Electromagnetic Detectability of the Oil Slicks on a Sea Surface in Bistatic Configuration

A. Coatanhay and C. Gervaise
Laboratory E3I2, EA 3876, ENSIETA, 29806 Brest Cedex 9, France

Abstract— This study evaluate the influence of a polluted sea surface upon the electromagnetic scattering. More precisely, we compare this influence with the electromagnetic field scattered by a non-polluted sea surface in the same weather conditions. Using a Monte-Carlo approach and a method of moment adapted to dielectric rough surfaces (a Forward-Backward approach), we statistically estimate the detectability of the pollution in various bistatic configurations using a contrast criterion.

1. INTRODUCTION

The detection of the oil slicks on the sea surface is a very important issue for coastal pollution prevention and for the identification of illegal discharges. Then, this issue was widely studied with several approaches using several sensors (optics, infrared, microwave, ...). When microwave sensors are considered, a great part of the scientific studies analyze the detectability of oil spills in the context of synthetic aperture radar (SAR) system [1–3]. And, the issue of oil spill detection using SAR systems usually leads to evaluate the efficiency of image processing methods.

In the present paper, we focus on the scattering of a single incident electromagnetic plane wave by a polluted (oil film) sea surface in bistatic configuration (forward configuration). As a matter of fact, independently of the radar signal processing, we try to determine if this scattered field is significantly influenced by the pollution in various weather conditions.

In a first part, we present the models used to describe a sea surface without any pollution in different weather conditions (wind speed and direction) and with different physical properties (temperature, salinity, ...). In a second part, we explain how to modify these models to take into account the presence of an oil film on the sea. Then the following section describe the numerical method applied to compute the electromagnetic field scattered by an ocean-like surface. Finally, we give our statistical approach to analyze the detectability of the oil film upon the electromagnetic scattering.

2. DESCRIPTION OF A NON-POLLUTED SEA SURFACE

From a global point of view, a sea surface can be assimilated to a dielectric random rough interface. The most standard way to describe the roughness of the sea surface is to determine the sea surface spectrum $S(K, \phi)$, considering the sea surface as a random, ergodic and stationary process. In scientific literature, many papers provides fully detailed description of various sea spectra, see Pierson and Moskovitz studies [4, 5] for instance. In this paper, we considered the Elfouhaily spectrum [6], called unified spectrum, that is very consistent with actual observations and presents no discontinuity at gravity and wind driven waves.

The sea spectrum is in the form:

$$S(K, \phi) = S(K) f(K, \phi) \tag{1}$$

where $S(K)$ represents the isotropic part of the spectrum modulated by the angular function $f(K, \phi)$. K and ϕ are respectively the spatial wave number and the wind direction.

Analytically, the Elfouhaily spectrum as a function of the wave number K is given by:

$$S(K) = \frac{K^{-3}}{2c}(\alpha_p c_p F_p + \alpha_m c_m F_m) R^{\exp\left[-\frac{\left(\sqrt{\frac{K}{k_p}}-1\right)^2}{2\delta^2}\right]} \exp\left(-\frac{5k_p^2}{4K^2}\right) \tag{2}$$

where

$$F_m = \exp\left[-\frac{1}{4}\left(\frac{K}{k_m}-1\right)^2\right], \quad F_p = \exp\left[-\frac{\Omega}{\sqrt{10}\left(\sqrt{\frac{K}{k_p}}-1\right)}\right] \tag{3}$$

$$\begin{cases} R = 1.7 & 0.84 < \Omega < 1 \\ R = 1.7 + 6\ln(\Omega) & 1 < \Omega < 5 \end{cases} \tag{4}$$

with $k_p = \frac{g}{U_{10}^2}\Omega^2$, $k_m = 356\,\mathrm{rad/m}$.

$$\alpha_c = 10^2 \begin{cases} 1 + \ln\left(\dfrac{u_f}{c_m}\right) & u_f \le c_m \\ & \\ 1 + 3\ln\left(\dfrac{u_f}{c_m}\right) & u_f > c_m \end{cases} \qquad \alpha_p = 6 \times 10^3\sqrt{\Omega} \tag{5}$$

