FETCH LIMITED SEA SCATTERING SPECTRAL MODEL FOR HF-OTH SKYWAVE RADAR

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1. INTRODUCTION

Barrick Theory has been considered a milestone in developing Radar Cross Section (RCS) prediction theory, many books and transaction papers have been published in last forty years in order to understand and predict the scattering behavior of target and ground sea echoes [1]-[8]. The scattering phenomena can be considered a resonance effect with detectable RCS when the target roughness has the same scale of the radar wavelength [1]. D.E. Barrick has modelled the scattering surfaces of man-made or natural media as "Rough Surfaces", provided that its wavenumber spectral density contains significant wavelengths compared to half the projected radiated signal wavelength [3]. For skywave radar at High Frequency (HF) band (wavelength between 10-100 m), the electromagnetic-wave propagates over the horizon by means of the ionospheric plasma resonance effect [2] and Backscattering of targets having an "harmonic range profile", like sea wave or collinear lands can be described statistically as Bragg resonance. For remote sensing of the ocean environment the first and second order scattering peaks are used to extract the sea wave state (wave height and swell direction) and in some cases the directional wavenumber spectra [6, 8]. In particular first and second order scattering theory for fully developed seas and Doppler spectra has been derived by Barrick and Lipa dealing with mono-static radar near grazing, and recently have been extended by Gill and Walsh for Bistatic scattering [6][8]. Gill and Walsh also have modelled the Doppler spectra of the HF radar signal as a function of the range resolution $\Delta\rho$, the Bistatic angle and the sea directional wave number spectra predicted by means of the Pierson-Moskovitz model [6]. Such models have found a great success for ground wave radar ocean remote sensing but are not appropriated to characterize Fetch-limited seas like the Mediterranean. In this paper, a sea Backscattering model is proposed from HF skywave radar that is based on Barrick first order model suitably modified to account for the fetch limited sea at high grazing angle. In details, the Fetch-limited Hasselmann sea wave spectral model has been introduced to compute the Normalized RCS Doppler spectrum (NRCS-Doppler). Results show that the absence of fully developed sea produces a substantial reduction of the NRCS and an evident modification of the Doppler spectrum.

2. REVIEW OF SCATTERING FROM MOVING ROUGH SURFACE

In this Section a review of the first order scattering model is proposed.

2.1. Sea and Land stationary RCS prediction at HF band

The static ground echo RCS can be predicted by the use of rough surface scattering model, derived originally by Barrick and Peake 1968 [1, 3]:

$$\sigma_{ij}(\beta) = 4\pi k_o^4 sin^4(\beta)\, |S_{ij}|^2 W(\Sigma, \phi)_{\Sigma=-2k_0 cos(\beta)} \tag{1}$$

Where $k_0 = 2\pi/\lambda$ is the wavenumber of the incoming electromagnetic wave β is the grazing angle measured from terrain (it is 0° at grazing incidence, and 90° for specular reflection), $W(\Sigma, \phi)$ is the wavenumber Σ height spectral density, S_{ij}, is the normalized scattering coefficient for transmitted i and received j polarizations:

$$\begin{bmatrix} S_{HH} = \frac{(\epsilon_r - 1)}{\left[sin(\beta) + \sqrt{\epsilon_r - cos(\beta)^2}\right]^2} \\ S_{HV} = S_{VH} = 0 \\ S_{VV} = \frac{(\epsilon_r - 1)\left[(\epsilon_r - 1)cos(\beta)^2 + \epsilon_r\right]}{\left(\epsilon_r sin(\beta) + \sqrt{(\epsilon_r - cos^2(\beta))}\right)^2} \end{bmatrix} \tag{2}$$

