Polarimetric Doppler Spectrum of Backscattered Echoes From Nonlinear Sea Surface Damped by Natural Slicks

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Abstract

Based on the Lombardini *et al.* model that can predict the hydrodynamic damping of rough sea surfaces in the presence of monomolecular slicks and the “choppy wave” model (CWM) that can describe the nonlinear interactions between ocean waves, the modeling of time-varying nonlinear sea surfaces damped by natural or organic sea slicks is presented in this paper. The polarimetric scattering model of second-order small-slope approximation (SSA-II) with tapered wave incidence is utilized for evaluating co- and cross-polarized backscattered echoes from clean and contaminated CWM nonlinear sea surfaces. The influence of natural sea slicks on Doppler shift and spectral bandwidth of radar sea echoes is investigated in detail by comparing the polarimetric Doppler spectra of contaminated sea surfaces with those of clean sea surfaces. A narrowing of Doppler spectra in the presence of oil slicks is observed for both co- and cross-polarization, which is qualitatively consistent with wave-tank measurements. Simulation results also show that the Doppler shifts in slicks can increase or decrease, depending on incidence angles and polarizations.

Keywords: Doppler spectrum, electromagnetic scattering, natural sea slicks, sea surfaces, second-order small-slope approximation (SSA-II)

2010 MSC: 00-01, 99-00

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1. INTRODUCTION

Doppler spectrum of radar echoes from rough sea surfaces is a promising technique in many areas such as ocean wave spectra estimation [1, 2], ocean surface wind retrieval [3, 4], sea surface wave height retrieval [5, 6], sea surface current measurement [7, 8], etc., which carries much more information than the average scattering coefficient of rough sea surfaces [9, 10, 11]. Due to the neglect of nonlinear interactions between ocean waves, the horizontal component of orbital motions of Bragg scatterers [12] due to long waves is absent in linear sea surface models. As a consequence, the Doppler spectrum of linear sea surfaces at moderate to large incidence angles has nothing to do with physical reality. To overcome the drawbacks of linear sea surface models, several nonlinear hydrodynamic models such as the Creamer model [13] and its reduced version [14], the “choppy wave” model (CWM) [15], the West model [16], the nonlinear fractal model [17], the Lagrange model with linked components [18] etc., have been proposed for better describing the hydrodynamic surface interactions of ocean waves. On the basis of these nonlinear hydrodynamic models, Doppler spectrum of radar echoes from one-dimensional [19, 20, 21, 22, 23, 24] and two-dimensional sea surfaces [25, 26, 27, 28, 14] has been extensively investigated by utilizing rigorous numerical methods or analytical approximate models. In these studies, it is demonstrated that at low-grazing angles Doppler spectrum is significantly affected by nonlinear hydrodynamic modulation. More precisely, nonlinear sea surfaces show larger Doppler shift and spectral bandwidth compared with the corresponding linear counterparts at moderate to large incidence angles.

However, only clean sea surfaces are considered in most of the studies including the aforementioned ones on Doppler spectrum of radar sea echoes. In ocean environment, natural or man-made sea slicks are encountered frequently. Remote sensing of oil slicks floating on sea surfaces has received considerable attention, and most of the research efforts on this topic have been devoted to analyzing and processing remote sensing data, particularly by synthetic aper-

ture radar (SAR) [29, 30, 31, 32, 33]. As a basis for remote sensing of oil slicks floating on sea surfaces, electromagnetic scattering modeling of sea surface in the presence of oil slicks has also been carried out [34, 35, 36, 37]. In [36, 37], the influence of oil slicks' damping on the roughness spectrum of sea surfaces has been investigated to evaluate the electromagnetic scattering signatures of oil-covered sea surfaces, indicating that the small-scale capillary waves of sea surfaces are strongly damped by oil slicks and that oil slicks' damping effect on the angular distribution of scattered intensity is also pronounced.

Motivated by oil slicks' strong damping effect on the small-scale capillary waves of sea surfaces, our focus in this paper is on natural sea slicks' damping effect on Doppler shift and spectral bandwidth of backscattered echoes from time-evolving sea surfaces, which is potentially valuable for remote sensing of natural sea slicks floating on sea surfaces. Due to the desirable properties such as analytical tractability and numerical efficiency, the nonlinear hydrodynamic model of CWM is adopted in this paper for describing the nonlinear interactions between ocean waves. In comparison with the classical model such as Kirchhoff approximation, small perturbation method, two scale model, etc., the modern analytical approximate model of second-order small-slope approximation (SSA-II) [11] takes into account facets' tilts modulation and second-order Bragg scattering, and thus can reasonably predict the depolarized scattering from rough sea surface both in and outside the plane of incidence. Therefore, the polarimetric scattering model of SSA-II is utilized in the present study for evaluating the polarimetric Doppler spectrum of backscattered echoes from clean and contaminated nonlinear CWM sea surfaces.

The remainder of this paper is organized as follows. In Section 2, oil slicks' damping effect on sea surfaces roughness spectrum is examined briefly, and the modeling of nonlinear sea surfaces in the presence of natural sea slicks is presented. Section 3 presents the polarimetric scattering model of SSA-II with tapered wave incidence for evaluating polarimetric Doppler spectrum of clean and contaminated nonlinear CWM sea surfaces. The numerical results of Doppler spectra of backscattered echoes from clean and contaminated sea

surfaces are discussed and analyzed in Section 4. Section 5 concludes this paper.