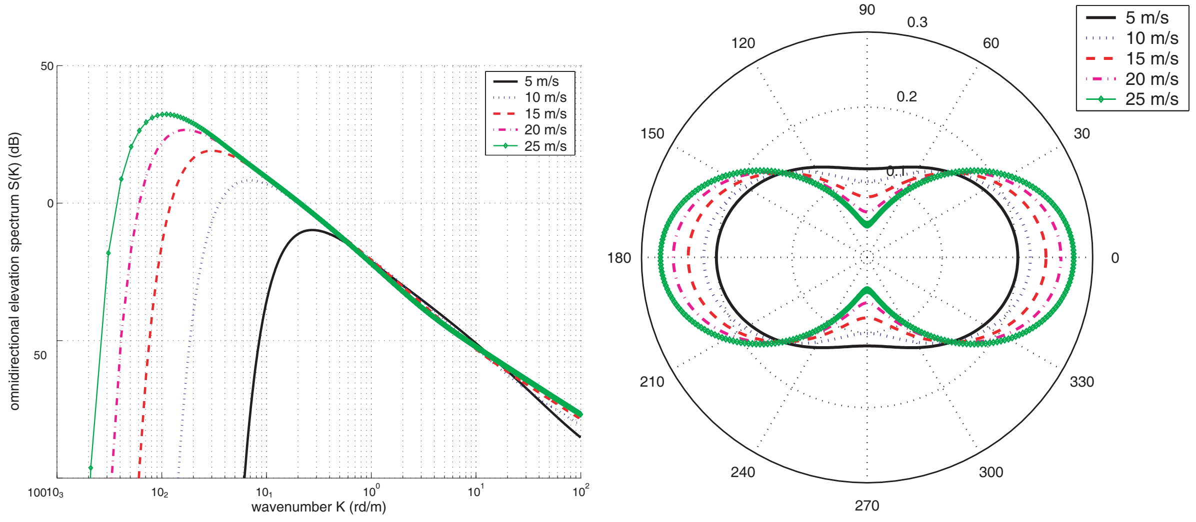
with

$$c = c(K) = \sqrt{\frac{g}{K}\left(1 + \frac{K^2}{k_m^2}\right)} \tag{6}$$

and

$$c_p = c(k_p) = \frac{U_{10}}{\Omega}, \quad c_m = c(k_m) = \sqrt{\frac{2g}{k_m}} \tag{7}$$

As a matter of fact, the Elfouhaily spectrum only depends on the wind direction ϕ, the wind speed measured at 10 meters above the sea surface U_{10} and the variable Ω that is related to the time of interaction between the wind and the sea. In the following of the text, we assume that this interaction is medium and we let $\Omega = 0.84$. So, we can estimate the roughness spectrum of the sea as a function of the wind speed and the wind direction, see Figure 1.



(a) Omnidirectional elevation spectrum

(b) Angular function

Figure 1: Elfouhaily sea surface spectra with different wind speeds.

In the case of a clean sea surface, the dielectric characteristic of the sea water can be modeled using the Debye theory [7] with adapted semi-empirical modifications. The so-obtained model that is a function of the frequency, can take into account the salinity and provides a good fit to the experimental data. Indeed, based on polar theory, Debye [7] gives the permittivity $\varepsilon(\varepsilon = \varepsilon' - i\varepsilon'')$ of the distilled water by the well-know expression.

$$\varepsilon = \varepsilon_\infty + \frac{\varepsilon_s - \varepsilon_\infty}{1 + j\omega\tau} \tag{8}$$

where τ is the relaxation time and ω is the circular frequency ($\omega = 2\pi f$). In the case of a saline solution, the complex permittivity is given by

$$\varepsilon = \varepsilon_\infty + \frac{\varepsilon_s - \varepsilon_\infty}{1 + (j\omega\tau)^{1-\alpha}} - j\frac{\sigma}{\omega\varepsilon_0} \tag{9}$$

where ε_0 is the vacuum electric permittivity, and σ is the ionic conductivity. This variable can be determined from the salinity and the temperature of the salt water [7]. Finally, a non-polluted sea surface can be described as a dielectric random rough interface where every parameters are known.

