

Simulation of GALILEO signals in a maritime environment using an electromagnetic scattering model: influence of the sea state

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Abstract—This paper deals with a simulation of GALILEO signals that takes into account the electromagnetic scattering by the sea surface. This scattering by the sea, considered as a rough surface, is estimated with a Two Scale Model (TSM) approximation. More, the geometric description of the sea surface is given by a realistic spectrum (Elfouhaily spectrum) and a slope probability density function (Cox-Munk distribution). Finally, we focus on the influence of the weather and sea condition upon the GALILEO signal.

I. INTRODUCTION

Due to economic (sea transport management) or safety (search and rescue) reasons, the satellite positioning is of the most importance in a maritime context. More, in some circumstances, as coastal or inshore navigation for instance, the accuracy and the reliability of the positioning become the key points. With this aim in mind, the coming soon GALILEO system has been designed to take up these challenging subjects. Nevertheless, the reception of positioning signals in a maritime environment can be smeared by the electromagnetic scattering from the sea surface. That is why the evaluation of the robustness of a GALILEO device in various sea conditions requires realistic simulations for GALILEO signal receiver above the sea.

The GALILEO signals can be schematically considered as a modulation of the carrier wave emitted by different satellites in L band. In this paper, we estimate the GALILEO in maritime environment using an electromagnetic simulation of the interaction between the L-band wave and the sea surface. More precisely, the sea surface is modeled by a random rough surface, described by a realistic sea spectrum (Elfouhaily spectrum) and a slope probability density function (Cox-Munk distribution). Then, the electromagnetic scattering by the sea surface is computed with a Two Scale Model (TSM) approximation. Finally, the GALILEO signal received above the sea surface is obtained using an adapted ray tracing approach.

This computation can provide a simulation of the GALILEO signals in maritime environment as a function of various at-

mospheric parameters. The purpose of our study is to evaluate the influence of these parameters (wind speed, wind direction,?) on the GALILEO signal reception.

II. PHYSICAL MODELS

A. Sea surface description

First and foremost, a valuable simulation of GALILEO signals above the sea involves a realistic description of the sea surface roughness. And, this description must be a function of wind speed and direction. The most standard ways to characterize the roughness are the spectrum and slope probability density function.

1) *Sea slopes distribution*: The $Z_{\vec{r}}$ sea slope at a position, denoted by \vec{r} , on the surface is given by:

$$Z_{\vec{r}} = \frac{z(\vec{r} + \Delta\vec{r}) - z(\vec{r})}{\Delta\vec{r}} \quad (1)$$

where z is the height coordinate. The sea surface, considered as a random process, is determined by the slope probability density $P(Z_x, Z_y)$. Although basic forms of probability density functions (gaussian expressions for example) could be used for a coarse description, a more sophisticated model is required for realistic simulations.

Based on the analysis of sun glitter photographs, Cox and Munk [1], [2], [3] generated a more reliable semi-empirical slope distribution law. Figure (1) shows the Cox Munk probability function with different wind speed and for upwind and crosswind configuration.

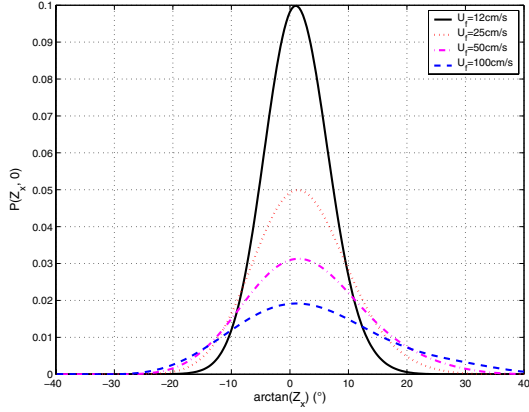
The Cox and Munk slope probability density function is given by:

$$P(Z_x, Z_y) = \frac{F(Z_x, Z_y)}{2\pi\sigma_u\sigma_c} \exp\left[-\frac{1}{2}\left(\frac{z_x^2}{m_u^2} + \frac{z_y^2}{m_c^2}\right)\right] \quad (2)$$