2. MODELING OF CONTAMINATED NONLINEAR SEA SURFACES

In the existing literature, only a few models that can take into account oil slicks and predict the hydrodynamic damping of rough sea surfaces in the presence of surface oil films are available [38, 39, 40]. In the present study, we put emphasis on the investigation of the influence of natural or organic sea slicks' damping effect on Doppler spectrum of backscattered echoes from sea surfaces. Hence, the Lombardini *et al.* model suitable for monomolecular slicks [40] is adopted in this paper. According to the model proposed by Lombardini *et al.*, the roughness spectrum of contaminated sea surfaces S_{cont} is related to that of clean sea surfaces S_{clean} by the following ratio [40, 37]

$$S_{cont}(k; \phi, U_{10}, E_0, \omega_D) = \frac{S_{clean}(k; \phi, U_{10})}{y_s(k; E_0, \omega_D)} \quad (1)$$

where y_s is the damping ratio. k and ϕ in polar coordinates denote the ocean wave wavenumber and the wave propagation direction, respectively. U_{10} is the wind speed at a height of 10m. For insoluble films and a fully covered sea, the damping ratio y_s is expressed by

$$y_s(f, E_0, \omega_D) = \frac{1 - 2\tau + 2\tau^2 - X + Y(X + \tau)}{1 - 2\tau + 2\tau^2 - 2X + 2X^2} \quad (2)$$

where

$$\tau = \left(\frac{\omega_D}{2\omega}\right)^{\frac{1}{2}} \quad X = \frac{E_0 k^2}{\rho(2\nu\omega^3)^{0.5}} \quad Y = \frac{E_0 k}{4\rho\nu\omega} \quad (3)$$

are dimensionless quantities and

$$f = \frac{\omega}{2\pi} = \frac{(\varsigma k^3/\rho + g_0 k)^{1/2}}{2\pi} \quad (4)$$

is the dispersion law. In (2)-(4), ρ is the water density, g_0 is the acceleration of gravity, $\nu = 10^{-6}$ m/s the kinematic viscosity, $\varsigma = 74 \times 10^{-3}$ N/m is the surface tension. E_0 denotes the elasticity modulus and ω_D represents a characteristic angular frequency, which depend on surface film characteristics. It should be

69 noted that Eq. (2) is only suitable for the fully covered sea surface by insoluble
70 films and that all simulations below in this paper are for the fully covered sea
71 surface by insoluble films. For partially covered sea surface by soluble oil films,
72 the damping ratio can be can be found in [40, 37].

In the present study, the roughness spectrum of sea surface proposed by Elfouhaily *et al.* is utilized for describing clean sea surfaces. The Elfouhaily spectrum in polar coordinates can be expressed as [41]

$$S_{clean}(k, \phi, U_{10}) = S_{clean}(k) \Phi(\phi) \quad (5)$$

where $S_{clean}(k)$ denotes the isotropic parts of clean sea surface roughness spectrum and can be expressed as

$$S_{clean}(k) = k^{-3} (B_L(k) + B_H(k)) \quad (6)$$

where B_L denotes the long-wave curvature spectrum and B_H represents the short-wave curvature spectrum. The detailed expressions of B_L and B_H can be found in [41]. In Eq. (5), $\Phi(\phi)$ represents the angular spreading function. In this paper, the angular spreading function is chosen as follows

$$\Phi(\phi) = \frac{1}{2\pi} (1 + \Delta(k) \cos(2(\phi - \phi_w))) \quad (7)$$

where ϕ_w is the wind direction with respect to the radar line of sight and

$$\Delta(k) = \tanh \left(\frac{\ln 2}{4} + 4 \left(\frac{c(k)}{c(k_p)} \right)^{2.5} + 0.13 \left(\frac{u_f}{c(k_m)} \right) \left(\frac{c(k_m)}{c(k)} \right)^{2.5} \right) \quad (8)$$

73 where $c(k) = \sqrt{g(1 + k^2/k_m^2)/k}$, $k_m = 370$ rad/m, $c(k_p) = U_{10}/\Omega_c$ with Ω_c
74 being inverse wave age, $c(k_m) = \sqrt{2g/k_m} \approx 0.23$ m/s, and u_f is the friction
75 velocity.

With the knowledge of the roughness spectrum of clean or contaminated sea surfaces, the root-mean-square (RMS) slope σ_s and RMS height σ can be derived as, respectively

$$\sigma_s = \sqrt{\int_0^{+\infty} k^3 dk \int_0^{2\pi} d\phi S(k, \phi)} \quad (9)$$

Figure 1: Height spectrum (isotropic part) and slope spectrum (isotropic part) of clean and contaminated sea surface versus wavenumber k . (a) Height spectrum, (b) slope spectrum.

$$\sigma = \sqrt{\int_0^{+\infty} k dk \int_0^{2\pi} d\phi S(k, \phi)} \quad (10)$$

