Estimation of NRCS of Oil-free and Oil-covered Sea Surfaces at L-band. Assessment with UAVSAR Data

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***Abstract*—This paper presents numerical simulations and analyses of EM (electromagnetic) scattering from oil-free and oil-covered sea surface. First, the influences caused by slicks on clean sea are studied and analyzed with the action balance function. Slicks on sea surface make significant impacts on the wind input, the nonlinear wave-wave interactions and the viscous dissipation. A damping model based on the action balance equation is introduced. And then, simulations are made by assuming the surface height spectra proposed by Elfouhaily et al. and Hwang, respectively. The two scale model (TSM) is used to calculate the normalized radar cross sections (NRCS) of oil-free and oil-covered sea surfaces. Additionally, an UAVSAR image which was collected during the Deep Water Horizon oil spill accident occurred in the Gulf of Mexico is served as a reference. The numerical comparisons between simulated results and measured data have shown that, for clean sea surface, the VV polarized NRCS simulated with Elfouhaily spectrum agree well with UAVSAR data, the HV polarized NRCS simulated with Hwang spectrum agree well with UAVSAR data. For polluted sea surface, the VV polarized NRCS simulated with Elfouhaily spectrum matches well with measured data. Overall, numerical simulations with Elfouhaily spectrum seem better than Hwang spectrum in our simulations.**

Keywords*—*synthetic aperture radar; sea spectrum; two scale model; oil spills monitoring

I. INTRODUCTION

Oil spills on the sea surface pollute ocean environment severely. In order to reduce the harms caused by oil spill accidents, a great effort has been made by scientists on developing effective methods that can monitor oil spills on the ocean surface. Synthetic aperture radar (SAR) is a useful tool that provides valuable measurements at both day and night. Besides, SAR could work under different atmospheric conditions. SAR has proven to be useful for oil spill observation [1−3]. It is known that the basic principle for oil spill detection with SAR is that oil spills on sea surface damp the short-gravity and capillary waves, which leads to the scattering mechanism on oil-covered sea surface is different with oil-free sea. To better take advantage of SAR for oil spill monitoring, it is necessary to study the EM scattering from an oil covered sea in theory.

In fact, the study of the detection of the oil spill on a sea surface has been conducted in many publications [3-7]. The contributions of these research works can be divided into two categories. The first focuses on the study and investigation on the detection oil spill on sea surface by using measured SAR data [3, 4]. The second category is the analyses and simulations of EM field scattered by the clean and polluted sea surfaces [5-7]. In this work, we try to make a combination between EM scattering models and experimental data. Accurate NRCS estimations of polluted and clean sea surfaces can be served as references to detect or discriminate oil spills from sea background.

The rest of this paper is organized as follows. In section 2, the influences caused by slicks on clean sea are investigated with action balance equation. In section 3, numerical simulations of clean sea and polluted sea are compared with UAVSAR data. The conclusions are presented in section 4.

II. DESCRIPTION OF POLLUTED SEA SURFACE

The polluted sea surface is significantly different with clean sea surface for the short-gravity waves and capillary waves are damped. In order to simulate the scattering on oil-covered sea surface, the sea surface height spectrum is essential. In this part, the description for the contaminated area is studied and analyzed by using the action balance equation.

The evolution of sea waves can be described by the action balance equation [8]

$$0 = \frac{dN^i}{dt} = S_{in}^i + S_{nl}^i - S_{dis}^i, \tag{1}$$

where $i \in \{o, w\}$ corresponds to oil-covered and oil-free sea surfaces, respectively. In Eq. (1), S_{in}^i, S_{nl}^i and S_{dis}^i represent source functions which describe the wind input, the nonlinear wave-wave interactions and the viscous dissipation, respectively. The spectral action density $N^i = (\omega/k)\psi^i$, ω is angular frequency and ψ^i is the sea spectrum. Here, we only consider the case of low to moderate wind speeds, the effect caused by wave breaking is not important which has been omitted in Eq. (1).

