A STUDY OF RADAR CROSS SECTION MODELS FOR THE OCEAN SURFACE BISTATIC SCATTERING APPLIED TO HFSWR RADARS

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Abstract-In this paper, we propose to compare Radar Cross Section (RCS) estimated by different models (Gill’s model, SPM, TSCM) for a sea scattering surface. To use RCS estimator, we need to characterize geometrically and physically a sea surface. To characterize geometrically sea surface, we interest to height spectrum or/slope probability. To model height spectrum, we use Elfouhaily spectrum. To model slope probability, we use Cox and Munk probability. To characterize physically sea surface, we interest to electrical permittivity and magnetic permeability. To model electrical permittivity, we use Debye model. Magnetic permeability of a sea surface is equal to vacuum magnetic permeability. We compare RCS estimated by these models in function of emission wave frequency, bistatic angle or wind direction.

I. INTRODUCTION

Radar are often used to control and survey sea surface. To cover a large distance, emission frequency should be in HF or VHF band because in this frequency band, electromagnetic waves follow earth curve while radars with emission frequency greater than this frequency band follow a straight line. Two problems limit the use of these radars. The first one is antenna dimension in this frequency band. It was solved by application of Meander Line Antenna (MLA) technology [5]. The second one is influence of ionosphere and sea clutter on this type of radar. To detect and identify a target thanks to radars, Radar Cross Section (RCS) must be visualised. In this paper, we interest about RCS of sea clutter. RCS estimators are grouped in two categories: exact methods and approximate methods (Kirchhoff Approximation, Small Perturbation Model …) don’t take account the movement of sea by make the approximation of a static sea [1, 2, 3, 14, 15]. Unfortunately, the movement of sea provokes the Crombie phenomenon (observed by Crombie in 1955). Barrick’s implemented a monostatic (emitter and receptor of radar are at the same place) model of radar cross section based on Crombie’s observation. Gill [9, 10, and 11] extended this model to bistatic configuration (Fig. 1).

II. SEA SURFACE CHARACTERIZATION

The use of models to estimate RCS of sea surface need physical and geometric knowledge about sea surface.

A. Physical Characterization

To characterize physically a sea surface, we interest to electrical permittivity ε and magnetic permeability μ. Sea magnetic permeability is equivalent to vacuum magnetic permeability μ0. Sea electrical permittivity depends on sea temperature, sea salinity and emission wave frequency (Fig.2).
To model electrical permittivity $\varepsilon$, we employ Debye model [18]:

$$\varepsilon = \varepsilon_0 + \frac{\varepsilon_s - \varepsilon_0 - j \frac{s}{\omega \varepsilon_0}}{1 + j \frac{\omega \tau}{\varepsilon_0}}$$  \hspace{1cm} (1)

$$\varepsilon = \varepsilon_0 \varepsilon_r$$  \hspace{1cm} (2)

Where $\varepsilon_0$ is vacuum electrical permittivity, $\varepsilon_\infty$ is high frequency electrical permittivity, $\varepsilon_s$ is static permittivity, $\tau$ is relaxation time and $s$ is ionic conductivity. Static permittivity, relaxation time and ionic conductivity depend on emission wave frequency, temperature and salinity.

In figure Fig. 2, we notice that a diminution of incident wave frequency causes an augmentation electrical permittivity. An augmentation of temperature provokes a diminution of electrical permittivity. An augmentation of permittivity causes an augmentation of electrical permittivity.

B. Geometrical Characterization

To characterize geometrically a sea surface, we interest to slope probability or to height spectrum. Height spectrum is the Fourier transform of autocorrelation function of surface height. To model slope probability, we choose Cox and Munk probability [6, 7, 13, and 16] because it considers the asymmetry of sea surface (figure 3).

Height spectrum is defined by:

$$S(K, \phi) = S(K) f(K, \phi)$$  \hspace{1cm} (3)

$S(K)$ is the isotropic spectrum (Fig.4).

K is the surface wave number. $f(K, \phi)$ (Fig. 5) is the spread function and $\phi$ is the gap between wind direction and observation direction.

To model Height spectrum, we choose Elfouhaily Spectrum [8, 17] because it is a unified model which depends on wind velocity. In figure 4, we observe that the augmentation of wind speed provokes the augmentation of gravity waves but it doesn’t affect capillarity waves. To consider wind direction, we add spread function with height spectrum. To model spread function, we use Elfouhaily spread function [8, 17].

Spread function shows us that height waves are smallest if observation direction is perpendicular to wind direction and spread function does not react the same way with wind speed for low, medium or high wave number.
III. RCS ESTIMATORS

To model RCS of the sea, we employ approximated models. Among approximate models we concentrate on Gill’s model, Small Perturbation Model and Two Scale Model.