Figures 1(a) and (b) present a comparison of the height spectrum (isotropic part) and slope spectrum (isotropic part) between clean and contaminated sea surfaces, respectively. In Fig. 1, $S(k)$ can be either $S_{clean}(k)$ or $S_{cont}(k)$. The wind fetch involved in Elfouhaily *et al.* spectrum is set as 300 km. In Fig. 1, we consider two types of natural or organic sea surface films with parameters $\{\omega_D = 6 \text{ rad/s}, E_0 = 9 \text{ mN/m}\}$ and $\{\omega_D = 11 \text{ rad/s}, E_0 = 25 \text{ mN/m}\}$, respectively. It needs to be noted that these values were retrieved from experiments conducted in the Sicilian Channel and the Gulf of Maine [40]. From Fig. 1, we can observe that oil film strongly damps the high frequency components corresponding to the small-scale waves of sea surfaces. In addition, we can also find that oil film with parameter $\{\omega_D = 11 \text{ rad/s}, E_0 = 25 \text{ mN/m}\}$ has a stronger damping effect compared with oil film with parameter $\{\omega_D = 6 \text{ rad/s}, E_0 = 9 \text{ mN/m}\}$. Comparing Figures 1(a) with (b), we can find that the influence of oil slicks on slope spectrum is much stronger in comparison with the height spectrum of sea surface.

Oil film's damping effect can exert nonnegligible influence on the geometrical

92 structure of sea surfaces such as surface heights and slopes, and on the statistical
 93 characteristics of sea surfaces such as surface RMS height and RMS slope. A de-
 94 tailed discussion of oil's damping effect on sea surface heights and slopes can be
 95 found in Pinel's work [37], and the main conclusions are listed here. Specifically,
 96 both surface heights and slopes of contaminated sea surfaces are smaller com-
 97 pared with clean sea surfaces. Moreover, the sea surface heights and slopes of
 98 contaminated sea surfaces with oil parameter $\{ \omega_D = 11 \text{ rad/s}, E_0 = 25 \text{ mN/m} \}$
 99 are smaller than those with $\{ \omega_D = 6 \text{ rad/s}, E_0 = 9 \text{ mN/m} \}$.

In the present study, the contaminated and clean sea surfaces are generated with the roughness spectrum of contaminated sea surfaces S_{cont} and that of clean sea surfaces S_{clean} , respectively. The spectral method under spatially homogeneous and time-stationary hypothesis is utilized for generating rough sea surface by taking into account its high efficiency, since the procedure of generating rough sea surface can be realized by fast Fourier transform. The generated rough sea surfaces including clean and contaminated sea, in essence, are realizations of Gaussian random process. All of the components of linear sea surfaces in Fourier domain are completely independent of random phases. This implies Gaussian statistics for sea surface elevations and their derivatives. The spatial Fourier amplitude at any time t can be expressed as follows

$$A(\bar{k}, t) = \gamma(\bar{k}) \sqrt{S(k, \phi) \delta k_x \delta k_y} \exp(i\omega t) + \gamma(-\bar{k})^* \sqrt{S(k, \pi - \phi) \delta k_x \delta k_y} \exp(-i\omega t) \quad (11)$$

100 where $\bar{k} = (k_x, k_y) = (k, \phi)$ is spatial wave vector. It should be noted that
 101 all the over bar symbol below in this paper represent vector symbol. $S(k, \phi)$
 102 is sea surface roughness spectrum. $\gamma(\bar{k})$ is a complex Gaussian random se-
 103 ries with zero mean value and unit variance. The sampling interval along x
 104 direction is $\delta k_x = 2\pi/L_x$ which is determined by Nyquist sampling criterion
 105 with L_x being the length of sea surface along x direction. Similarly, the sam-
 106 pling interval along y direction $\delta k_y = 2\pi/L_y$ with L_y being the length of sea
 107 surface along y direction. According to the gravity-capillary dispersion rela-
 108 tion, the angular frequency ω is related to the spatial wavenumber $k = |\bar{k}|$ by

109 $\omega = \sqrt{g_0 k (1 + k^2/k_m^2)}$ with g_0 being the gravity acceleration constant.

Then, the linear sea surface elevation $h(\bar{r}, t)$ at spatial position $\bar{r}$ for time t can be expressed by

$$h(\bar{r}, t) = \sum_{\bar{k}} A(\bar{k}, t) \exp(i\bar{k} \cdot \bar{r}) \quad (12)$$

Eq.(12) can be efficiently accomplished by inverse fast Fourier transform. To ensure that $h(\bar{r}, t)$ is real, $A(\bar{k})$ is required to satisfy the conjugate symmetry about the origin as follows

$$A(k_x, k_y) = A^*(-k_x, -k_y), \quad A(k_x, -k_y) = A^*(-k_x, k_y) \quad (13)$$

The nonlinear hydrodynamic model of CWM is adopted in this paper for describing nonlinear interactions between wave components, which is analytically tractable and numerically efficient. The CWM is based on a Lagrangian description of ocean waves and can be constituted by horizontal displacement of Hilbert transform of a reference linear surface. Given a linear sea surface $h(\bar{r}, t)$ and its Hilbert transform, the CWM nonlinear sea surface $\tilde{h}(\bar{r}, t)$ is defined by [15]

$$\tilde{h}(\bar{r} + \overline{D}(\bar{r}, t), t) = h(\bar{r}, t) \quad (14)$$

The displacement can be written as [15]

$$\overline{D}(\bar{r}, t) = \int -i \frac{\bar{k}}{k} \hat{h}(\bar{k}, t) \exp(i\bar{k} \cdot \bar{r}) d\bar{k} \quad (15)$$

where

$$\hat{h}(\bar{k}, t) = \frac{1}{(2\pi)^2} \int d\bar{r} \exp(-i\bar{k} \cdot \bar{r}) h(\bar{r}, t) \quad (16)$$

110 is the spatial Fourier transform. The model of CWM is numerically efficient as
111 it can be entirely generated by fast Fourier transform.

