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Doppler spectra of electromagnetic fields scattered from two-dimensional fetch- and depth-limited nearshore sea surfaces

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ABSTRACT

Doppler spectral signatures of sea echoes from two-dimensional (2-D) fetch- and depth-limited sea surfaces are investigated using the second-order small-slope approximation (SSA-II) model. For the description of 2-D nearshore sea surface, the revised choppy wave model (RCWM) is applied, which takes into account the wind fetch effect and water depth effect in nearshore marine environment. Comparisons of computed results in co-polarizations and cross polarization at various incident angles show that Doppler shift and spectral bandwidth can be greatly influenced by hydrodynamic modulation of waves in the large wind fetch and small water depth marine environment, which indicates that the hydrodynamic modulation induced by shoaling effect would be greatly enhanced in the situation of the nearshore shallow sea with a long wind fetch. The differences in variation trend between results in co-polarizations and cross polarization also reflect varying degrees of influence of aforementioned hydrodynamic modulation on different scattering mechanisms.

1. Introduction

The Doppler spectrum of electromagnetic backscattered sea echoes can indeed provide much more valuable information than the mere radar cross section (RCS), thus the study of the Doppler spectral characteristics from dynamic oceanic surfaces has attracted great attention for its myriad applications in research areas such as ocean surface wind retrieving, remote sensing in marine environment and so on [1–8]. Back in the 50s of the last century, Crombie [9] first observed the backscattering from ocean surfaces based on the high-frequency (HF) electromagnetic waves, he found the Doppler shift and spectral broadening characteristics from the sea echoes. Barrick [10], Barrick and Lipa [11], and Weber and Barrick [12] developed the perturbation method for the modeling and inversion of second-order high frequency radar Doppler spectra of sea-echoes, they stressed that the energy in the second-order spectrum increases as the water depth decreases. Zavorotny and Voronovich [13] proposed a composite surface scattering model to evaluate the sea-echo Doppler spectral characteristics, however, the contribution from the non-Bragg scattering was not included. With further investigation, it was found that nonlinear hydrodynamics links the motion of waves with different scales, which should be paid great attention. Thus, Rino et al. [14] studied the Doppler spectral features of echoes from time-varying linear and nonlinear Creamer sea surfaces. Toporkov and Brown [15,16] made a comprehensive study of the Creamer nonlinear surface scattering characteristics in L band. Johnson et al. [17] and Hayslip et al. [18] also carried out related researches for other nonlinear sea surface models. Soriano et al. [19] investigated the Doppler spectral signatures of scattered signals from two-dimensional (2-D) nonlinear sea surfaces (3-D electromagnetic scattering issues). Nouguier et al. [20] applied the

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nonlinear choppy wave model (CWM) and the weighted curvature approximation (WCA) to simulate ocean Doppler signatures at microwave frequencies.

In spite of the advantages in aforementioned researches, some essential points still should be mentioned: the computation of Doppler spectra of echoes from 2-D dynamic sea surfaces is quite time-consuming, which is prohibitive for some numerical methods. Moreover, the joint influence of the physical environment of nearshore waters, such as water depth and wind fetch, is also much essential to the Doppler simulation but is rarely investigated in detail. Duncan et al. [21] studied Doppler spectra of backscattered echoes in wave tanks under different wind fetches and wind speeds circumstances and they found some factors other than fetch and wind speed would also greatly impact the Doppler spectra. Hasselmann et al. [22] investigated the wave growth and the continuous transition of wind-sea spectrum from a fetch-limited state to a fully developed state based on experimental observations, but the effect of water depth was not included in their research. In a word, it is still far from a clear understanding of the joint influence of water depth and wind fetch on Doppler spectral characteristics of sea echoes.

In this paper, the second-order small-slope approximation (SSA-II) model is applied to investigate the Doppler spectral characteristics of backscattered signals from 2-D fetch- and depth-limited sea surfaces, which has presented good balance between the computational accuracy and efficiency in published researches [16,23]. Another advantage of this model is that SSA-II can also provide the polarization information of higher-order contributions, namely cross polarization. The relevant investigation is also presented in this paper.

The paper is organized as follows. In Sections 2, 2-D nearshore sea surfaces for different wind fetches and water depths are firstly simulated, and the analysis of statistical characteristics of the simulated sea waves is also carried out. Section 3 presents the formulation of SSA-II method for evaluating the joint influence of wind fetch and water depth on Doppler spectra of sea echoes. The numerical results of the Doppler spectra of backscattered echoes from 2-D sea surfaces in different fetches and depths cases are presented in Section 4, and then the Doppler shift and spectral bandwidth are mainly discussed. Section 5 is devoted to the concluding remarks.