and $\epsilon_r = 78 + j\,0.1$ is the mean sea complex dielectric constant (3.5% salinity) measured at HF band. Barrick model is able to describe the scattering of a rough surface at Bragg resonance, varying the grazing angle β, the dielectric relative constant ε_r, where g is the gravity acceleration and $\Omega_s = 2\pi\Psi_s$ is the sea wave pulsation and Ψ_s is the sea frequency. According to this model, the shorter is the sea wave pulsation the faster it will propagate. Considering a monochromatic wave, the sea wavelength Ω_s and the sea wavenumber Σ_s can be derived:

$$\Omega_s = 2\pi/T_s, \quad \Sigma_s = 2\pi/\Lambda_s \tag{6}$$

The propagation effect can be described by the Brillouin diagram [6]:

$$\Omega_s = \sqrt{g\Sigma_s tanh\left(\Sigma_s D\right)},\ lim_{D\to\infty}\Omega_s = \sqrt{g\Sigma_s},\ lim_{D\to\infty}c_s = \sqrt{g/\Sigma_s} \tag{7}$$

In narrow band MTD radar, the target Doppler shift $f_d = 2V_r/\lambda_0$ depends on target radial speed V_r and depends on the radar wavelength λ_0. The Doppler pulsation ω_d is derived by using surface speed V_t and grazing incidence β:

$$\omega_d = 2\pi f_d = 4\pi V_r/\lambda_0 = 2k_0 V_r = 2k_0 V_t cos\left(\beta\right) \tag{8}$$

Bragg scattering from sea surface occurs if the projected length of the sea wavelength $\Lambda_{proj} = cos\left(\beta\right)\Lambda_s$ is equal to half the transmitter wavelength λ_0:

$$2\Lambda_s^{Bragg} cos\left(\beta\right) = \lambda_0,\ \Sigma_s = 2k_0/cos\left(\beta\right) \tag{9}$$

By merging eq. (8) and (9), and considering the swell phase speed c_s as the target tangent speed V_t we obtain:

$$\omega_d = 2k_0 cos\left(\beta\right)\sqrt{g/\Sigma_s} = \sqrt{4k_0^2 g cos^2\left(\beta\right)/2k_0 cos\left(\beta\right)} = \sqrt{2gk_0 cos\left(\beta\right)} \tag{10}$$

For Continuous Wave (CW) HF Radar, the resonance is generated by a single sea wavelength. According to the first order model proposed by Lipa and Barrick, the NRCS spectral density is modeled by a two Dirac delta functions centered on the resonant Doppler frequency ω_d [5, 6]:

$$\sigma\left(\omega_d\right)_{ij\pm} = 4\pi k_o^4 sin^4\left(\beta\right)\left|M_{ij}\right|^2 W\left(\Sigma_s,\phi\right)_{\Sigma_s=\Sigma^*}\delta\left(\omega_0 \mp \omega_d\right),\ \Sigma^* = -2k_0 cos\left(\beta\right), \phi = \pi/2 + \theta_k - \theta_w \pm \pi/2 \tag{11}$$

Where θ_k is the radar look angle projected along to the ground direction and θ_w is the mean wind direction in a cylindrical coordinate reference system centered on the radar antenna. This formula exhibits certain limits, because it is derived for CW radar systems, that are not capable to perform range profiling.

Walsh has recently modified such model for coded radar waveform introducing the effect of time limited pulse coding on radar Doppler spectra. By using of variable grazing mono static geometry and following the procedure described by Gill and Walsh, after a straightforward calculation, the pulse coded Doppler spectra expression are derived in closed form [7, 8]:

$$\sigma_{ij}\left(\omega_d\right)_\pm = 2k_o^2 sin^4\left(\beta\right)\left|M_{ij}\right|^2 W\left(\Sigma_s,\phi\right)_{\Sigma_s=\Sigma^*}\cdot\frac{\Sigma_s^{5/2}}{\sqrt{g}}cos\left(\beta\right)\Delta\rho Sa^2\left[\frac{\Delta\rho}{2cos(\beta)}\left(\Sigma_s \mp m2k_0 cos\left(\beta\right)\right)\right] \tag{12}$$

where $\Delta\rho = c\tau/2$ is the range resolution, and $Sa\left(x\right) = sin\left(\pi x\right)/\pi x$ the sampling function. It is worth noting that for $\Delta\rho \to \infty$ the Lipa-Barrick and Gill-Walsh expressions are equivalent [7].