112 **3. POLARIMETRIC SCATTERING MODEL OF SSA-II MODEL** 113 **FOR CALCULATING DOPPLER SPECTRUM**

114 The small-slope approximation theory consists of a basic approximation of
115 the theory (SSA-I) and second-order corrections to it (SSA-II) and represents a

Figure 2: Geometry of sea surface scattering problem.

116 systematic expansion of a scattering amplitude with respect to slopes of rough
 117 surface, which has been successfully applied to evaluate microwave scattering
 118 from rough sea surfaces. The modern analytical approximate model of SSA-II
 119 takes into mutual transformation of the two linear polarization states caused by
 120 facets tilts as well as the second-order Bragg scattering, and thus can predict
 121 the depolarized scattering from rough sea surface both in and outside the plane
 122 of incidence [11].

123 To the authors' knowledge, two different ways can be found in literature
 124 for dealing with electromagnetic scattering from rough sea surfaces covered by
 125 oil films. The first way just considers the damping effect of oil film on sea
 126 surface but ignore the thickness of oil film, as done in [35] by Nunziata *et al.*
 127 For this approach, oil film's damping effect is taken into account by modifying
 128 sea surface roughness spectrum with the use of Marangoni damping theory
 129 suitable for describing monomolecular organic film floating on ocean surface
 130 whose thickness is extremely small compared to electromagnetic wavelength. It
 131 should be noted that Nunziata's way implies an assumption that sea biogenic
 132 slicks have a zero-thickness. Thus, Nunziata's way cannot take into account
 133 multiple scattering between air-oil and oil-water interface. In principle, this

134 assumption depends on incidence angles, since multiple scattering between air-
 135 oil and oil-water interface becomes pronounced under large incidence angles.

136 The second one considers both oil film's damping effect and oil film's thick-
 137 ness, as done in [37] by Pinel *et al.* In fact, Pinel's way [37] significantly d-
 138 iffers from Nunziata's way [35]. More specifically, the former is a two-layered
 139 rough surface scattering problem, whereas the latter is a single-layered rough
 140 surface scattering problem. One obvious advantage of Pinel's approach [37] is
 141 that it can take into account multiple scattering between air-oil and oil-water
 142 interface. In addition, the absorption of incident electromagnetic energy due
 143 to oil film can also be considered by Pinel's approach. However, the rigor-
 144 ous numerical methods such as method of moments (MoM) and its improved
 145 versions encounter convergence problems when dealing with electromagnetic s-
 146 cattering problems of sea surfaces covered by monomolecular organic film, since
 147 the thickness of monomolecular organic film is extremely small compared to
 148 electromagnetic wavelength.

149 In the present study, monomolecular organic film is considered with emphasis
 150 on its influence on Doppler spectrum of backscattered echoes from 2-D time-
 151 varying ocean surfaces. Thus, we adopt Nunziata's [35] way by modifying sea
 152 surface roughness spectrum with the use of Marangoni damping theory to take
 153 into account oil films damping effect on ocean waves, in which oil film's damping
 154 effect on ocean waves is considered but the thickness of oil film is ignored. This
 155 implies that the effects of oil slicks on sea surface geometrical structures such
 156 as surface heights and slopes can be taken into account with the damping ratio
 157 proposed by Lombardini *et al.* [40]. Therefore, the polarimetric scattering
 158 model of SSA-II can be utilized for calculating co-polarized (HH, VV) and cross-
 159 polarized (HV, VH) radar echoes from both clean and contaminated sea surfaces.

The geometry of the electromagnetic wave scattering problem is illustrat-
 ed in Fig. 2. The configuration angles $(\theta_i, \varphi_i, \theta_s, \varphi_s)$ represent the incident
 angle, incident azimuth angle, scattering angle, and scattering azimuth angle,
 respectively. $\bar{k}_i = (\bar{k}_0, q_0)$ and $\bar{k}_s = (\bar{k}, q)$ are the incident wave vector and
 scattering wave vector, respectively. In this paper, a tapered plane wave in cho-

sen as the incident field to reduce the edge effect caused by the limited surface size of $L_x \times L_y$, which is expressed as [42]

$$\bar{E}_i(\bar{r}) = T(\bar{r}) \exp(i\bar{k}_i \cdot \bar{r}) \quad (17)$$

$$T(\bar{r}) = \exp[i(\bar{k}_i \cdot \bar{r})w] \exp(-t_x - t_y) \quad (18)$$

where

$$t_x = \frac{(x \cos \theta_i \cos \varphi_i + y \cos \theta_i \sin \varphi_i + z \sin \theta_i)^2}{g^2 \cos^2 \theta_i} \quad (19)$$

$$t_y = \frac{(-x \sin \varphi_i + y \cos \varphi_i)^2}{g^2} \quad (20)$$

$$w = \frac{1}{k_i^2} \left(\frac{2t_x - 1}{g^2 \cos^2 \theta_i} + \frac{2t_y - 1}{g^2} \right) \quad (21)$$