A. Gill’s model

In HF band, Gill’s model is often quoted [9, 10, 11 and 19]. Gill’s model is an extension of the well-known Barrick’s model to bistatic case. Barrick implemented RCS in vertical polarisation for sea surface based on Walsh approximation (Fig. 6).

Gill distinguishes 4 cases of reflection: simple reflection, double reflection to emitter, double reflection to receptor and double reflection to the surface (figure 7).

Gill expresses RCS of sea surface as:

\[
\sigma_g(\omega_0) = 2^\pi \pi^2 k^4 \cos \phi_0 \sum_{m=1}^{\infty} \sum_{m=1}^{\infty} \int \int S[m, \frac{k}{g}] S[m, \frac{k}{g}] \, \Delta \phi \, S[X] \left[ \frac{\Delta \phi}{2} \left( \frac{K}{\cos \phi_0} - 2k \right) \right]
\]  

(4)

Where g is gravity acceleration, \( \Delta \phi \) is the patch of the surface, \( \phi_0 \) is bistatic angle, \( S[X] \) is sinus cardinal of X.

For double reflection to emitter, he expresses RCS:

\[
\sigma_{g_e}(\omega_0) = 2^\pi \pi^2 k^4 \cos \phi_0 \sum_{m=1}^{\infty} \sum_{m=1}^{\infty} \int \int S[m, \frac{k}{g}] S[m, \frac{k}{g}] \, \left| \frac{k}{g} \int D(\omega_0 - D(Y_\tau)) \, g^{-1/2} Y_\tau \, dD \, d\theta \right|
\]

(5)

Where:

\[
D(Y_\tau) = \sqrt{m_1 Y_\tau + m_2 \sqrt{K_1}}
\]

\( \Gamma_e \) is hydrodynamic coefficient for double reflection to emitter.

For double reflection to receptor, he expresses RCS:

\[
\sigma_{g_r}(\omega_0) = 2^\pi \pi^2 k^4 \cos \phi_0 \sum_{m=1}^{\infty} \sum_{m=1}^{\infty} \int \int S[m, \frac{k}{g}] S[m, \frac{k}{g}] \, \left| \frac{k}{g} \int D(\omega_0 + m_1 \sqrt{K_1} + m_2 \sqrt{K_2}) \, dD \, d\theta \right|
\]

(7)

\( \Gamma_r \) is hydrodynamic coefficient for double reflection to receptor.

For double reflection to the surface, he expresses RCS:

\[
\sigma_{g_s}(\omega_0) = 2^\pi \pi^2 k^4 \cos \phi_0 \sum_{m=1}^{\infty} \sum_{m=1}^{\infty} \int \int S[m, \frac{k}{g}] S[m, \frac{k}{g}] \, \left| \frac{k}{g} \int D(\omega_0 + m_1 \sqrt{K_1} + m_2 \sqrt{K_2}) \, dD \, d\theta \right|
\]

(8)

\( \Gamma_s \) is hydrodynamic coefficient for double reflection to the surface.

The total RCS of the surface is:

\[
\sigma(\omega_0) = \sigma_g(\omega_0) + \sigma_{g_e}(\omega_0) + \sigma_{g_r}(\omega_0) + \sigma_{g_s}(\omega_0)
\]

(9)

This model express a bistatic RCS in vertical polarisation for sea surface. To obtain RCS only with bistatic angle, we integrate RCS on Doppler pulsation. It is valid for grazing angles and electrical permittivity tending to infinity.

B. Kirchhoff Approximation (KA)

Kirchhoff Approximation [3, 14 and 15] is based on the hypothesis that a surface can be assimilating by its tangent. RCS is estimated by:

\[
\sigma_{pq} = \frac{\pi k^2 \eta^2}{q^2} \left| U_{pq} \right|^2 \text{Prob}(Z_x, Z_y)
\]

(10)

Where \( U_{pq} \) are polarisation coefficients (which depend of angles and electrical permittivity of the surface), \( \text{Prob}(Z_x, Z_y) \)
is slope probability, and \( q = \vec{n}_x - \vec{n}_j = q_x \vec{x} + q_y \vec{y} + q_z \vec{z} \). This model is valid for \( kL > 6 \), \( kL > 4\sqrt{2}k\sigma \) and \( k\sigma > \sqrt{10}\cos\theta + \cos\theta \) with \( \sigma \) is height standard deviation, \( L \) is correlation length. KA is applied on high rough surface.

