The Influence of Ripple Damping on Electromagnetic Bistatic Scattering by Sea Surface

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***Abstract*— Organic films and oil slicks modify the sea surface physics (permittivity, spectrum and slope distribution) depending on their viscosity, their bulk concentration and their diffusion coefficient. In this paper, special focus is given to the influence of a pollutant upon the electromagnetic scattering by the sea surface. Our study is based on the sea spectrum variation described with a fluid mechanic model. More, the electromagnetic scattering is evaluated in various bistatic configurations using a Two-Scale Model (TSM).**

I. INTRODUCTION

Oil-spills may adopt different aspects depending on its physical and chemical characteristics and wind speed. Indeed when wind velocity is high, oil tend to be in continuous emulsion with water. In this case, the most significant effect will be the variation of the sea surface permittivity [1]. However, oil induces a film at the sea surface when wind speed is relatively low. As a consequence, the sea spectrum is attenuated and this phenomena is known as the ripple damping effect.

In this paper, we first recall the ripple damping description of the oil slick based on the damping ratio elaborated by Cini and Lombardini [2].

In the second part, we present a new modeling polluted surface approach based on electromagnetic scattering estimation. We calculate the scattering matrix in different configurations (backscattering, forward and bistatic) using a Two Scale Model (TSM) [3], [4].

II. DAMPING EFFECT ON SEA SURFACE

Applying theory to experimental data, Cini [2], [5], [6] demonstrated that ripples on a water surface covered by a film exhibit a damping effect witch is characterized by a maximum located in the gravity-capillary region. This damping effect is expressed by the attenuation coefficient explicitly given by Cini and Lombardini [2]:

$$y(f) = \frac{1 \pm 2\tau + 2\tau^2 - X + Y(X+\tau)}{1 \pm 2\tau + 2\tau^2 - 2X + 2X^2} \quad (1)$$

where

$$\tau = (\frac{\omega_D}{2\omega})^{\frac{1}{2}} \ ; \ \ X = \frac{\epsilon_0 k^2}{\rho(2\nu\omega^3)^{1/2}} \ ; \ \ Y = \frac{\epsilon_0 k}{4\nu\rho\omega} \quad (2)$$

adimensional quantities and

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

the dispersion law, σ surface tension, ρ water density, g acceleration of gravity, k wavenumber, ν kinematic viscosity; furthermore, the constant characteristic parameters of the film used are: elasticity modulus $\epsilon_0 = d\sigma/d(\ln\Gamma)$ where Γ is the surface concentration, and characteristic frequency ω_D which for soluble films depends upon the diffusional relaxation, and for insoluble films, depends upon structural relaxation between intermolecular forces. In (1) a plus sign refers to soluble films, while a minus sign indicates insoluble films [6].

According to Lombardini et al. [7], the spectrum of slicky water $S_d(f)$ is related to the clean water spectrum $S_c(f)$ by the damping ratio

$$y_s(f) = \frac{S_c(f)}{S_d(f)} \quad (4)$$

In general the damping ratio $y_s(f)$ should not be directly interpreted as corresponding to (1). It would be so if the film was uniformly dispersed by wind and waves, so that the surface investigated results only partially covered by the film. In this case we shall introduce a fractional filling factor, F, i.e., the ratio for the area covered by film with respect to the total area considered, and write for the damping ratio (4) the expression

$$y_s(f) = \frac{1}{1 - F + F/y(f)} \quad (5)$$

Figure 1 shows the damping ratio variation with frequency for different fractional filling factors.

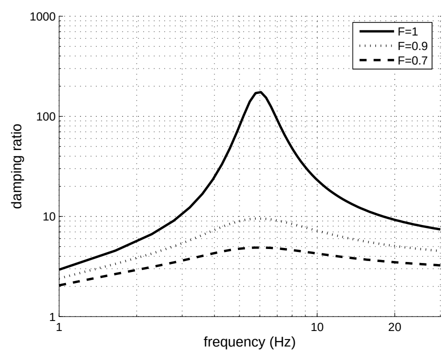

Fig. 1. Damping ratio curves for different fractional filling factors

There is a wide panoply of sea spectrum models. In the present case, we chose a recent one that fits well to the actual measurements: the Unified spectrum elaborated by Elfouhaily and al. [8]. Figure 2 underlines the sea spectrum attenuation due to the pollutant film for different fractional filling factors. This attenuation is essentially located at the gravity-capillary waves.