and g is the parameter that controls the tapering of the incident wave. Thus, the original scattering amplitude of the SSA-II model can be expressed as follows after introducing the tapered incident wave

$$S(\bar{k}, \bar{k}_0) = \frac{2\sqrt{q_0 q}}{(q_0 + q)\sqrt{P_{inc}}} \int \frac{d\bar{r}}{(2\pi)^2} T(\bar{r}) \times \exp(-i(\bar{k} - \bar{k}_0) \cdot \bar{r} + i(q + q_0)h(\bar{r})) \\ \times \left(B(\bar{k}, \bar{k}_0) - \frac{i}{4} \int M(\bar{k}, \bar{k}_0; \bar{\xi}) h(\bar{\xi}) \times \exp(i\bar{\xi} \cdot \bar{r}) d\bar{\xi} \right) \quad (22)$$

where

$$h(\bar{\xi}) = \frac{1}{(2\pi)^2} \int h(\bar{r}) \exp(-i\bar{\xi} \cdot \bar{r}) d\bar{r} \quad (23)$$

160 is the Fourier transform of the surface elevation. P_{inc} is the incident wave power
 161 captured by sea surface. The kernel functions of B and M are 2×2 matrices
 162 describing mutual transformations of the EM waves of different polarization-
 163 s, which depend primarily on the polarizations, configuration angles, and the
 164 permittivity of the lower medium. It can be proved that, in a general case,
 165 $M(\bar{k}, \bar{k}_0; 0) = 0$. For this reason, the term related to the function M in Eq.
 166 (22) is, in fact, proportional to the slopes of rough surface rather than to the
 167 elevations themselves. This term provides a correction to the first-order small

168 slope approximation (SSA-I). Thus, Eq. (22) corresponds to the SSA-II, and us-
 169 ing $M = 0$ in it results in the SSA-I. A detailed derivation and the corresponding
 170 kernel functions in the SSA framework can be found in [43].

Different from linear sea surfaces model whose spatial sample intervals are uniform, the spatial sample intervals of the CWM nonlinear sea surfaces model are not uniform. Therefore, Eq.(22) cannot be directly applied to CWM nonlinear sea surfaces. When the SSA-II model is applied to the CWM nonlinear sea surfaces model, the integral variables $\bar{r}$ in Eq.(22) should be replaced by $\tilde{r} = \bar{r} + \bar{D}(\bar{r})$. The Jacobian transformation of J from $\bar{r}$ to $\tilde{r}$ can be utilized to accomplish this change of integral variables. Therefore, to apply the SSA-II model to CWM nonlinear sea surfaces, Eq.(22) should be rewritten as

$$\begin{aligned}
 S(\bar{k}, \bar{k}_0) = & \frac{2\sqrt{q_0 q}}{(q_0 + q)\sqrt{P_{inc}}} \int \frac{d\bar{r}}{(2\pi)^2} |J(\bar{r}, t)| \times T(\bar{r} + \bar{D}(\bar{r}, t)) \\
 & \times \exp(-i(\bar{k} - \bar{k}_0) \cdot (\bar{r} + \bar{D}(\bar{r}, t)) + i(q + q_0)h(\bar{r})) \\
 & \times \left(B(\bar{k}, \bar{k}_0) - \frac{i}{4} \int M(\bar{k}, \bar{k}_0; \bar{\xi}) h(\bar{\xi}) \times \exp(i\bar{\xi} \cdot \bar{r}) d\bar{\xi} \right) \quad (24)
 \end{aligned}$$

where

$$J(\bar{r}, t) = \begin{vmatrix} 1 + \partial D_x(\bar{r}, t)/\partial x & \partial D_x(\bar{r}, t)/\partial y \\ \partial D_y(\bar{r}, t)/\partial x & 1 + \partial D_y(\bar{r}, t)/\partial y \end{vmatrix} \quad (25)$$

The Doppler spectrum is defined as the power spectral density of the random time-varying scattering amplitude and can be evaluated by utilizing a standard spectral estimation technique by the following expression[23]

$$S(f) = \left\langle \frac{1}{T} \left| \int_0^T S(\bar{k}, \bar{k}_0; t) e^{-i2\pi f t} dt \right|^2 \right\rangle \quad (26)$$

171 where $S(\bar{k}, \bar{k}_0; t)$ is the scattering amplitude from sea surfaces at time t . The
 172 angular bracket denotes the ensemble average over random surface realizations
 173 and T represents the sea surface evolution time. In what follows, we consider
 174 only the backscattering case, i.e. $\theta_s = \theta_i$, $\varphi_i = 0^\circ$, and $\varphi_s = 180^\circ$.

The Doppler shift f_c , i.e. the spectral centroid, and the bandwidth of Doppler spectrum f_w are defined by the following expressions to quantitatively

measure Doppler spectrum

$$f_c = \frac{\int f S(f) df}{\int S(f) df} \quad (27)$$

$$f_w = \sqrt{\frac{\int (f - f_c)^2 S(f) df}{\int S(f) df}} \quad (28)$$

175 The Doppler shift f_c , which is an important parameter of Doppler spectrum,
 176 corresponds to a power-weighted mean line-of-sight velocity of the scatterers.
 177 The bandwidth of Doppler spectrum f_w is determined by the variance of the
 178 velocity distribution of the scattering facets at sea surfaces.