3. DIRECTIONAL SPECTRAL MODEL OF FETCH LIMITED SEA SURFACE

In this section we describe three different models used to predict sea directional spectra. The directional sea spectrum, in circular reference system $W\left(\Sigma_s,\phi\right)$ depends on the wind intensity U, the wind direction θ_{wind}, the look direction θ_k and Fetch F. The Fetch is the measure of the length of water over which a given wind blows with regular intensity. Barrick has firstly defined the maximum directional sea spectrum for fully developed sea by the use of the Phillips model [4]. Barrick and Lipa, and recently Gill and Walsh have used the Pierson Moskovitz spectrum in order to predict the Fetch unlimited ocean directional sea spectrum function of wind intensity and direction [6]. The use of Philips and Pierson-Moskovitz directional spectral models in eq. (12) provides good prediction for open sea, but it is not appropriate to represent closed seas, like the Mediterranean. To overcome this problem we introduce the Hasselmann model in eq. (12) to simulate closed sea, directional sea spectrum as function of wind intensity, wind direction and wind Fetch. Results of σ_{ij} after applying Hasselmann spectrum to (12) will be compared with NRCS coming from the use of open sea spectrum models. Generally, ocean Spectral model may be considered as a product of a non directional spectrum $W\left(\Sigma_s\right)_{max}^{1-D}$ and a normalized directional distribution $g\left(\phi\right)$ [6]:

$$W\left(\Sigma_s,\phi\right) = W\left(\Sigma_s\right)^{1D-max} g\left(\phi\right) \tag{13}$$

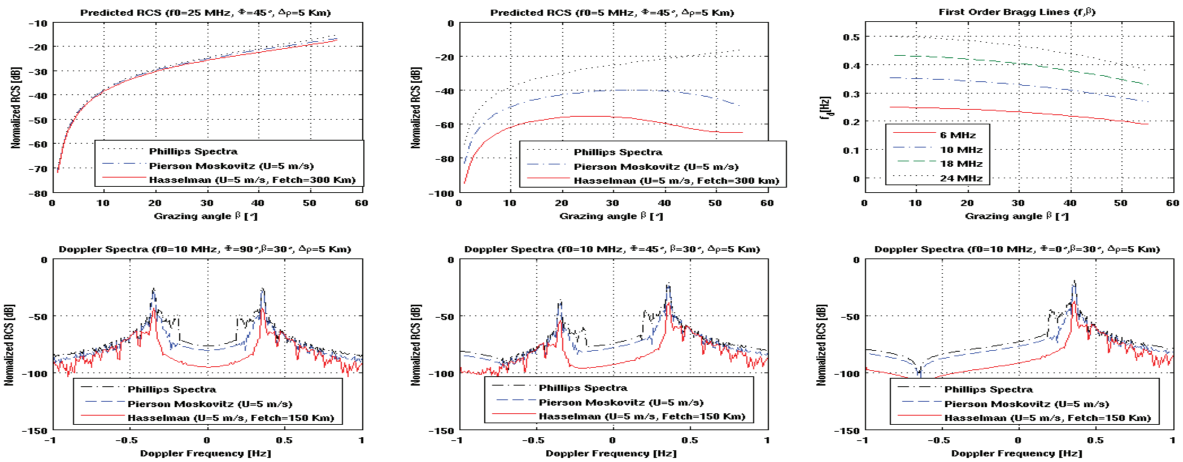

Fig. 1. Simulation Results: a) NRCS(β), f_0=25 MHz , b) NRCS(β), f_0=5 MHz c) Resonant Doppler Frequency $f_d\,(\beta, f_0)$, d) Doppler Spectra $\sigma_{vv}\,(f_d)$,$\Phi = 90$, e) Doppler Spectra $\sigma_{vv}\,(f_d)$,$\Phi = 45$, f) Doppler Spectra $\sigma_{vv}\,(f_d)$,$\Phi = 0$