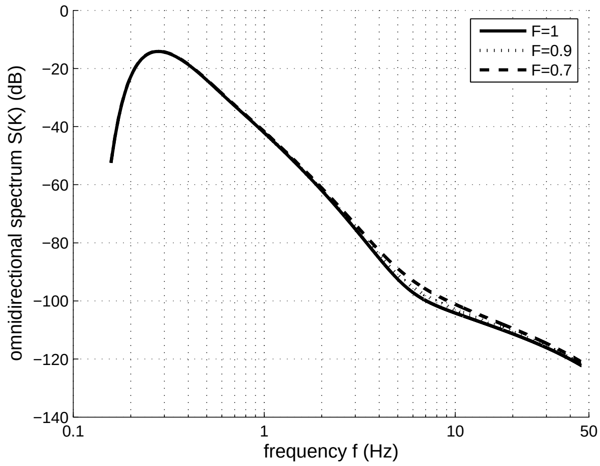

Fig. 2. Sea surface attenuation with different fractional filling factors : wind=15m/s (10m above the sea surface)

Next section treats the outcomes of the pollutant film on the electromagnetic sea surface scattering.

III. POLLUTED SURFACE SCATTERING

In the wide literature on sea monitoring, oil slick is studied through SAR images or satellite photos. These techniques are scalar approaches and give a limited set of information of the polluted surface. In this paper we are interested in the oil slick effect on electromagnetic surface scattering coefficients in a bistatic configuration. This method povides us with a larger view of the problem since we treat the polarization aspect.

Then we first estimate the scattering matrix coefficients using a Two-Scale Model (TSM) [3]. In the next part we evaluate these coefficients for the polluted surface in different configuration.

A. Scattering matrix estimation

Two-Scale Model (TSM) introduced by Fuks [9] and Fung [10] in backscattering configuration and validated by Khenchaf [4], [11] in bistatic configuration, has a wider application domain of the classic approach such as Kirchhoff Approximation (KA) and Small Perturbation Method (SPM).

In this approach, sea surface scattering is estimated in two steps. In the first, we focus on small scale waves using the small perturbation model, then by a tilting process we may easily determine the global component (see figure 3).

Assume the incident wave E^i to be

$$E^i = E_0 a \text{ with } E_0 = |E_0| e^{-jkn_i.r} \tag{6}$$

where a is the unit polarization vector (vertical polarization v or horizontal polarization h), k is the wave-number of the illuminating wave, and n_i is the unit vector in the incident direction.

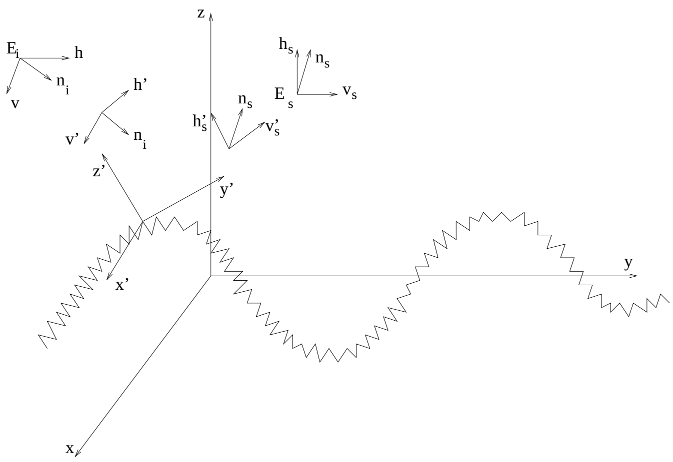

Fig. 3. Geometry of the two-scale sea surface

In the local reference the incident field can be written as

$$E^i = E^i_{v'} v' + E^i_{h'} h' = ((a.v')v' + (a.h')h')E_0 \tag{7}$$

and the locally scattered field due to incident waves is

$$\begin{aligned} E^s &= E^s_{v'_s} v'_s + E^s_{h'_s} h'_s = [S]E^i \\ &= \begin{bmatrix} S_{v'_s v'} E^i_{v'} + S_{v'_s h'} E^i_{h'} \\ S_{h'_s v'} E^i_{v'} + S_{h'_s h'} E^i_{h'} \end{bmatrix} \end{aligned} \tag{8}$$