179 4. NUMERICAL RESULTS AND DISCUSSION

180 In the following simulations, the influence of natural sea slicks with param-
 181 eter $\{\omega_D = 11 \text{ rad/s}, E_0 = 25 \text{ mN/m}\}$ on Doppler spectrum of sea echoes is
 182 investigated in detail. The incident wave frequency is 1.2 GHz. At the frequen-
 183 cy of 1.2 GHz, the relative permittivity of sea surface is $\varepsilon_r = 73.2 + i67.2$ at
 184 sea water temperature of 20 °C and salinity of 30 parts per thousand in terms
 185 of Debye expression [44]. The sampling interval is $\lambda/8$ where λ is electromag-
 186 netic wavelength. The sizes of sea surfaces are $L_x = L_y = 128\lambda = 32 \text{ m}$ and
 187 $L_x = L_y = 256\lambda = 64 \text{ m}$ for wind speed $U_{10} = 3 \text{ m/s}$ and $U_{10} = 5 \text{ m/s}$, re-
 188 spectively. The tapering parameter g is set to $L_x/6$. The wind fetch is taken
 189 as 300 km. The time step is set to 0.02 s to obtain sufficient unambiguous
 190 Doppler bandwidth, and each realization of Doppler spectrum is performed on
 191 256 time samples to obtain sufficient Doppler spectral resolution. The final
 192 Doppler spectrum is an ensemble average over 50 realizations of sea surfaces.

193 Figures 3 and 4 present the average Doppler spectra of backscattered echoes
 194 from clean and contaminated CWM nonlinear sea surfaces with wind speed
 195 $U_{10} = 3 \text{ m/s}$ and $U_{10} = 5 \text{ m/s}$, respectively. For all simulations in Figures 3
 196 and 4, the radar is looking upwind. For reference, the Bragg lines are also plot-
 197 ted with vertical short dotted lines, which are predicted by small perturbation
 198 method (SPM) at first order and can be calculated by $f_B = \pm\sqrt{g_0 K_B}/2\pi$ where

Figure 3: Average Doppler spectra of backscattered echoes from clean and contaminated CWM nonlinear sea surfaces with wind speed $U_{10} = 3$ m/s at various incidence angles. The left column, middle column, and right column is for HH, VV, and HV polarization, respectively. The vertical short dotted lines represent Bragg lines. The radar is looking upwind.

Figure 4: Similar to Fig. 3, but with wind speed $U_{10} = 5$ m/s.

$K_B(\theta_i) = 2k_0 \sin(\theta_i)$ is the Bragg wavenumber. The polarimetric scattering model of SSA-II is utilized for evaluating co-polarized (HH, VV) and cross-polarized (HV, VH) scattering field from 2-D time-varying sea surfaces, since there is no difference of normalized Doppler spectrum predicted by SSA-I between HH and VV polarization. Due to the reciprocity in backscattering which means that HV-polarized backscattering is equal to VH-polarized backscattering, thus for cross-polarization only HV-polarized Doppler spectra are presented. In addition, rigorous numerical simulations have demonstrated that the Doppler spectra of linear sea surfaces are extremely narrow at low-grazing angles [23]. This is exceedingly unrealistic and is not consistent with measurements, because the linear sea surface model is just a collection of harmonics each propagating independently of others, in which the hydrodynamic interactions between ocean waves are ignored. Hence, it is necessary to adopt nonlinear sea surface model to investigate oil film's damping effect on Doppler spectra of radar sea echoes, in particular for Doppler spectra at moderate to large incidence angles. The linear sea surface model completely misses the horizontal components of orbital motions that shorter waves experience due to long waves. However, the CWM nonlinear sea surface does capture these orbital motions correctly by adding a horizontal displacement of Hilbert transform of a reference linear surface. Accordingly, the Doppler spectra at moderate to large incidence angles predicted by CWM nonlinear sea surfaces are much more consistent with radar measurements in comparison with linear sea surface model. Thus, the SSA-II model combined with the CWM nonlinear sea surface model is utilized in the present study to examine oil film's damping effect on Doppler spectrum signatures of radar sea echoes such as Doppler shift and Doppler spectral bandwidth.

Comparing the Doppler spectra of clean and contaminated sea surfaces illustrated in Figures 3 and 4, we can observe that for both co-polarization and cross-polarization the Doppler spectra of contaminated sea surfaces are narrower than those of clean sea surfaces. That is, a narrowing of Doppler spectrum in slicks is observed regardless of incidence angles. To quantitatively compare the Doppler spectrum width between clean and contaminated sea surfaces, the

230 Doppler spectral bandwidth calculated by Eq. (28) is presented in Figures 6(a)
 231 and (b) for wind speed $U_{10} = 3$ m/s and $U_{10} = 5$ m/s, respectively. Obviously,
 232 the Doppler spectral bandwidths of contaminated sea surfaces are smaller than
 233 those of clean sea surfaces as depicted in Figures 6(a) and (b). This is due to the
 234 fact that Doppler spectral bandwidth depends mainly on the variance of orbital
 235 velocities of ocean waves. The orbital velocities of ocean waves are reduced by
 236 oil slicks, since the magnitude of the sea surface roughness spectrum is decreased
 237 due to oil slicks' damping effect. In addition, for contaminated sea surfaces, it
 238 is indicated that the difference of Doppler spectral bandwidth between HH and
 239 VV polarizations is almost indistinguishable. For both clean and contaminated
 240 sea surfaces, the Doppler spectral bandwidths for co-polarization are smaller for
 241 than those for cross-polarization.