The wind input term S_{in}^{i} can be expressed as

$$S_{in}^{i} = \beta^{i} N^{i}, \tag{2}$$

and

$$\beta^{i} = 0.04 \cos\phi \left(u_{*}^{i}/c_{p}\right)^{2} \omega, \tag{3}$$

where β^{i} denotes the wind wave growth rate, c_p is the phase velocity of sea waves, ω denotes the angular frequency of sea waves and it can be defined as

$$\omega = \sqrt{gk + \frac{\tau k^{3}}{\rho_{w}}}. \tag{4}$$

In Eq. (4), g denotes the acceleration of the gravity, τ is the surface tension and ρ_w is the density of sea water.

The frictional velocity for oil-free surface can be calculated by

$$u_{*}^{w} = \sqrt{C_{10}} U_{10}, \tag{5}$$

$$C_{10} = \left(0.8 + 0.06 U_{10}\right) \times 10^{-3}. \tag{6}$$

U_{10} denotes the wind speed at a height of 10 meters. Compared with oil-free surface, the frictional velocity for oil-covered surface is smaller which leads to the energy inputted form wind is decreased. Thus, a coefficient duo to the reduction of the friction velocity should be multiplied for oil-covered surface,

$$u_{*}^{o} = \xi u_{*}^{w}, \tag{7}$$

Here, ξ is set to 0.7 [9].

With respect to the nonlinear wave-wave interaction term, S_{nl}^{i} can be written as

$$S_{nl}^{i} = \alpha^{i} N^{i}, \tag{8}$$

where

$$\alpha^{w} \approx -1.15 \beta^{w}, \tag{9}$$

$$\alpha^{o} \approx \alpha^{w} + \Delta\alpha, \tag{10}$$

$$\Delta\alpha = 2 c_{g} \Delta_{\max}^{o} \left(\frac{k}{k_{m}}\right)^{3/2} \left(\frac{u_{*}^{w}}{u_{*,c}}\right)^{2}. \tag{11}$$

In Eq. (11), $\Delta_{\max}^{o}$ is the maximum of Δ^{o}, k_m is the Marangoni resonance wave number, $u_{u*,c}$ is the critical wind stress which determined by experiments.

The viscous dissipation term S_{dis}^{i} can be expressed as

$$S_{dis}^{i} = 2 c_{g} \Delta^{i} N^{i}, \tag{12}$$

where c_g is the wave group velocity, Δ^{i} is the viscous damping coefficient, for oil-free sea

$$\Delta^{w} = \frac{4k^{2}\eta\omega}{\rho_{w} g + 3\tau k^{2}}, \tag{13}$$

where η denotes the dynamic viscosity. The viscous damping coefficient of oil-covered sea surface can be written as $\Delta^{o} = y(k)\Delta^{w}$. For more details about the damping model, please see [10].

Inserting Eqs (2), (8), and (12) into Eq. (1), we can obtain that

$$\frac{\psi^{o}(k,\phi)}{\psi^{w}(k,\phi)} = \frac{\beta^{w} - 2c_{g}\Delta^{w} + \alpha^{w}}{\beta^{o} - 2c_{g}\Delta^{o} + \alpha^{o}}. \tag{14}$$

Thus, sea spectrum of oil-covered area can be easily calculated by using clean sea spectrum and Eq. (14).

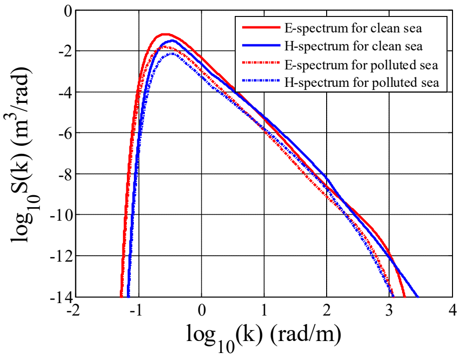

Fig.1 Sea spectra of oil-free and oil-covered surfaces, U_{10} = 5m/s.