3. POLLUTED SEA SURFACE

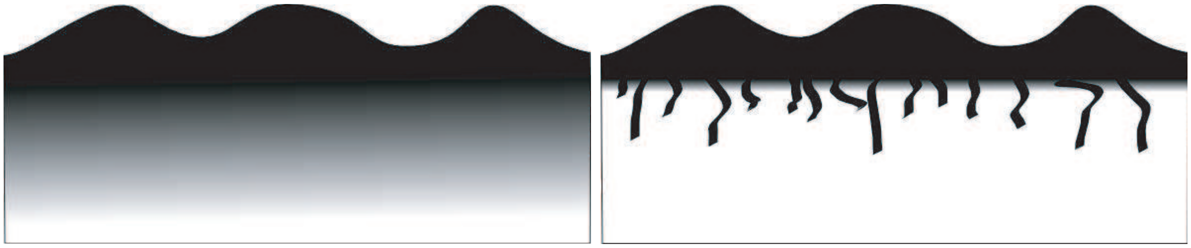
With the presence of pollutant, oil for example, mechanical properties (viscosity, tension surface, ...) of the sea surface is modified and a new roughness spectrum must take into account. Letting $S_n(K)$ and $S_p(k)$, respectively, denote the non-polluted and the polluted surface spectrum, we can define a damping ratio $y(K)$ as follows:

$$y(K) = \frac{S_n(K)}{S_p(K)} \tag{10}$$

where K is the spatial wave number of the sea wave.

In low or moderate wind conditions (wind speed at 10 meters height $U_{10} < 10\,\mathrm{m/s}$), the pollutant often forms a film spreading on the ocean surface. The physicochemical-hydrodynamics theory applied in the present study can model the damping effect. Actually, this theory distinguishes two different cases: a soluble and an insoluble pollutant.

As shown in Figure 2, the film of a soluble pollutant on the sea surface induces a continuous concentration gradient interface. And, in the a similar way, an insoluble pollutant induces random precipitations on contact with sea water. In both cases, the notion of pollutant layer could lead to physical model difficulties. To avoid these difficulties, we assume, in our electromagnetic study, that the pollutant layer can be approximated by a homogeneous half-space (permittivity of the pollutant) with a rough interface whose the roughness spectrum is given by the physicochemical-hydrodynamics theory [8]. In the present paper, the pollutant is supposed to be an insoluble oil whose relative permittivity is equal to 5.



(a) Concentration gradient layer

(b) Homogeneous layer with precipitations

Figure 2: Schematic presentation for two types of pollutant layers: (a) Soluble pollutant, (b) Insoluble pollutant.

For insoluble surface films, it is assumed that thermodynamic equilibrium exists within the subsurface. Below the subsurface, however, the process of precipitation is assimilate to a diffusion one characterized by a diffusional frequency ω_D. The characterization of pollutant mechanical properties can be reduced to the elasticity modulus E_0. Then, the damping ratio in this case can be expressed as follows [8]:

$$y(K) = \frac{1 - 2\tau + 2\tau^2 - X_0 + Y_0(X_0 + \tau)}{1 - 2\tau + 2\tau^2 - 2X_0 + 2X_0^2} \tag{11}$$

with

$$X_0 = \frac{E_0 K^2}{\rho_\omega \sqrt{2\nu_\omega \omega^3}} \qquad Y_0 = \frac{E_0 K}{4\rho_\omega \nu_\omega \omega} \qquad \omega = \sqrt{\zeta_\omega K^3/\rho_\omega + Gk} \qquad \tau = \sqrt{\frac{\omega_D}{2\omega}} \tag{12}$$

where ρ_ω, ν_ω and ζ_ω are respectively the sea water density, the kinematic viscosity of the sea water and the surface tension of the sea surface.