242 In wind-wave tank measurements [45], the influence of natural sea slicks on
 243 Doppler spectrum of radar sea echoes has been investigated. During the exper-
 244 iments, measurements of radar backscattering were performed at X- and Ka-
 245 bands with fixed incidence angles 35° and 53° , respectively. The scatterometers
 246 were operating at only VV polarization. Monomolecular slicks were produced
 247 by disturbing oleyl alcohol on water surface to simulate natural sea slicks. The
 248 wind-wave tank measurements have confirmed that, the Doppler spectrum in
 249 slicks is narrower in comparison with clean sea surfaces [45]. It should be noted
 250 that due to the severe computational burden our numerical simulations are lim-
 251 ited to lower frequency band, i.e., L-band (1.2 GHz), while the wind-wave tank
 252 measurements [45] were performed at much higher frequency bands, i.e., X- and
 253 Ka-bands. Thus, we cannot fairly compare our simulation results with the mea-
 254 surements [45]. Nonetheless, the simulation results are qualitatively consistent
 255 with the wave-tank measurements [45]. In addition, the effect of sea slicks on
 256 Doppler spectrum width at incidence angles of 0° and 10° was investigated by
 257 using an empirical formula of Doppler spectral bandwidth [46], indicating also
 258 that at low to moderate wind speeds the Doppler spectrum width in slicks is
 259 decreased due to the presence of oil slicks.

260 The Doppler spectral bandwidths of radar sea echoes are reduced due to the

261 presence of sea slicks regardless of incidence angles, as indicated in the previous
 262 discussions. However, the variation of Doppler shift in the presence of oil slicks
 263 is very complicated in comparison with Doppler spectral bandwidth. More
 264 specifically, the simulation results indicate that the Doppler shift of radar sea-
 265 echoes in the presence of natural sea slicks can decrease or increase, depending on
 266 incidence angle and polarization state. To our knowledge, for cross-polarization
 267 case, the investigation of oil slicks' damping effect on Doppler spectrum has not
 268 been reported in literature. From Figures 3 and 4, it is readily observed that
 269 the movement tendency of Doppler spectra peaks in slicks is different between
 270 co-polarization and cross-polarization. Moreover, for cross-polarization case at
 271 small to moderate incidence angles, the Doppler shifts of contaminated sea
 272 surfaces are obviously increased compared with those of clean sea surfaces. In
 273 what follows, we will discuss the variation of Doppler shift in the presence of oil
 274 slicks in detail.

275 For co-polarization case, it is indicated in Fig. 4 that for near-nadir con-
 276 figuration ($\theta_i = 5^\circ$) the Doppler spectra of contaminated sea surfaces at wind
 277 speed $U_{10} = 5$ m/s are shifted to higher frequencies compared with those of
 278 the corresponding clean sea surfaces. For the lower wind speed $U_{10} = 3$ m/s,
 279 however, the Doppler spectra peaks of clean and contaminated sea surfaces can
 280 hardly be distinguished at incidence angle $\theta_i = 5^\circ$. As incidence angle increases,
 281 the co-polarized Doppler spectra peaks in slicks are shifted to lower frequencies
 282 relative to those of clean sea surfaces as illustrated in Figures 3 and 4 for wind
 283 speed $U_{10} = 3$ m/s and $U_{10} = 5$ m/s, respectively. To better measure the
 284 difference of Doppler shift between clean and contaminated sea surfaces, the
 285 Doppler shifts defined by Eq. (28) are presented in Figures 7(a) and (b) for
 286 wind speed $U_{10} = 3$ m/s and $U_{10} = 5$ m/s, respectively. From Fig. 7(b), we
 287 can observe that at incidence angle $\theta_i = 5^\circ$ the co-polarized Doppler shifts of
 288 contaminated sea surfaces are larger than those of clean sea surfaces with wind
 289 speed $U_{10} = 5$ m/s. However, the Doppler shifts of clean and contaminated sea
 290 surfaces are close to each other at incidence angle $\theta_i = 5^\circ$ for the lower wind
 291 speed $U_{10} = 3$ m/s as depicted in Fig. 7(a). As incidence angle increases pro-

gressively, the co-polarized Doppler shifts in slicks are decreased in comparison with clean sea surfaces. In particular at small to moderate incidence angles, the co-polarized Doppler shifts are significantly reduced due to the presence of sea slicks as illustrated in Figures 7(a) and (b) for wind speed $U_{10} = 3$ m/s and $U_{10} = 5$ m/s, respectively.

For cross-polarization case, the Doppler spectra peaks of contaminated sea surfaces are shifted to higher frequencies as depicted in Figures 3 and 4 for wind speed $U_{10} = 3$ m/s and $U_{10} = 5$ m/s, respectively. As expected, the cross-polarized Doppler shifts of contaminated sea surfaces are larger than those of clean sea surfaces as illustrated in Figures 7(a) and (b) for wind speed $U_{10} = 3$ m/s and $U_{10} = 5$ m/s, respectively. Comparing Doppler shifts in slicks between co- and cross-polarizations, we can observe that the Doppler shifts in slicks can decrease or increase, which depends strongly on polarization. In addition, the difference of Doppler shift in slicks between co- and cross-polarization is much smaller in comparison with clean sea surfaces as illustrated in Figures 7(a) and (b) for wind speed $U_{10} = 3$ m/s and $U_{10} = 5$ m/s, respectively.