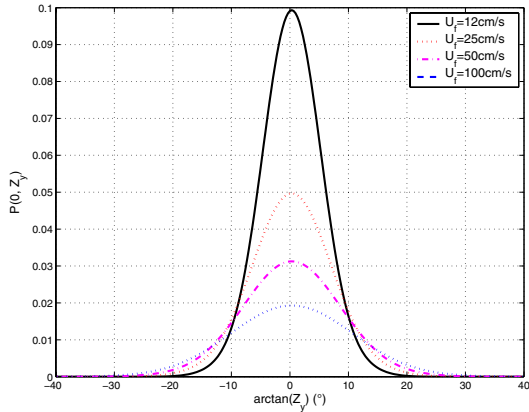
where

$$\begin{aligned}
 F(Z_x, Z_y) = & 1 - \frac{C_{21}}{2} \left[\frac{Z_y^2}{\sigma_c^2 - 1} \right] \frac{Z_x}{\sigma_u} - \\
 & \frac{C_{03}}{6} \left[\frac{Z_x^3}{\sigma_u^3} - 3 \frac{Z_x}{\sigma_u} \right] + \\
 & + \frac{C_{40}}{24} \left[\frac{Z_y^4}{\sigma_c^4} - 6 \frac{Z_y^2}{\sigma_c^2} + 3 \right] + \\
 & \frac{C_{22}}{4} \left[\frac{Z_y^2}{\sigma_c^2 - 1} \right] \left[\frac{Z_x^2}{\sigma_u^2 - 1} \right] + \frac{C_{04}}{24} \left[\frac{Z_x^4}{\sigma_u^4} - 6 \frac{Z_x^2}{\sigma_u^2} + 3 \right]
 \end{aligned} \quad (3)$$

where σ_u , σ_c , m_u , m_c , C_{21} , C_{03} , C_{40} , C_{22} and C_{04} are parameters that depends on sea characteristics, see [1], [2], [3].



(a) Cox & Munk distribution



(b) Cox & Munk distribution

Fig. 1. (a) upwind distribution and (b) crosswind distribution for different wind speeds (measured at 12.5 meter above the sea)

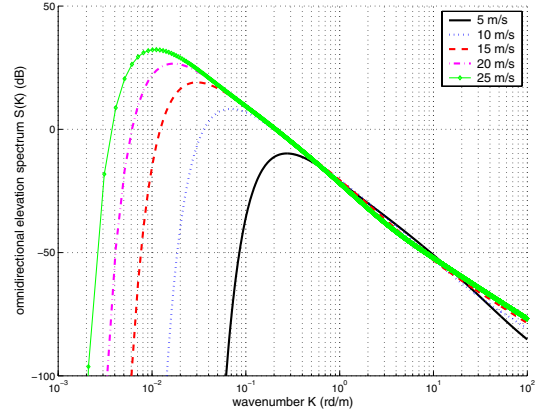
2) *Sea spectrum*: The second standard way to describe the roughness of the sea surface is to determine the sea surface spectrum $S(K, \phi)$, considering the sea surface as a random, ergodic and stationary process. In scientific literature [4], [5],

[6], [7], many papers provides fully detailed description of various sea spectra, see Pierson and Moskowitz studies [8], [9] for instance. In this paper, we considered the Elfouhaily spectrum [10], called unified spectrum, that is very consistent with actual observations and presents no discontinuities at gravity and wind driven waves.

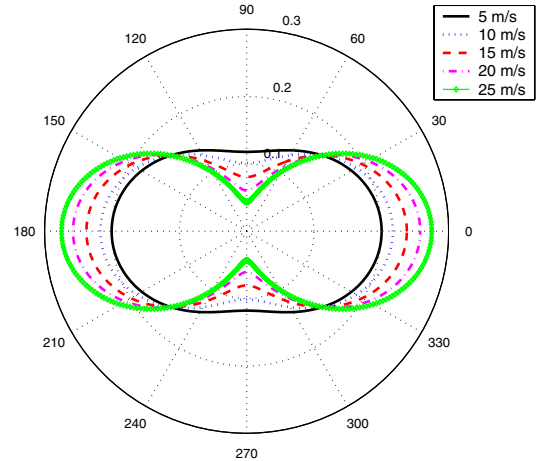
The sea spectrum is in the form:

$$S(K, \phi) = M(K)f(K, \phi) \quad (4)$$

where $M(K)$ 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. Figure (2) illustrates the spectrum behavior of the sea surface with the spatial wave number for different wind speeds.



(a)



(b)

Fig. 2. Elfouhaily sea surface spectra with different wind speeds: a) omnidirectional elevation spectrum and, b) angular function

The both surface representations (slope probability function and sea spectrum) are a key feature when estimating the

electromagnetic sea surface scattering of a GALILEO signal by the sea surface.