2. Waves in fetch- and depth-limited nearshore sea

In the nearshore region, the water waves will be influenced by much more marine environment factors, such as the water depth, seabed topography, wind fetch and intense nonlinear hydrodynamic effect. Thus the shape and the statistical characteristics of coast waves will undergo much greater transformation compared with waves in deep sea, therefore, the geometry of nearshore waves should be constructed in detail to ensure that the subtle structures can be captured completely. In this paper, the revised choppy wave model (RCWM) [24,25] would be used in the nearshore sea surface simulation and successive Doppler spectra analysis. The sea surface elevation at time t can be expressed as

$$h(\boldsymbol{r},t)=\int \boldsymbol{F}(\boldsymbol{r},\boldsymbol{k};t)\exp(j\boldsymbol{k}\cdot\boldsymbol{r})\mathrm{d}\boldsymbol{k} \tag{1}$$

with

$$\boldsymbol{F}(\boldsymbol{r},\boldsymbol{k};\boldsymbol{t})=\frac{1}{2\pi}\left[\zeta(\boldsymbol{k})\sqrt{\frac{\Psi(k,\varphi)}{L_xL_y}}\exp(j\omega t)+\zeta(-\boldsymbol{k})^*\sqrt{\frac{\Psi(k,\pi-\varphi)}{L_xL_y}}\exp(j\omega t)\right] \tag{2}$$

where vector $\boldsymbol{k}=(k_x,k_y)$ represents a 2-D vector for wavenumber of ocean waves, and $|\boldsymbol{k}|=k$. Vector $\boldsymbol{r}=(x,y)$ represents the coordinates of horizontal position. $\zeta(\boldsymbol{k})$ are complex Gaussian series with zero mean and unity standard deviation, as well as no correlation between disjoint wavenumbers, and the superscript $*$ denotes the conjugation operation. $\Psi(k,\varphi)$ is the 2-D sea spectrum containing the spreading function, L_x and L_y are the lengths of the sea surface along x-axis direction and y-axis direction respectively, and angular frequency $\omega=2\pi f=\sqrt{gk(1+k^2/k_m^2)\tanh(kd)}$ with $k_m=363.2\ rad/m$, d is the water depth. Based on aforementioned expressions, the fetch- and depth-limited nearshore sea surfaces can be constructed by the following transformation:

$$\{\boldsymbol{r},h(\boldsymbol{r},t)\}\mapsto\{\boldsymbol{r}+\boldsymbol{C}_h(\boldsymbol{r},t),h(\boldsymbol{r},t)\} \tag{3}$$

where $\boldsymbol{C}_h$ is the Riesz transform of the integral kernel $\boldsymbol{F}$ in Eq. (2)

$$\boldsymbol{C}_h(\boldsymbol{r},t)=\int -j\frac{\boldsymbol{k}\cosh(kd)}{k\sinh(kd)}\boldsymbol{F}(\boldsymbol{r},\boldsymbol{k};t)\exp(j\boldsymbol{k}\cdot\boldsymbol{r})\mathrm{d}\boldsymbol{k} \tag{4}$$

In Eq. (2), the 2-D sea spectrum that is applied to appropriately illustrate nearshore fetch- and depth-limited water waves could be denoted as follows:

$$\Psi(k,\varphi)=S(k)\Phi(\varphi)\tau \tag{5}$$

where $S(k)$ is the popular unified Elfouhaily sea spectrum, which is valid over all wavenumbers and agrees well with many past and recent corresponding experiments and observations [26]

$$S(k)=k^{-3}(B_l+B_h) \tag{6}$$

B_l represents the long-wave curvature spectrum

$$B_l=0.5\alpha_pF_pc(k_p)/c(k) \tag{7}$$

where $c(k)=\sqrt{g(1+k^2/k_m^2)/k}$ is the wave phase speed, $k_p=g\Omega^2/U_{10}^2$ denotes the wavenumber corresponding to the spectral peak, g is the gravity acceleration, U_{10} is the wind speed at a height of 10 m above the sea surface, the generalized Phillips–Kitaigorodskii equilibrium range parameter for long waves $\alpha_p=6\times10^{-3}\sqrt{\Omega}$, the dimensionless inverse-wave-age $\Omega=0.84\tanh[((gX)/(2.2\times10^4U_{10}^2))^{0.4}]^{-0.75}$, which is indispensable to describe gravity waves. X represents the wind fetch in meters, which plays its role via parameter Ω during the simulation of sea waves

$$F_p=L_{PM}J_p\exp\left\{-\Omega[(k/k_p)^{1/2}-1]/\sqrt{10}\right\} \tag{8}$$

where L_{PM} is the Pierson–Moskowitz shape spectrum, $L_{PM}=\exp[-1.25(k_p/k)^2]$, and the peak enhancement factor