Contribution To Sea Scattering Estimation For Various Wind Direction

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***Abstract*— In this paper, we apply a modification to the directional part of the sea surface height spectrum of Elfouhaily model. More particularly, we substitute the Elfouhaily directional function $f(K, \psi)$ by that suggested by McDaniel. With this modified spectrum, we study the anisotropic sea surface scattering problem by using the first order of the Small Slope Approximation (SSA) model. Calculations of the normalized radar cross sections (NRCS) are made with the modified spectrum and compared with those of the Elfouhaily's one. The comparison with published experimental data shows an improvement about 3 dB for backscattering results in the crosswind direction. This spectrum modification is more important at moderate wind speeds than at higher ones. In bistatic configuration, the NRCS results is less sensitive to this spectrum modification.**

I. Introduction

The scattering problem from the sea surface is an important matter in remote sensing applications. Feasibility of deriving the wind speed at the sea surface from satellite altimeter data has been convincingly demonstrated during the three past decades with output from many experimental programs and more recently with the WindSAT mission [1]. In this context, the basis for relating radar measurements to wind vector is that the Normalized radar cross sections (NRCS) is dependent on the surface roughness and that in the ocean, the surface roughness is mainly caused by wind generated surface waves [2]. On one hand, these applications require developing accurate electromagnetic models to predicts numerical results. We solved this problem in our simulations by invoking the first order of small slope approximation (SSA-1) [3]. The advantage of using the SSA model is removal an arbitrary (within certain limits) scale-dividing parameter K_d of 1/40 to 2/3 of the radio wavelength [4]. On the other hand, computation of the NRCS requires the knowledge of either the sea surface or the sea correlation function obtained from the Fourier transform of the sea spectrum, in other words, a precise modeling of the surface is required. Among the several sea spectrum models published in the literature, Elfouhaily *et al* [5] proposed a unified directional spectrum for long and short wind-driven waves. Its agreement with the slope model proposed by Cox and Munk [6] and with actual remote sensing data make it a credible model.

The Elfouhaily directional wave spectrum $W(\boldsymbol{K}) = W(K, \psi)$ is defined as the product of the non-directional spectrum $W(K)$ with a directional function $f(\boldsymbol{K})$:

$$W(K, \psi) = W(K) \times f(K, \psi) \quad (1)$$

where

$$f(K, \psi) = [1 + \Delta(K)\cos(2\psi)]/2\pi \quad (2)$$

Whereas this model provided acceptable agreement with averaged backscattering cross sections for scattering from isotropic seas [7], it fails to adequately describe scattering from directional seas. To remedy this problem, Voronovich proposed in [8] to multiply the directional parameter $\Delta(K)$ in equation (1) by a correcting term. However, parameters of this term were determined by fitting theoretical and experimental results for each sea state. In the same way, another proposition was suggested by McDaniel [7] which based on the substitution of the Elfouhaily directional function $f(K, \psi)$ by that of Banner [9] model after some modifications. So, in this study, we will use the last suggestion, and the new obtained spectrum will be denoted as the *modified spectrum*. In our investigation we paid special attention to azimuthal anisotropy of scattering and we point out the improvements obtained by modifying the directional function of the Elfouhaily model.

II. Electromagnetic scattering problem

To study the scattering problem from randomly rough surfaces, the approximate models are still a necessity due to the insurmountable numerical complexity of realistic scattering problems. We can refer to [10] which is the latest critical and up-to-date survey of the analytical approximate models.

A. Polarimetric scattering

From measurements made in microwave band [11] for co-polarizations cases (VV and HH), the directional dependence of measured NRCS σ^0 may be approximated by

$$\sigma^0 = A_0 + A_1\cos(\psi) + A_2\cos(2\psi) \quad (3)$$

The second term on the right-hand side of (3) corresponds to upwind-downwind asymmetry of the backscattering field. This asymmetry, which is weak, results from a non-Gaussian wave-height distribution. The azimuthal asymmetry of interest in this study is that represented by the third term on the right-hand side of (3). It is convenient to introduce the notation $\sigma^0_{ud} = (\sigma^0_u + \sigma^0_d)/2$, where σ^0_u and σ^0_d are the respective cross

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sections reported for upwind and downwind headings. The ration A_2/A_0 can be defined as :

$$\frac{A_2}{A_0} = \frac{\sigma^0_{ud} - \sigma^0_c}{\sigma^0_{ud} + \sigma^0_c} \tag{4}$$