B. Electromagnetic scattering

A plane wave impinging a rough surface is scattered in any direction. Indeed, the sea surface "reflection" of the incident wave, coming from the satellite, must be considered as a fully bistatic configuration, see figure (3). For a given E^i

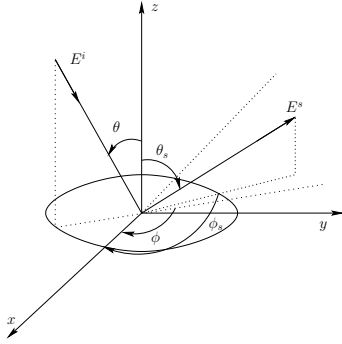


Fig. 3. geometric presentation

incident wave, the S scattering matrix provides the scattered polarization and amplitude of the E^s scattered wave:

$$E^s = \begin{bmatrix} E_{v_r}^s \\ E_{h_r}^s \end{bmatrix} = \begin{bmatrix} S_{v_r v} & S_{v_r h} \\ S_{h_r v} & S_{h_r h} \end{bmatrix} \begin{bmatrix} E_v^i \\ E_h^i \end{bmatrix} \quad (5)$$

$$= [S] E^i$$

Many approaches were developed to evaluate electromagnetic this scattering matrix. In this paper, cited approaches are: Geometrical optics or physical optics methods, called Kirchhoff Approximations (KA) [11], Small Perturbation Method (SPM) [12], [13] and Two-Scale Model (TSM) [14], [15].

1) *Kirchhoff Approximation (KA)*: In few words, KA approach [11] assumes the sea surface can be approximated by a tangent plane at each point of the surface, see figure (4).

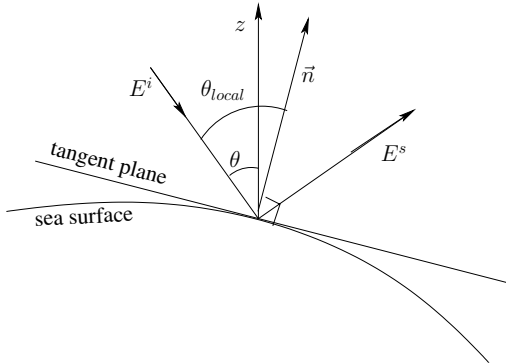


Fig. 4. Geometric optics approximation

The scattered waves is in the form:

$$\vec{E}^s = K \vec{n}_s \wedge \int \{ \vec{n} \wedge \vec{E} - \eta \vec{n}_s \wedge (\vec{n} \wedge \vec{H}) \} e^{jk\vec{r} \cdot (\vec{n}_s - \vec{n}_i)} ds \quad (6)$$

where \vec{n}_s is the unit vector in the scattered direction, \vec{n} is the unit vector normal to the surface, $\eta = \frac{\mu}{\epsilon}$ is the intrinsic

impedance of the medium, \vec{E} is the total electric field and \vec{H} is the magnetic field. Using several assumptions, the scattered waves can be obtained from the slope probability density function of the sea surface (Cox-Munk distribution).

The KA approach is only valid for a surface with an important horizontal roughness scale and average curvature radius compared to the electromagnetic wavelength. This approach is well adapted to the scattering by the gravity waves and to the computation of the specular component.

2) *Small-Perturbation Method (SPM)*: On the contrary, the SPM approach is more adapted to small roughness scales and small sea amplitude. That is the case for wind driven waves. The SPM model fit the experimental data when the phase difference due to height variation, see figure (5), is much smaller than 2π , and the slope is much smaller than unity. The computation of the SPM is based on a spectral description of the sea surface (Elfouhaily spectrum). Actually, the first order

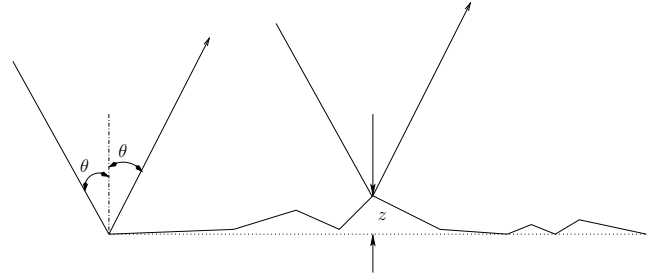


Fig. 5. Surface roughness

SPM approach provides an accurate estimation of the diffuse component (Bragg scattering) of the electromagnetic scattered wave.

3) *Two-Scale Model (TSM)*: The purpose of the TSM approaches is to take advantage of the both KA and SPM validity domains and to manage the both roughness scales (gravity waves and wind driven waves). Quite recently, Khenchaf developed a robust two-scale model [14], [15] that can be applied to determine the direct or cross polarization coefficients in fully bistatic configurations. The figure (6) schematically represents the both roughness scales of the sea.