To describe the sea waves, many sea spectra have been developed. In this work, the sea spectra proposed by Elfouhaily et al. (1997) [11] and Hwang (2008) [12] are used to conduct numerical simulations. For convenience sake, in the following, we denote the spectrum proposed by Elfouhaily et al. as E-spectrum, and Hwang as H-spectrum. Fig.1 presents the E-spectrum and H-spectrum for clean sea and polluted sea. From Fig.1, one can see that slick damps not only the short waves but also the longer waves. This phenomenon corresponds to the description of [8]. The spectral energy of oil-covered sea spectrum is smaller than oil-free sea which leads to the backscattered energy of oil-covered surface is weaker than oil-free sea.

III. NUMERICAL SIMULATION AND DISCUSSION

To evaluate the effectiveness of the damping model mentioned in section II for oil spill observation. In this part, scattering coefficients of oil-free surface and oil-covered surface are computed by using two scale model, and the simulations results are compared with measured SAR data which contains polluted and clean areas.

A. UAVSAR data

The SAR data used in this paper is collected by UAVSAR (Uninhabited Aerial Vehicle Synthetic Aperture Radar) during the DWH oil spill accident in the Gulf of Mexico. UAVSAR is a fully polarimetric L-band SAR. The incident angle ranges from 22° to 65°. The measured wind speed (U_{10}) is approximately 2.5~5m/s. The wind direction is about 115°~126°.

Fig.2 shows the VV-polarized intensity image. In Fig.2, the 'dark area' is oil spills caused by the accident. One can see that the pixels on the left side are brighter than those on the right side. This is because the incident angle increases along the range direction. The scattering coefficients of oil-covered sea used in following comparison are extracted along transect (white line) which crosses oil spill. While scattering coefficients of oil-free sea are extracted along transect (red line) which crosses clean area.

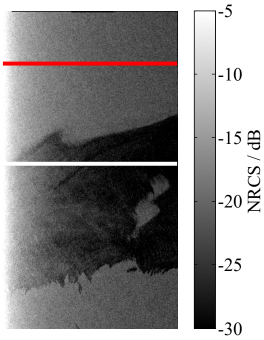

Fig.2 UAVSAR VV-polarized intensity image collected during the DWH event.

B. Two scale model

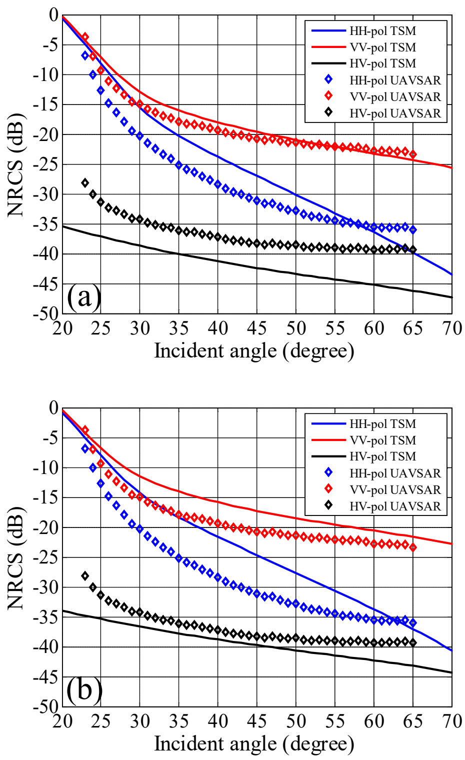

Fig.3 Comparison between numerical simulation and UAVSAR data for clean sea. (a) Numerical simulation with E-spectrum, U_{10}=3.75m/s. (b) numerical simulation with H-spectrum.