In the open ocean experiments carried out in 1997-1998 on the Black Sea [47, 48], it was indicated that the variations of Doppler shifts in slicks is very complicated. The VV-polarized radar measurements performed at X- and Ka-bands with fixed incidence angle 55° showed that Doppler shifts in slicks can increase or decrease, depending on radar wavelength and surface film characteristics [47, 48]. It should be noted that our simulations are limited to L-band (1.2 GHz) due to the severe computational burden encountered in large-scale Monte Carlo simulations, while the open ocean experiments were performed at X- and Ka-bands [47, 48]. Hence, our simulation results cannot be fairly compared with the measurements [47, 48]. In addition, at wind speed 7-9 m/s, a strong reduction of Doppler shifts in slicks at X-band is observed in the wind-wave tank measurements performed at incidence angle of 35° for VV polarization [45].

Figure 5 show the comparison of normalized Doppler spectra of backscattered echoes from clean and contaminated CWM nonlinear sea surface. The wind speed is $U_{10} = 3$ m/s, and the radar is looking crosswind. From Figure 5,

Figure 5: Comparison of normalized Doppler spectra of backscattered echoes from clean and contaminated CWM nonlinear sea surface at wind speed $U_{10} = 3$ m/s. The vertical solid lines represent Bragg lines. The radar is looking crosswind.

two obvious peaks can be observed for both co- and cross-polarization. For co-
 polarization, the two peaks corresponding to the positive and negative frequen-
 cies are centered at first-order Bragg peaks produced by ocean waves moving
 toward and away from the radar. However, the two peaks for cross-polarization
 are not so much closer to the first-order Bragg peaks in comparison with co-
 polarization case. Comparing the Doppler spectra of clean and contaminated
 sea surfaces, we can readily observe that the Doppler spectra of contaminated
 sea surfaces are narrower than those of clean sea surfaces. This can be attribut-
 ed to the fact that Doppler spectral bandwidth depends mainly on the variance
 of orbital velocities of ocean waves, and that the orbital velocities of ocean waves
 are reduced due to the presence of sea slicks. In addition, the Doppler spectral

334 peaks of contaminated sea surfaces are shifted to higher frequencies relative to
 335 those of clean sea surfaces.

Figure 6: Comparison of Doppler spectral bandwidths for clean and contaminated sea surfaces. (a) $U_{10} = 3$ m/s. (b) $U_{10} = 5$ m/s.

Figure 7: Comparison of Doppler shifts for clean and contaminated sea surfaces. (a) $U_{10} = 3$ m/s. (b) $U_{10} = 5$ m/s.

336 5. CONCLUSION

337 In this paper, natural or organic sea slicks' damping effect on sea surface
 338 roughness spectrum is examined briefly, indicating that the heights and slopes

339 of sea surfaces are reduced due to oil slicks' damping effect. On this basis, the
340 influence of natural sea slicks on polarimetric Doppler spectra is investigated in
341 detail by comparing the Doppler spectra of contaminated sea surfaces with those
342 of clean sea surfaces. The polarimetric scattering model of SSA-II combined with
343 CWM nonlinear sea surfaces model is utilized for evaluating the co-polarized
344 and cross-polarized Doppler spectra of backscattered echoes from clean and
345 contaminated CWM nonlinear sea surfaces.

346 A narrowing of Doppler spectra in the presence of oil slicks is observed for
347 both co-polarization and cross-polarization, which is qualitatively consistent
348 with wave-tank measurements performed at X- and Ka-bands [45]. However,
349 the variation of Doppler shift in slicks is very complicated in comparison with
350 Doppler spectral bandwidth. The simulation results show that the Doppler
351 shifts in slicks can decrease or increase, which depends on polarizations and
352 incidence angles. The open ocean experiments carried out in 1997-1998 on the
353 Black Sea performed at X- and Ka-bands with fixed incidence angle indicated
354 that Doppler shifts in slicks can increase or decrease, which depends on radar
355 wavelength and surface film characteristics [47, 48]. In addition, at wind speed
356 7-9 m/s, a strong reduction of Doppler shifts in slicks at X-band is observed
357 in the wind-wave tank measurements performed at incidence angle of for VV
358 polarization [45].

359 These qualitative results of Doppler shift and spectral bandwidth are poten-
360 tially valuable for remote sensing of natural sea slicks floating on sea surfaces,
361 although the present study is limited to L-band due to a severe computational
362 burden. It needs to be pointed out that by developing GPU-based simulation
363 codes the further investigation on this topic will be carried out at higher fre-
364 quency bands such as X- and Ka-bands, which are more sensitive to oil slicks. In
365 addition, the Doppler spectra differences between oil films with different film e-
366 lasticity and the discrimination between oil films and look-alikes deserve further
367 investigation, which goes beyond the scope of this paper.

368 Acknowledgement

369 This work was supported by the National Science Foundation for Distin-
370 guished Young Scholars of China (Grant No.61225002).

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