Finally with any given weather conditions, we can evaluated the roughness spectra of both a non-polluted sea surface and the corresponding surface polluted by an insoluble oil.

4. NUMERICAL ESTIMATION OF THE SCATTERED FIELD

Assuming the statistical roughness spectrum as known, the electromagnetic scattering by a dielectric random rough surface can be estimated using an asymptotic approach like Small Perturbation Method, Two scale model or Small Slope Approximation. And then, the influence of the pollutant upon the electromagnetic scattered field can be studied [9, 10]. However, the asymptotic approaches only provide the mean value of the scattered field for a given geometrical configuration. For instance, the standard deviation of the scattering remains undetermined and the detectability of the pollutant from the electromagnetic field is difficult to quantify.

In the present study, the scattering from a given rough surface (deterministic surface) is computed using a numerical algorithm based on the Method of Moment. More precisely, we apply an efficient Method of Moments (MoM) called the Forward-Backward method (FB-MOM). In its original formulation [11], the Forward-Backward method only applies to scattering from perfectly conducting surfaces. It is true that Holliday and et al. [12] introduced a more generalized algorithm that can treat imperfect conductors. However it is to be noted that this generalization assumes that the imaginary part of the complex permittivity is large. This assumption could be valid for non-polluted sea but this assumption is not applicable for pollutants like oil. More recently, Iodice [13] presented a modified version that can take into account the dielectric properties of the sea water and the pollutants.

The sea surface, denoted S, is assimilated to a one dimension height profile in the form $z = f(x)$ constant along the y direction. If the incident field is horizontally polarized $\vec{E}^{inc} = E^{inc}\hat{y}$, the electric field $\vec{E} = E\hat{y}$ above the rough surface is given by the following integral equations:

$$E(\vec{r}) = \frac{1}{2} + \int_S j\omega\mu_0 G_0(\vec{r}, \vec{r}')J_S(\vec{r}') + E(\vec{r}') \cdot [\hat{n} \cdot \nabla G_0(\vec{r}, \vec{r}')]d\vec{r}' \tag{13a}$$

$$0 = \frac{1}{2} - \int_S j\omega\mu_0 G_1(\vec{r}, \vec{r}')J_S(\vec{r}') + E(\vec{r}') \cdot [\hat{n} \cdot \nabla G_1(\vec{r}, \vec{r}')]d\vec{r}' \tag{13b}$$

where J is the electric surface current density, $\hat{n}$ is the outgoing normal to the surface and G_0 (resp. G_1) is the two dimensional Green function above the surface (resp. beneath the surface). By using rectangular pulse basis functions and the point matching method, the previous integral equations can be expressed in the form $2N \times 2N$ linear equation:

$$\begin{aligned} S_0 E_N + Z_0 J_N &= E_N^{inc} \\ S_1 E_N + Z_1 J_N &= 0 \end{aligned} \tag{14}$$

where S_0, S_1, Z_0 and Z_1 are $N \times N$ matrix. E_N and J_n are N dimensional vectors that contain the unknowns of the discretized problem. To avoid the use of time-consuming algorithms to solve this linear system, we split the electrical field and the current density in two "Forward" and "Backward" components in the same way that original Forward-Backward theory [11]:

$$E_N = E_N^f + E_N^b \qquad J_N = J_N^f + J_N^b \tag{15}$$

Letting

$$\begin{aligned} S_0 &= S_0^L + S_0^D + S_0^U & S_1 &= S_1^L + S_1^D + S_1^U \\ Z_0 &= Z_0^L + Z_0^D + Z_0^U & Z_1 &= Z_1^L + Z_1^D + Z_1^U \end{aligned} \tag{16}$$

where L, D and U respectively denote the lower part, the diagonal part and the upper part of the matrix, the linear system (14) can be decomposed into forward-propagation and backward-propagation pairs of equations:

$$\begin{aligned} S_0^D E_N^f + Z_0^D J_N^f &= E_N^{inc} - S_0^L(E_N^f + E_N^b) - Z_0^L(J_N^f + J_N^b) \\ S_1^D E_N^f + Z_1^D J_N^f &= -S_1^L(E_N^f + E_N^b) - Z_1^L(J_N^f + J_N^b) \\ S_0^D E_N^f + Z_0^D J_N^f &= -S_0^U(E_N^f + E_N^b) - Z_0^U(J_N^f + J_N^b) \\ S_1^D E_N^f + Z_1^D J_N^f &= -S_1^U(E_N^f + E_N^b) - Z_1^U(J_N^f + J_N^b) \end{aligned} \tag{17}$$

