the two-scale method. The wind speed is 10 m/s, and the incident wave is 1 GHz.

is stored in the z buffer of the computer. If the projections of two different facets are overlapped, the facet with bigger z' is defined to be shadowed.

Different from the correction functions of the scattering coefficients, the Z-Buffer shadowing correction examines every facet on the concrete scatterer of which the scattering filed can be calculated. Since this method, which is based on the fluctuation of the sea surface realizations, involves the whole geometry information of the ship-sea model, it is more practical than the former empirical formulas.

5. NUMERICAL RESULTS AND ANALYSIS

Since the measured data of the scattering from the ship on large area sea surface are rare in the previous literatures, the SAR image is simulated to demonstrate the validity of the algorithm in the paper. As shown in Figure 2, the comprehensive ship-model in Figure 1 is imaged. It is obvious that the background of the sea clutter is rather strong and randomly distributed, and the mast of the ship is an important scattering source. Moreover, the interaction of the ship hull and the sea surface is emphasized by the left side strong scattering of the ship in Figure 2.

To validate the MEC, the backscattering coefficient of the sea surface is also calculated with the MEC and the two-scale method [15] respectively in Figure 3. The sea surface generated from the JONSWAP spectrum is illuminated by plane wave. The two-scale

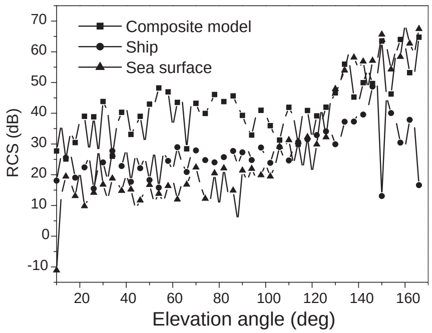

Figure 4. RCS of the components of the composite scattering versus the elevation angle. The effects of the coupling filed is strong the backward direction.

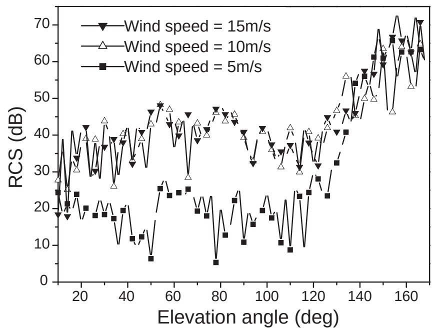

Figure 5. Relationship of composite scattering with wind speed. The draft depth keeps 4 m, and the wind speeds to generate the sea surface are 5 m/s, 10 m/s and 15 m/s respectively.

method is a kind of conventional method mentioned in Section 2 of this paper. Though it is only suitable for the calculation of scattering coefficient of the sea surface, its accuracy is generally accepted. Figure 2 shows that the MEC is in good agreement with the two-scale method, which proves that the MEC is applicable to the sea surface scattering.

The comprehensive ship-sea model is built based on the actual situation, as shown in Figure 1. 50 sea surface models of which the area is 400 m×300 m are generated as realizations of the JONSWAP spectrum. The ship used here is 120 m long, 20 m wide and 25 m high. Located on the x-y plane of the Cartesian coordinate system, the ship-sea model is illuminated by the plane incident wave with frequency 1 GHz, and the incident angle is 70°. The radar cross section (RCS) of bistatic scattering is calculated by the scattering field

$$\mathrm{RCS} = 4\pi \lim_{R\to\infty} R^2 \frac{|\mathbf{E}_s|^2}{|\mathbf{E}_{\mathrm{inc}}|^2}. \tag{10}$$

Because the high frequency method is not limited by the memory of the computer, the numerical results given as follows are all accomplished on a PC with 2.0 GHz processor, and the computing time is just 9 minutes per degree.

Figure 4 depicts the components of the composite scattering versus the elevation angle. The coherent scattering effect gives rise to a high RCS of the total composite scattering in the specular direction. It

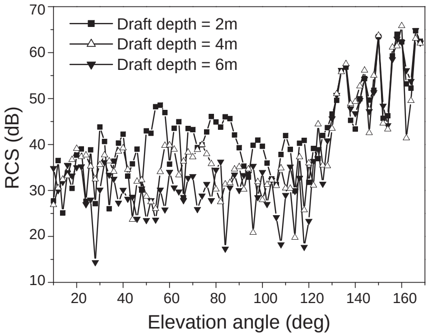

Figure 6. RCS of composite scattering for different draft depth. The wind speed keeps 10 m/s, and the draft depths of the ship are 2 m, 4 m, and 6 m respectively.

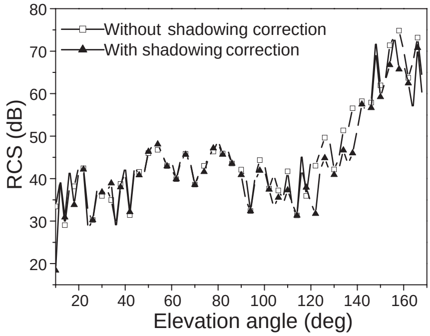

Figure 7. Effect of the shadowing correction. The wind speed is 15 m/s, and the draft depth is 4 m.

is also observed that the interaction of the hull and sea surface is remarkable at the 60° elevation angle. Thus, this phenomenon can be taken as the basis for the target detection from the sea clutter.

The influence of the sea state on the composite scattering is shown in Figure 5. It can be seen that the faster is the wind speed, the larger is the results of RCS. Since the increasing wind speed leads to larger RMS height of the rough sea surfaces, the incoherent scattering field is enhanced by the rougher surface consequently. As the relationship of the wind speed and the RCS is not linear, the RCS of the 15 m/s and 10 m/s are much higher than 5 m/s.

As shown in Figure 6, the scattering intensity of the hull-surface structure decreases with the draft depth of the ship which is related to the area of the broadside. The variation of the RCS curves is not distinct in the specular direction, because the coherent scattering of the sea surface is very strong in this direction.

Because of the electrically large size of the ship-sea model, the effect of shadowing correction is obvious in Figure 7. Therefore, the calculation accuracy is promoted with the application of the shadowing correction. Meanwhile, it can be seen that the difference of the two curves is inconspicuous when the elevation angle is smaller than 90°. It can be explained that the shadowing correction is concealed by the strong coupling scattering of the hull-surface structure.

6. CONCLUSION

The composite scattering of the electrically large ship on two-dimensional sea surface is evaluated with the hybrid high-frequency method in the paper. The advantage of this method is that it does not need the matrix operation; thus the calculation efficiency is promoted markedly; and the computing process can be realized with the microcomputer. The validity of the method is verified by the SAR image for the ship-sea model and the agreement with the two-scale method.

The numerical results show that the composite scattering is influenced by many factors. The strong coupling field caused by the hull-surface structure dominates the total scattering in the vicinity of the backward direction, which can be the basis for the target detection from the sea clutter in remote sensing. Moreover, the roughness of the sea surface which is related to the coherent scattering of the sea surface also plays an important role in the composite scattering. The numerical results indicate that the radar signature of the ship on the sea surface is sensitive to the sea state and the draft depth. So the work of this paper could be the theory basis of the electrically large target detection on the sea surface.

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