C. Small Perturbation Model (SPM)

Small Perturbation Model [3, 14 and 15] is based on the hypothesis that a natural surface can be expressed by a Fourier series because it is both periodic and random. RCS is expressed as:

\[
\sigma_{pq} = 8k^3 |\cos\theta| \cos\theta \alpha_{pq} I(k_x, k_y) \tag{12}
\]

Where \( k \) is the wave number of incident wave, \( \alpha_{pq} \) are polarisation coefficient (which depend on angles and electrical permittivity of the surface), \( S \) is height spectrum of the surface and \( k_x, k_y \) are defined by:

\[
\begin{align*}
  k_x &= -k \sin \theta \cos \phi + k \sin \theta \cos \phi \\
  k_y &= -k \sin \theta \sin \phi + k \sin \theta \sin \phi
\end{align*}
\]

This model is valid for \( k\sigma < 0.3 \) and \( m < 0.3 \) with \( \sigma \) is height standard deviation, \( m \) is slope standard deviation.

SPM is applied on low rough surface. To consider sea surfaces with high roughness or low roughness, we can use hybrid models like Two Scale Model.

D. Two Scale Composite Model (TSCM)

Two Scale Composite Model [14, 15] is a combination of Kirchhoff Approximation and Small Perturbation Model. It consists to consider that a surface has two roughness levels: high roughness and low roughness (Fig. 8).

Diffuse component of RCS is expressed as:

\[
\sigma_{p_q}^d = \frac{4\pi^2}{A^3} \left( \frac{E_{inc}}{E_{ref}} \right)^3
\]

\[
\begin{align*}
  &= \left( [p_x^2] [q_w] \right) \sigma_{p_q}^d + \left( [q_w^2] [q_w] \right) \sigma_{p_q}^d + \left( [p_w^2] [q_w] \right) \sigma_{p_q}^d \\
  &+ \left( [q_w^2] [q_w] \right) \sigma_{p_q}^d + \left( [p_w^2] [q_w] \right) \sigma_{p_q}^d + \left( [q_w^2] [q_w] \right) \sigma_{p_q}^d \\
  &= \left( [p_x^2] [q_w] \right) \sigma_{p_q}^d + \left( [q_w^2] [q_w] \right) \sigma_{p_q}^d + \left( [p_w^2] [q_w] \right) \sigma_{p_q}^d \\
  &+ \left( [q_w^2] [q_w] \right) \sigma_{p_q}^d + \left( [p_w^2] [q_w] \right) \sigma_{p_q}^d + \left( [q_w^2] [q_w] \right) \sigma_{p_q}^d \\
  &= \left( [p_x^2] [q_w] \right) \sigma_{p_q}^d + \left( [q_w^2] [q_w] \right) \sigma_{p_q}^d + \left( [p_w^2] [q_w] \right) \sigma_{p_q}^d \\
  &+ \left( [q_w^2] [q_w] \right) \sigma_{p_q}^d + \left( [p_w^2] [q_w] \right) \sigma_{p_q}^d + \left( [q_w^2] [q_w] \right) \sigma_{p_q}^d
\end{align*}
\]

Where \( p \) and \( q \) are the polarisation, and

\[
\sigma_{p_q}^d = \frac{4\pi^2}{A^3} \left( \frac{E_{inc}}{E_{ref}} \right)^3
\]

\[
\begin{align*}
  &= \left( [p_x^2] [q_w] \right) \sigma_{p_q}^d + \left( [q_w^2] [q_w] \right) \sigma_{p_q}^d + \left( [p_w^2] [q_w] \right) \sigma_{p_q}^d \\
  &+ \left( [q_w^2] [q_w] \right) \sigma_{p_q}^d + \left( [p_w^2] [q_w] \right) \sigma_{p_q}^d + \left( [q_w^2] [q_w] \right) \sigma_{p_q}^d \\
  &= \left( [p_x^2] [q_w] \right) \sigma_{p_q}^d + \left( [q_w^2] [q_w] \right) \sigma_{p_q}^d + \left( [p_w^2] [q_w] \right) \sigma_{p_q}^d \\
  &+ \left( [q_w^2] [q_w] \right) \sigma_{p_q}^d + \left( [p_w^2] [q_w] \right) \sigma_{p_q}^d + \left( [q_w^2] [q_w] \right) \sigma_{p_q}^d
\end{align*}
\]

RCS estimated by Two Scale Composite Model is the addition of diffuse component and Kirchhoff model:

\[
\sigma_{pq} = \sigma_{pq}^d + \sigma_{pq}^k
\]

Where \( \sigma_{pq}^k \) is estimated by Kirchhoff Approximation.

IV. SIMULATIONS

In these simulations, we observe the variation of RCS in dB in vertical polarisation estimated by several models function of frequency of emitting wave, bistatic angles, and wind speed and wind direction. Gill’s model is valid for grazing angles. Gill’s model estimate RCS for vertical polarisation.