For small scales, the main point of this approach is to consider the tangent plane related to the gravity waves as a local reference. With this tilting process, the scattering by the wind driven sea waves is estimated with the SPM approach (Elfouhaily spectrum) weighted with probability of the tangent plane slope (Cox-Munk distribution). The specular contribution (computed with KA) added with the integration of these local contributions provides a very reliable Two Scale Model.

Letting E^i be the incident wave. In the local reference, E^i is in the form:

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

where h' and v' are respectively the horizontal and the vertical polarisation vectors in the local reference. Then, the locally

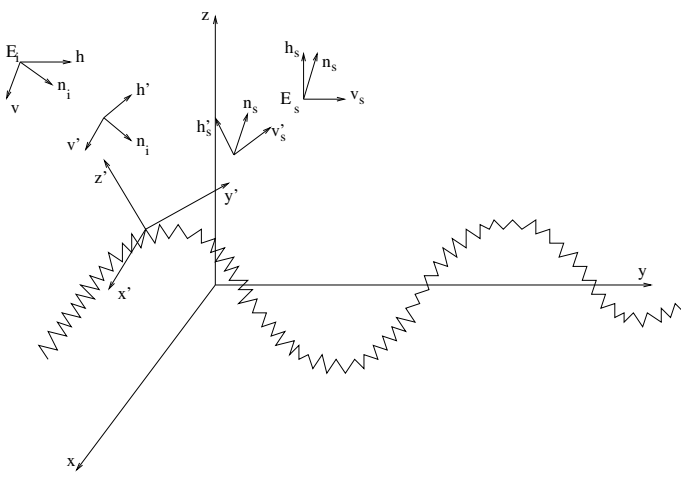


Fig. 6. surface geometry

scattered field due to incident wave is given by:

$$E^s = E_{v'_s v'_s}^s + E_{h'_s h'_s}^s = [S]E^i \quad (8)$$

$$= \begin{bmatrix} S_{v'_s v'_s} E_{v'_s}^i + S_{v'_s h'_s} E_{h'_s}^i \\ S_{h'_s v'_s} E_{v'_s}^i + S_{h'_s h'_s} E_{h'_s}^i \end{bmatrix}$$

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

$$E^s = E_{v'_s a}^s v'_s + E_{h'_s a}^s h'_s = [S]E^i \quad (9)$$

where the scattering matrix is given by

$$E^s = [S]E^i = \begin{bmatrix} v'_s \cdot v_s & h'_s \cdot v_s \\ v'_s \cdot h_s & h'_s \cdot h_s \\ S_{v'_s v'_s} & S_{v'_s h'_s} \\ S_{h'_s v'_s} & S_{h'_s h'_s} \end{bmatrix} \begin{bmatrix} v' \cdot v & h' \cdot v \\ v' \cdot h & h' \cdot h \end{bmatrix} E^i \quad (10)$$

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

$$E_{pq}^s = (v'_s \cdot p) \{ (q \cdot v') S_{v'_s v'_s} + (q \cdot h') S_{v'_s h'_s} \} + (h'_s \cdot p) \{ (q \cdot v') S_{h'_s v'_s} + (q \cdot h') S_{h'_s h'_s} \} E_0 \quad (11)$$

In this way, the scattered field induced by the small scale roughness in the local reference can be computed. So, the integration weight by the slope probability can provide the global scattering coefficients as a function of the transmitter polarization q and the receiver polarization p .

Finally, the TSM approach based on sea surface description (slope probability density function or sea spectrum) allows to estimate the scattering coefficient due to an elementary sea surface, see figure (7), as a function wind direction and wind speed.

C. GALILEO signal simulation

The simulation of the GALILEO signal consists to add the contribution of each elementary sea surface. More, each

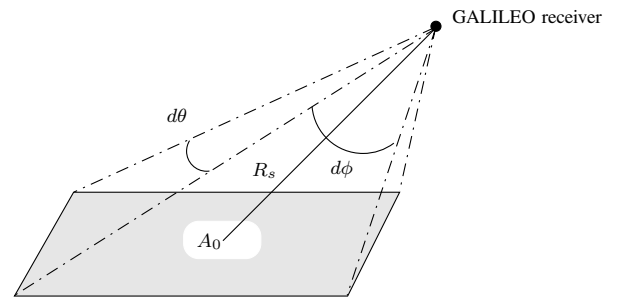


Fig. 7. Elementary sea surface

elementary contribution is associated with a random phase (between 0 and 2π) so that the sum is incoherent.