B. A unified scattering model: SSA

SSA was proposed by Voronovich [3] as a unifying theory that could reconcile the Small Perturbation Model (SPM) and Kirchhoff approximation (KA) without introducing the roughness scale division parameter K_d. Thus it encompasses both Bragg and Kirchhoff mechanisms of scattering. Both the first-order approximation (denoted as SSA-1) and the second order approximation (referred to SSA-2), which is a correction of the first-order one, can be calculated. Many publications [4][7][12] show that for radar microwave backscattering (monostatic case) and for the range of scattering angles of interest for remote sensing, SSA-1 can be used with a mean accuracy of about 1 dB.
Thus, this model was verified in bistatic configurations (Forward and fully bistatic cases) in [13] and [14] respectively. In the first order of the SSA the expression for the NRCS can be written as a simplified form for numerical calculations [12]:

$$\sigma_{\alpha\alpha_0}(\boldsymbol{k}, \boldsymbol{k}_0) = \frac{1}{\pi} \left| \frac{2q_k\ q_0}{q_k + q_0} B_{\alpha\alpha_0}(\boldsymbol{k}, \boldsymbol{k}_0) \right|^2 exp[-Q^2 \rho(\boldsymbol{0})]$$
$$\times \int_0^\infty J_0(k_s r) \left[\exp(Q^2\rho_0(r)) I_0(Q^2 \rho_2(r)) - 1\right] rdr \tag{5}$$

Here $\boldsymbol{k}_0$, q_0 are horizontal and vertical projections of the wave vector of an incident wave, and $\boldsymbol{k}$, q_k are appropriate components of the wave vector of scattered wave. $B_{\alpha\alpha_0}(\boldsymbol{k}, \boldsymbol{k}_0)$ depends on polarization and the complex dielectric constant of the roughness surface (sea water) dimensionless regular function, explicit expressions for it can be found in [4]. Where $\rho(r)$ is the surface correlation function, $Q = q_k + q_0$, $k_s = \|\boldsymbol{k} - \boldsymbol{k}_0\|$, and J_0, I_0 denote the Bessel function of the first and second kind of order 0, respectively. The next section will be dedicated to describe this surface in spectrum representation.

III. Sea surface spectrum

In the literature, there are many spectrum models to the sea surface. We can quote the Pierson spectrum, Apel model, Elfouhaily one and many other ones. The work of Lemaire [15] presents a typical review of the existing models.

A. Elfouhaily model

In this study, we will use the Elfouhaily model for sea roughness spectrum (unified spectrum), which was recently developed based on available field and wave-tank measurements. It is important to note that this model was developed without any relation to remote-sensing data. Its agreement with the slope model proposed by Cox and Munk and with actual remote sensing data make it a credible model.
When $f(K, 0)$ and $f(K, \pi/2)$ represent the respective values of $f(\boldsymbol{K})$ in the upwind and crosswind directions, coefficient $\Delta(K)$ in (2) is analogous to the ratio A_2/A_0 in (4) employed in radar scattering

$$\Delta(K) = \frac{f(K,0) - f(K,\pi/2)}{f(K,0) + f(K,\pi/2)} \tag{6}$$

B. Modified model

Based on the directional function of Banner [9], the function suggested by McDaniel [7] can be written in the following form :

$$f(K,\psi) = \frac{f_N}{2}[\text{sech}^2(\beta\psi) + \text{sech}^2(\beta\,|\psi \pm \pi|) + 2\alpha_2(K)\cos(2\psi)] \tag{7}$$

Explicit expressions and values of parameters in equation (7) can be found in [7].

Firstly, in order to evaluate this function variations with respect to the Elfouhaily model we plot in figure 1 the wavenumber dependence of $\Delta(K)$ for the three models cited above. The wind speed U_{10} is fixed to 5m/s.

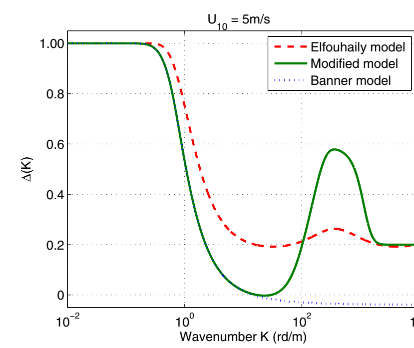
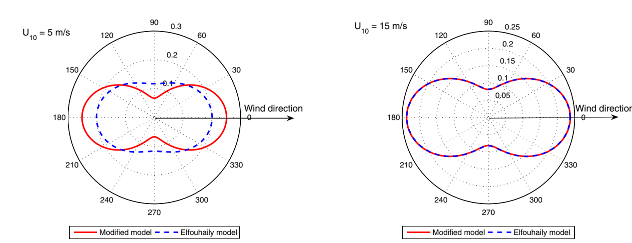


Fig. 1. Wavenumber dependence of the ratio $\Delta(K)$ predicted by three directional models for a wind speed of 5 m/s

Comparison between curves of figure 1 shows that the modification applied by McDaniel with respect to Elfouhaily means much more isotropic spectrum for long waves and a more directional spectrum for shorter waves. This remark is similar to the one observed by Voronovich [8].