where $S_{p'q'}$ is the scattered field for unit incident fields calculated using small perturbation model. Then the scattered field can be written as

$$E^s = E^s_{v_s a} v'_s + E^s_{h_s a} h'_s = [S]E^i \tag{9}$$

where the scattering matrix [S] is given by

$$\begin{aligned} [S] &= \begin{bmatrix} v'_s \cdot v_s & h'_s \cdot v_s \\ v'_s \cdot h_s & h'_s \cdot h_s \end{bmatrix} \\ & \begin{bmatrix} S_{v'_s v'_s} & S_{v'_s h'_s} \\ S_{h'_s v'_s} & S_{h'_s h'_s} \end{bmatrix} \begin{bmatrix} v' \cdot v & h' \cdot v \\ v' \cdot h & h' \cdot h \end{bmatrix} \end{aligned} \tag{10}$$

For the received polarization p (v_s or h_s) and the transmitted polarization q (v or h), the scattered polarization and depolarized fields are obtained from

$$\begin{aligned} E^s_{pq} &= (v'_s.p)\{(q.v')S_{v'_s v'} + (q.h')S_{v'_s h'}\}E_0 \\ &+ (h'_s.p)\{(q.v')S_{h'_s v'} + (q.h')S_{h'_s h'}\}E_0 \end{aligned} \tag{11}$$

Then the average $\left\langle E^s_{pq} E^{s*}_{p'q'} \right\rangle$ with respect to the large-scale roughness can be calculated and rewritten in terms of the scattering coefficients σ^s_{pq} [11] as a function of the transmitter polarization q and the receiver polarization p.

From the previous mathematical developments we notice that TSM is based on the small perturbation approach adapted to intermediate and grazing angles by the tilting process. The specular component will be appreciated using the Kirchhoff approach. Then the full wave number spectrum must be filtered in some logical by a high pass filter at a wave number k_d [12], [13], [14], [15].

TSM has a lager application domain than the Kirchhoff and the small-perturbation approaches. It covers small and large waves. In other word our bistatic two-scale approach is very well adapted to estimate the specular electromagnetic fields as well as intermediate and grazing ones for any sea condition.

B. *Numerical results*

Having the necessary tools developed in the previous paragraph, in this section we present the impact of the pollutant on the electromagnetic sea surface for different configurations from backscattering to bistatic configurations.

1) Backscattering configuration: In this case emitter and receiver are at the same position, then the scattering matrix must be computed with the incident angle equal to the observed one. Figure 4 presents the electromagnetic matrix coefficient variation with the received angle for both clean and polluted surface. The incident field frequency is set to f=15.48 GHz, the sea salinity and temperature to respectively S=35ppt and T=20°C, where the pollutant is considered insoluble and its permittivity is fixed by experimental measurements [16].

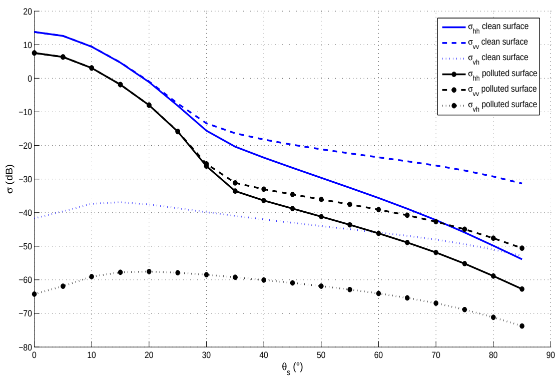

Fig. 4. Backscattering coefficient deviation with pollutant f=14GHz, $T = 20°C$, S=35ppt, wind speed=5m/s (at 10 meters) and factor filling F=1

The above simulation points out the fact that the influence of the pollutant is closely related to the polarization coefficient. For cross polarized coefficients (σ_{vh}, σ_{hv}), the difference between polluted and clean sea surfaces is approximately constant and is located around 20 dB. The case is significantly different for σ_{vv} since we notice a high contrast increasing in the grazing region (30 dB) and a negligible difference in normal incidence. The situation is quite the same for σ_{hh} but the maximum difference is about 10dB.