In order to generate realistic sea spectra we have considered a uniform cardioid directional distribution:

$$g\,(\phi, m) = \frac{4}{3\pi} cos\left(\frac{\phi}{2} + (1-m)\,\frac{\pi}{4}\right)^4,\ m = \pm 1,\ \phi = \theta_k - \theta_{wind} \qquad (14)$$

The Phillips [2], Pierson-Moskovitz [7] and Hasselmann spectra describe the non directional wave number distributions:

$$\begin{array}{c} W\,(\Sigma_s)^{1D-max}_{Phillips} = \frac{B}{\Sigma_s^4},\ B = 0.0081 \\ W\,(\Sigma_s)^{1D-max}_{Pierson-Moskovitz} = \frac{B}{\Sigma_s^4} exp\left(\frac{-0.74 g^2}{\Sigma_s^2 U^4}\right) \\ W\,(\Sigma_s)^{1D-max}_{Hasselmann} = \frac{B}{2\Sigma_s^4} exp\left[\frac{-5}{4}\left(\frac{k_p}{\Sigma_s}\right)^2\right] \cdot \\ \gamma^{exp\left[\frac{-1}{2\sigma^2 k_p}\left(\sqrt{\Sigma_s} - \sqrt{k_p}\right)^2\right]}, \\ k_p = \frac{22 g^{8/3}}{U F^{2/3}},\ \sigma = \left\{ \begin{array}{l} 0.07\Sigma_s \leq k_p \\ 0.09\Sigma_s > k_p \end{array} \right.,\gamma = 3.3 \end{array} \qquad (15)$$

where U is the wind intensity [m/s], F is the sea Fetch [m] and $g = 9.81\ m/s^2$the gravity constant. It is worth noting that the Hasselmann model only includes the Fetch F in its formula.

4. SIMULATION RESULTS

In this section, typical Mediterranean sea parameters and radar system parameters have been used to predict sea directional spectra, RCS and Doppler spectra (Fig.1). The first and second subplots show the normalized RCS as function of grazing angle for the three sea spectral models at two different frequencies f_0=5 MHz, 25 MHz, for typical Mediterranean mean wind condition (U=5 m/sec, F=300 Km). It is worth noting that: A) RCS increases with grazing, B) Fetch limited seas contain less energy in low wave number regions, producing a RCS reduction at lower radar frequencies (5 MHz). The third plot shows the first order Bragg frequency depending only on the transmitted frequency and the grazing angle. Finally the last three plots trace the simulated Doppler spectra for $U = 5\ m/s$ and for three different swell angles $\phi = \pi/2$, $\phi = \pi/4$, $\phi = 0$ respectively, for $\beta = \pi/6$ and $f_0 = 10$ MHz. The dependence on wind angles is similar for all sea models, while the Fetch-limited (F=150 Km) Hasselmann model provides lower and narrower Bragg peaks respect to wind limited (Pierson-Moskovitz) and unlimited (Phillips) open ocean models.

5. CONCLUSION

Sea RCS, and Doppler spectra have been revised for HF-OTH Clutter Modelling. The Hasselmann model is firstly introduced to predict the sea directional spectrum of Fetch-limited sea and results have been compared with the Pierson-Moskovitz model used for large scale ocean remote sensing. Results show that the closed Fetch-limited sea has lower RCS compared with ocean for similar wind intensity and direction. For this reason RCS and Doppler spectra must be predicted taking into account of the Fetch dimension. In future work we will generalize this interesting approach to Fetch-Limited wind, Time-Limited pulse, in order to show the waveform effect on Doppler Spectra.

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