Iodice [13] show that this new linear system can be solved using a very efficient iterative algorithm ($O(N^2)$). In the case of a vertically polarized incident field, a similar method can be applied using the magnetic field.

Finally, this Forward-Backward theory can efficiently compute the electromagnetic field scattered by a given non-polluted or polluted sea surface.

5. OBSERVABILITY ANALYSIS

To realize a statistical comparison between the polluted surfaces and the non-polluted ones, we use a Monte Carlo approach and we compute the scattering from a great number of equivalent rough surfaces associated with the same sea spectrum. The convolution of a spectrum with an unitary white Gaussian random signal generates a one-dimensional profile (one realization) that represents an ocean surface for given weather conditions, see Figure 3. For fixed weather conditions and pollutant mechanical properties, the polluted and non-polluted sea spectra induce two different rough surface with the same unitary white Gaussian random signal. So, using many random signal sequences and the Forward-Backward computation of the scattering by each realization, we can estimate the statistical parameters (mean value, standard deviation, ...) of the scattered field in both polluted and non-polluted case. These parameters are functions of the incident angle θ.

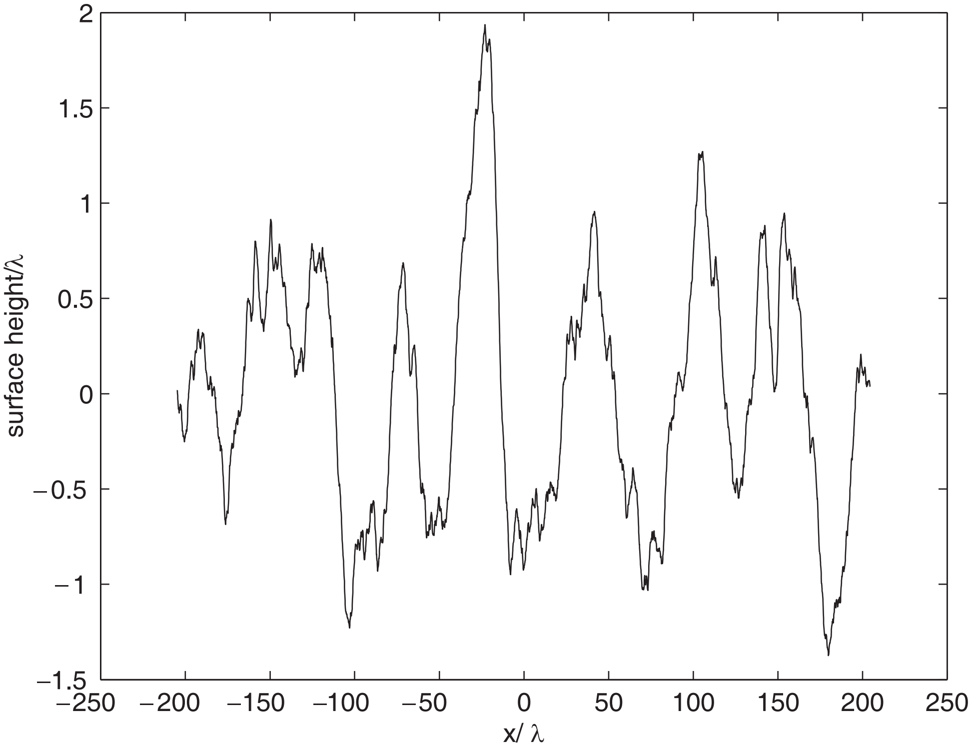


Figure 3: Realization of an ocean surface.