The two scale model is a combination of Kirchhoff Approximation and Small Perturbation Method. This model introduces a scale-dividing parameter k_d separating small- and large-scale components of the roughness [13]. The Kirchhoff solution and the Small Perturbation Method solution correspond to the large scale component and small scale component, respectively. In this paper, the k_d is set as $k_i/3$, k_i denotes the wavenumber of incident waves. And the Cox-Munk sea surface slope model is used when we simulate NRCS with TSM [14].

Fig.3 shows the comparison between numerical simulations and UAVSAR data for clean sea surface. The wind speed U_{10} used here is equal to 3.75m/s corresponding to the mean value of measured wind speed. In Fig.3 (a), there is a good agreement between the calculated NRCS and the ocean measurements for VV polarized channel while the incident angle ranges from 26° to 65°. Moreover, one can note that the VV polarization result agrees better with the UAVSAR data than the HH polarization. This phenomenon is consistent with the conclusion given by Wright [15]. With respect to HV polarized channel, it seems that the simulated result with H-spectrum provides a better prediction.

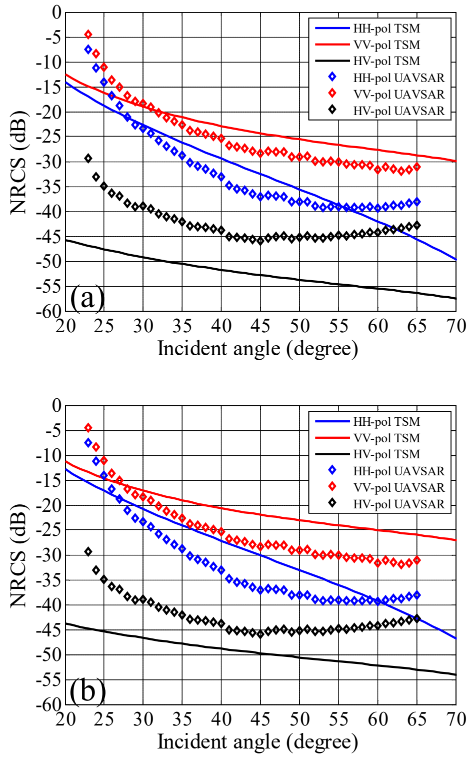

Fig.4 Comparison between numerical simulation and UAVSAR data for polluted sea, U_{10}=3.75m/s. (a) E-spectrum, (b) H-spectrum.

Fig.4 presents the comparison between numerical simulation and UAVSAR data for contaminated sea surface. Compared with sea water, the dielectric constant of oil slicks is much smaller. Microwaves can easily penetrate oil layers which leads to that the scattering fields are mainly caused by sea water under slick layers. Thus, the dielectric constant of slicks is set same with sea water in this paper. In Fig.4(a), for VV polarization, the difference between the theoretical result of E-spectrum and the experimental data is smaller (about less than 4 dB) while the incident angle ranges from 25° to 65°. As the exact physical parameters of the oil spills in the UAVSAR image cannot be obtained exactly, the difference between the numerical simulations and the UAVSAR data may be introduced in part by physical parameters used in the simulations. Nevertheless, it illustrates that the theoretical damping model introduced in section 2 can predict scattering coefficient of oil-covered sea effectively. But for HH and HV polarization, the simulated results cannot agree as well as VV polarization. In this part of the simulations, E-spectrum performs better than H-spectrum.

IV. CONCLUSIONS AND PERSPECTIVES

In this paper, the influences caused by slicks on clean sea surface are investigated with the action balance equation. A damping model based on the action balance equation has been introduced. Then, the NRCS of oil-free and oil-covered sea are simulated using TSM with sea spectra proposed by Elfouhaily et al. and Hwang, respectively. Through the experimental comparison, it has shown that the damping model can be used to simulate the EM scattering of sea surface covered with slicks. Furthermore, an accurate prediction of polluted sea NRCS could sever as a reference for oil spill detection. In this paper, only the mineral oil slicks are investigated. As there are many types of oils and emulsions with different electromagnetic properties, in the further works, the EM scattering properties of varies kind of slicks will be studied and analyzed.

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