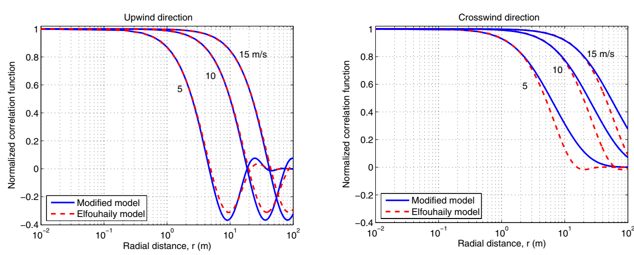


(a) (b)

Fig. 2. Variations of the directional function $f(K, \psi)$ versus the azimuthal angle measured with respect to the mean wind direction, the wavenumber is fixed to 370 rd/m, (a) U_{10}= 5 m/s and (b) U_{10}= 15 m/s

Figure 2 shows a comparison between the directional functions predicted by the two models for a wavenumber equal to 370 rd/m at two wind speeds. By examining curves in figure 2-a, we can see that for a moderate wind speed (5m/s), the directional function based on the Elfouhaily model is higher than that based on the modified model in the crosswind direction. This overestimation proves the remark signaled by Voronovich [4] about an error by 2-4 dB in backscattering results in the crosswind direction. However, in the upwind direction, the opposite behavior takes place. Differently, for higher wind speed of 15 m/s, the two directional functions are confused. As we will present later, the NRCS numerical simulations highlight well the previous behaviors.

For complete analysis about the introduced modification, we plot in figure 3 the correlation functions calculated with the two spectrum models.



(a) (b)

Fig. 3. Normalized correlation functions versus the radial distance r obtained with two models for three wind speeds $U_{10} = \{5, 10, 15 m/s\}$, (a) for upwind direction (b) for crosswind direction

The normalized correlation functions are plotted versus the radial distance r in upwind case ($\psi = 0°$) in (a) and in crosswind case ($\psi = 90°$) in (b). Note that the correlation length increases very quickly with the wind speed and that there is a significant range of negative values not present in most correlation functions for land surfaces. This negative region represents a critical parameter in some scattering cases at L-band [16]. As is apparent in this figure, the difference between correlation functions of two spectrum models is more important in crosswind direction than in the upwind direction.

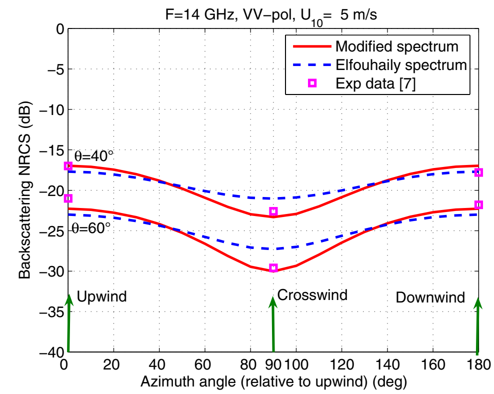
These surface representations will be a key feature when estimating the electromagnetic sea surface scattering object of the next section.

IV. Results and Discussion

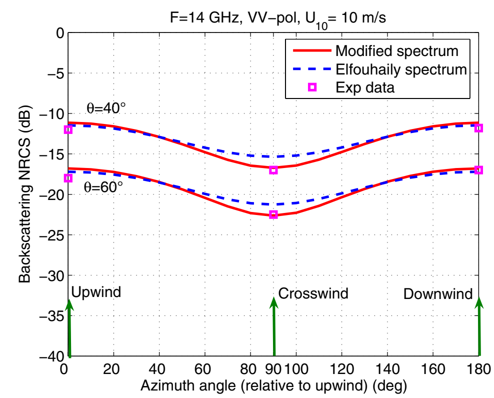
This section presents the NRCS numerical results of the 2-D anisotropic ocean surface based on two sea spectrum models presented in the last section.