2) Forward-scattering configuration: In the forward-scattered configuration the specular component is of the major importance for the observed field. Indeed emitter and receiver located in the same plane facing each other and separated by the electromagnetic field impact on the surface.

In figure 5, incident angle θ is fixed to $70°$ and observed angle θ_s vary form $0°$ to $90°$. Every parameter previously fixed in the backscattering configuration remains unchanged.

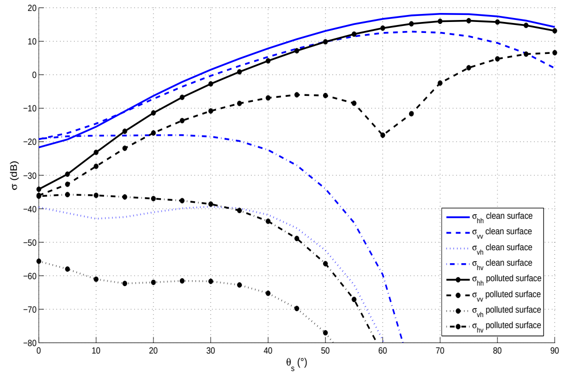

Fig. 5. Forward-scattering coefficient deviation with pollutant f=14GHz, $T = 20°C$, S=35ppt, wind speed=5m/s (at 10 meters) and factor filling F=1

When examining the coefficient variation in figure 5, several items of importance may be deduced. First the presence of the pollutant on the surface has a little influence on σ_{hh} coefficient which is a naturel statement since this later represents the specular component that is not dependent on the gravity capillary waves. The deviation of 3 to 4 dB on σ_{hh} is essentially due to the pollutant permittivity. However σ_{vv} exhibits a different comportment due to the Brewster angle phenomena [4]. The cross polarization coefficients shows a constant variation: they represent the diffuse component.

3) Bistatic configuration: To provide a different view of the polluted surface scattering, we fix both the emitter and receiver angles to $\theta = \theta_s = 40°$ and we vary the receiver azimuth ϕ_s from $0°$ to $360°$ (see figure 6)

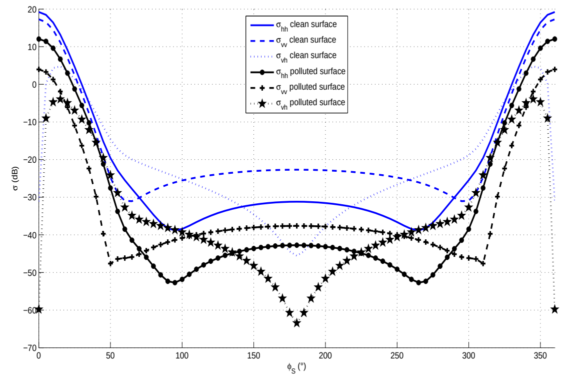

Fig. 6. Bistatic scattering coefficient deviation with pollutant f=14GHz, $T = 20°C$, S=35ppt, wind speed=5m/s (at 10 meters) and factor filling F=1

From figure 6 one can note that the oil influence is more significant on the diffuse component ($\phi_s \in [30°, 330°]$) due to both the gravity capillary waves attenuation and pollutant permittivity than the specular component ($\phi_s \leq 30°$ or $\geq 330°$).

IV. Conclusion

In the present paper, oil slick influence on the sea surface geometry is described and modeled using a realistic sea wave spectrum: Unified spectrum. The pollutant effect is then proved to attenuate the gravity-capillary waves.

Electromagnetic scattering simulations showed the various impact of oil slick on both specular and diffuse component in different configurations (backscattering, forward scattering and bistatic configuration).

Finally, our bistatic description could be of importance for the detection of oil spills on sea surface using the electromagnetic surface scattering especially if it is completed with the inverse problem.

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