From a statistical viewpoint, the detectability of the pollutant become the evaluation of the similarity between two data sets. To quantify this similarity we introduce a t-value expression T (t-test) [14]:

$$T(\theta) = \frac{m_p(\theta) - m_n(\theta)}{\sigma(\theta)} \qquad \sigma(\theta) = \sqrt{[\sigma_p^2(\theta) + \sigma_n^2(\theta)]/n} \tag{18}$$

where m_p and σ_p (resp. m_n and σ_n) are the mean value and the standard deviation of the scattering by a polluted (resp. non-polluted) surface. n is the number of realizations.

6. CONCLUSION

The methodology presented is this paper enables to quantify the detectability of a pollution on an ocean surface independently of the radar signal processing. Our approach can be applied to optimize the bistatic configuration (angle of incidence) to detect a pollutant for given weather conditions.

REFERENCES

1. Franceschetti, G., A. Iodice, D. Riccio, G. Ruello, and R. Siviero, "SAR raw signal simulation of oil slicks in ocean environments," *IEEE Trans. Geoscience Remote Sensing*, Vol. 40, No. 9, 1935–1949, 2002.
2. Bertacca, M., F. Berizzi, and E. D. Mese, "A FARIMA-based technique for oil slick and low-wind areas discrimination in sea SAR imagery," *IEEE Trans. Geoscience Remote Sensing*, Vol. 43, No. 11, 2484–2493, 2005.
3. Migliaccio, M., A. Gambardella, and M. Tranfaglia, "SAR polarimetry to observe oil spills," *IEEE Trans. Geoscience Remote Sensing*, Vol. 45, No. 2, 506–511, 2007.
4. Pierson, W. and L. Moskovitz, "A proposed spectral form for fully developed wind sea based on the similarity theory of s. a. kitaigorodskii," *J. Geophys. Res.*, Vol. 69, 5181–5190, 1964.
5. Pierson, W., "The theory and applications of ocean wave measuring systems at and below the sea surface, on land, from aircraft and from spacecraft," *NASA Tech. Rep.*, 1991.
6. Elfouhaily, T., B. Chapron, K. Katsaros, and D. Vandemark, "A unified directional spectrum for long and short wind-driven waves," *Journal of Geophysical Research*, Vol. 102, No. C7, 15781–15796, 1997.
7. Debye, P., Polar Molecules, Chemical Catalog Company, NewYork, 1929.
8. Fiscella, B., P. P. Lombardini, and P. Trivero, "Ripple damping on water surface covered by a spreading film: Theory and experiment, *Il Nuovo Cimento*, Vol. 8C, No. 5, 491–500, 1985.
9. Ayari, M. Y., A. Coatanhay, and A. Khenchaf, "The influence of ripple damping on electromagnetic bistatic scattering by sea surface," *IGARSS*, Seoul, Korea, July 25–29, 2005.
10. Coatanhay, A., M. Y. Ayari, and A. Khenchaf, "Oil slick effect on electromagnetic bistatic scattering from the ocean surface in low/moderate wind conditions," (submitted).
11. Holliday, D., L. L. DeRaad, and G. C. St-Cyr, "Forward-backward: A new method for computing low-grazing angle scattering," *IEEE Trans. Antennas Propagat.*, Vol. 44, No. 5, 722–729, 1996.
12. Holliday, D., L. L. DeRaad, and G. C. St-Cyr, "Forward-backward method for scattering from imperfect conductors," *IEEE Trans. Antennas Propagat.*, Vol. 46, No. 1, 101–107, 1998.
13. Iodice, A., "Forward-backward method for scattering from dielectric rough surfaces," *IEEE Trans. Antennas Propagat.*, Vol. 50, No. 7, 901–911, 2002.
14. Press, W. H., S. A. Teukolsky, W. T. Vetterling, and B. P. Flannery, *Numerical Recipes in C: The Art of Scientific Computing*, Cambridge University Press, 2007.