A. Improvement on monostatic case

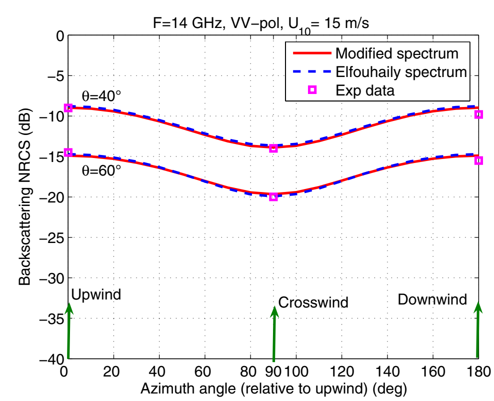
In figure 4 we show numerical simulations of the backscattering NRCS based on the two sea spectrum models, then the results are compared with experimental data published in [4]. For frequency of 14 GHz (K_u-band), simulations are made at three wind speeds 5,10 and 15 m/s for two incident angles 40° and 60° versus the azimuthal angle (relative to upwind direction). From the case (a) of this figure (U_{10}= 5 m/s), we can see that using the modified spectrum improves the backscattering NRCS clearly in the crosswind direction by 3



(a) U_{10}= 5 m/s



(b) U_{10}= 10 m/s



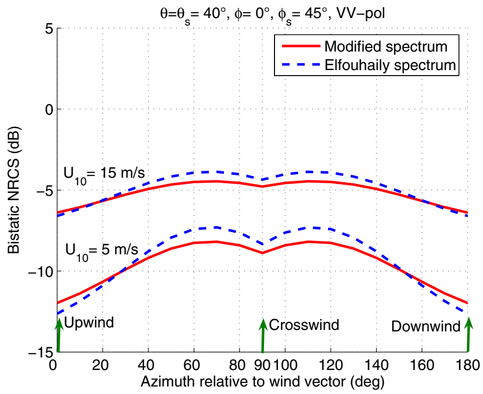
(c) U_{10}= 15 m/s

Fig. 4. Backscattering NRCS predicted with the SSA-1 model simulated with the two spectrum models and compared to experimental data published in [4], for two incident angles 40° and 60° versus the azimuth angle at wind speeds of, (a) 5 m/s, (b) 10 m/s and (c) 15m/s

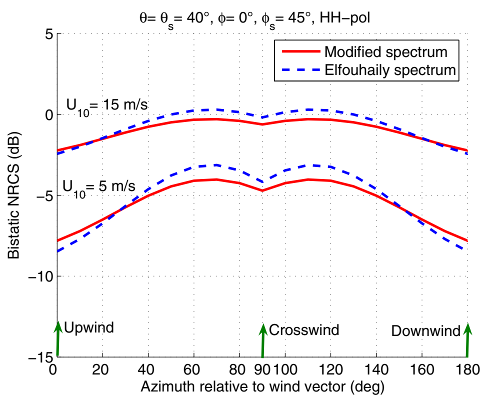
dB for moderate wind speeds. However, This improvement reduces with the increasing wind speed (U_{10}= 10 m/s). For 15m/s case there is no difference between NRCS results predicted with the two spectrum models.

B. Influence on bistatic case

Figure 5 shows the NRCS numerical results in bistatic case obtained by using the two spectrum models at two wind speeds. This bistatic configuration is defined with the following parameters: $\theta = \theta_s = 40°$, $\phi = 0°$ and $\phi_s = 45°$.



(a) VV-polarization



(b) HH-polarisation

Fig. 5. Bistatic NRCS predicted with the SSA-1 model simulated with two spectrum models for $\theta = \theta_s = 40°$, $\phi = 0°$ and $\phi_s = 45°$ at two wind speeds 5 and 15 m/s, (a) VV-polarization (b) HH-polarization

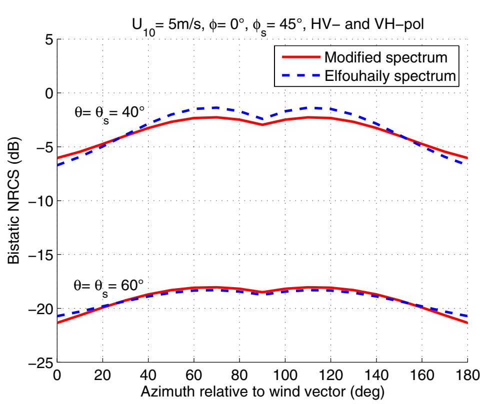


Fig. 6. With the same parameters as the last figure for cross-polarization cases

In examining curves in figure 5, we can see that around the crosswind direction, the results based on the Elfouhaily spectrum are higher than results obtained with the modified spectrum. Still the difference remains within about 1 dB. Figure 6 shows results for cross-polarizations cases for the same bistatic configuration as in the last figure. There is a difference around the crosswind direction, but remains within about 1 dB. The difference becomes negligible when the incident /scattered angle increases.

V. Conclusion

A modification on the directional part of the Elfouhaily spectrum is applied to evaluate the NRCS from the sea surface by using the small slope approximation scattering model in its first order. From the numerical examples presented in backscattering cases, it is clear that a better agreement with measurements could be obtained by modifying the directional part of the Elfouhaily spectrum. The improvement is clearly in the crosswind direction which is about 3 dB for moderate wind speeds. In bistatic case, this spectrum modification is less important than in monostatic case where a difference of about 1 dB takes place.

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