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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.

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 [9–11]. 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 [19–24] and two-dimensional sea surfaces [25–28,14] 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

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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 aperture radar (SAR) [29–33]. 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 [34–37]. 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 [38–40]. 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]:

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

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 10 m. For insoluble films and a fully covered sea, the damping ratio y_s is expressed by

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

where

$$\tau=\left(\frac{\omega_D}{2\omega}\right)^{\frac{1}{2}}\quad X=\frac{E_0k^2}{\rho(2\nu\omega^3)^{0.5}}\quad Y=\frac{E_0k}{4\rho\nu\omega} \tag{3}$$

are dimensionless quantities and

$$f=\frac{\omega}{2\pi}=\frac{(\varsigma k^3/\rho+g_0k)^{1/2}}{2\pi} \tag{4}$$

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, $\varsigma=74\times10^{-3}$ 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 noted that Eq. (2) is only suitable for the fully covered sea surface by insoluble films and that all simulations below in this paper are for the fully covered sea surface by insoluble films. For partially covered sea surface by soluble oil films, the damping ratio 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]

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

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

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

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:

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

where ϕ_w is the wind direction with respect to the radar