Angles are related by:

\[
\cos(2\phi_o) = -\sin\theta \sin\theta \cos(\phi_o - \phi) + \cos\theta \cos\theta
\]

These simulations are made for monostatic configuration and bistatic configuration. Sea temperature is 20° and sea salinity is 35 ppm.

A. Monostatic Configuration

Monostatic configuration appears when emitter and receptor are co-localised. For this configuration, bistatic angle \( \phi_0 \) is null, \( \theta_o = \theta = 88° \), \( \phi_o = 0° \) and \( \phi_o = 180° \). Figure Fig. 9(a) was implemented by SPM for this configuration by Guedon [12]. He shows us that in vertical polarisation, for frequencies
greater than 10 MHz, RCS estimated for different wind speed tend to the same value. For wind speed less than 10 MHz, more wind speed is high; more RCS estimated by SPM is high value.

To obtain figures Fig. 9(b), Fig. 9(c) and Fig. 9(d), we fixed wind direction to 0°. We varied emission wave frequency from 3 MHz to 30 MHz. In figures Fig. 9(b), Fig. 9(c) and Fig. 9(d), we observe that Gill’s model converges to SPM and TSCM when frequency grows. RCS estimated by Gill’s model and SPM are nearest of Guedon’s results than TSCM. For a wind speed of 5 m/s, RCS estimated by SPM varies hardly and TSCM decreases slowly in function of frequency from 10 MHz. Until 10 MHz, RCS estimated by SPM and TSCM increase when frequency increases. RCS estimated by Gill’s model increases when frequency increases until and from 10 MHz. In figure Fig. 9(c) and Fig. 9(d), RCS estimated by SPM are constants. In these figures, SPM is constant while RCS estimated by TSCM decreases and RCS estimated by Gill increases when frequency increases. For low emission wave frequencies (less than 10 MHz), more wind speed is high; more RCS estimated by these models is high value. For high emission wave frequencies, RCS varies little in function of wind speed.

When the radar is near of surface normal, RCS in vertical polarisation is the same for emission wave frequency of 10 MHz or 100 MHz. In figures Fig. 10(a) and Fig. 10(b), we notice that the gap between RCS, in vertical polarisation estimated for emission wave frequency of 10 MHz or 100 MHz, becomes greater when radars approaches the surface (or when the angle becomes grazing). In figure Fig. 10(b), we compare RCS in vertical polarisation for emission wave frequency of 10 MHz and 100 MHz estimated by SPM and TSCM. When angle become grazing, the gap between RCS for emission wave frequency of 10 MHz and 100 MHz increases. The gap between RCS estimated by SPM and TSCM become high when angle become grazing. RCS estimated SPM is nearest of Barrick’s results than TSCM.

To obtain figure Fig. 11, we fixed emission wave frequency to 25 MHz and we vary wind direction. In monostatic configuration, RSC estimated by TSCM and SPM evolute the same way and the gap between RCS estimated by these models is constant. RCS estimated by Gill’s model evolutes between RCS estimated by SPM and TSCM.
B. Bistatic Configuration

Bistatic configuration is the general configuration of radar link.

We study the evolution of RCS in function of bistatic angles (figure 12).

![Figure 12: Comparison between RCS estimated by Gill’s model, SPM and TSCM in function of bistatic angle](image)

We choose an emission wave frequency of 25 MHz, \( \theta_s = \theta_i = 85^\circ, \phi_i = 0^\circ \). This configuration is the same for figures Fig. 13 and Fig. 14.

We notice that these models evolve the same way. When the bistatic angles grows the gap between models reduce until \( \phi_i = 88^\circ \). From this value, TSCM diverge. In function of frequency, the different models have the same way. As we see for monostatic configuration, the gap between models reduces when frequency grows.

![Figure 13: RCS in function of frequency](image)

![Figure 14: RCS in function of wind direction](image)

In figure Fig. 14, we observe that in function of wind direction, when bistatic angle is not null, RCS estimated by Gill’s model evolves between RCS estimated by SPM and TSCM.

V. CONCLUSION

In this paper, we described RCS estimated by Gill’s model, SPM and TSCM for a sea surface model by Elfouhaily spectrum and/or Cox and Munk Probability slope. To characterize physically the sea, we interested to electrical permittivity and magnetic permeability. We consider sea magnetic permeability equal to vacuum magnetic permeability and we use Debye model to model sea electrical permittivity. We compare RCS models in vertical polarisation. We conclude that in function of frequency or bistatic angle, these models are equivalent. A perspective is to create a version of TSM varying function of Doppler frequency.

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