Nevertheless, this sum must take into account the delay related to each ray (elementary contribution). Therefore, we must add the contributions with the same delay. In the present case, these contributions correspond to sea surfaces in the area limited by intersection of two Fresnel ellipsoids, see figure (8).

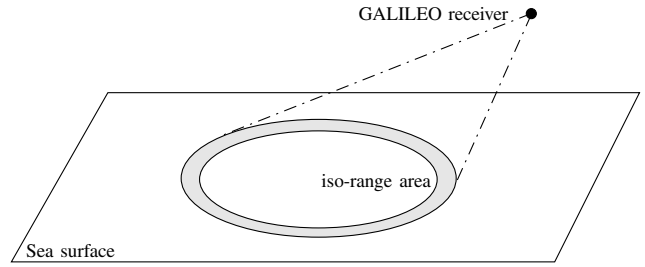


Fig. 8. Elementary iso-range area

Then, these annulus zones, between two iso-range lines, are divided into a great number of angular sectors to obtain elementary surfaces, see figure (9).

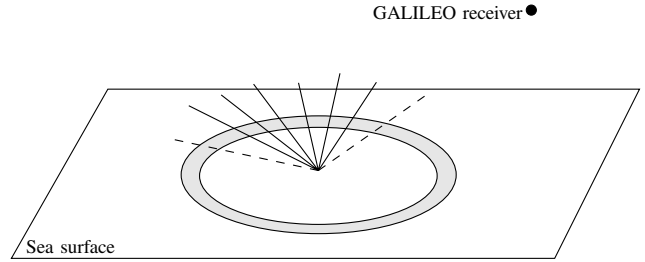


Fig. 9. Angular sections

To compute the scattering coefficients using the TSM approach, the GALILEO signal whose carrier wave is circularly polarized, is split into two linearly polarized waves (horizontal and vertical components). Finally, The figure (10) shows a simulation example of the impulse response of the GALILEO signal for receiver at 50 meters above the sea. The amplitude is related to the amplitude of the direct line of sight signal (no reflection by the sea), and the delay is related to the delay between the direct signal and the specular signal.

III. INFLUENCE OF THE SEA STATE

With the simulation process, we can study the influence of the sea conditions upon the reception of GALILEO signals in a maritime environment. The figure (11) illustrates the modification of the power density distribution (impulse response) when the weather conditions become worse or better. For a quite low coefficient on the Beaufort scale, the sea speculated can be reduced to a quasi specular reflection. But, when the coefficient is higher, the diffuse component is important and the average delay of the scattered signals grows.

IV. CONCLUSION

In this paper, a simulation of the GALILEO signals based on a bistatic TSM electromagnetic model is presented. More, this simulation takes into account realistic descriptions of the sea surfaces (Elfouhaily sea spectrum and Cox-Munk sea slope probability density function) that depends on the wind speed and direction.

Finally, the influence of the sea condition coefficient (Beaufort scale) on GALILEO reception is pointed out. These simulations are very usefull to evaluate the performance of the GALILEO receivers in various maritime conditions. More, these simulations show the GALILEO could be considered as an interesting system for the passive monitoring of the sea surface.

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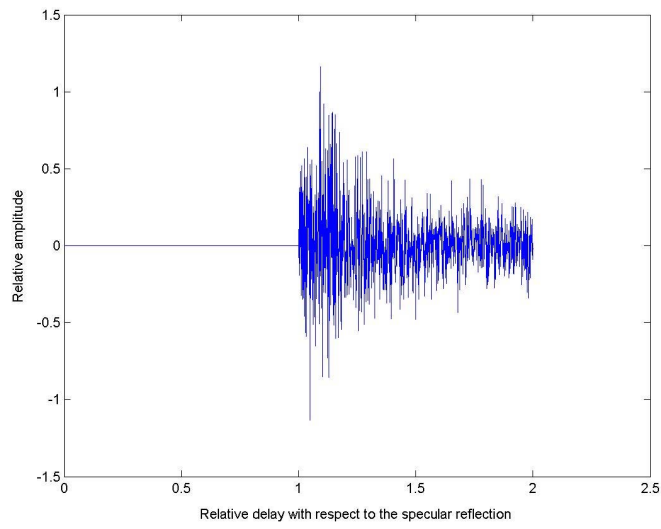


Fig. 10. Numerical simulation of a GALILEO signal (impulse response) received above sea surface (with 6.5 Beaufort wind scale)

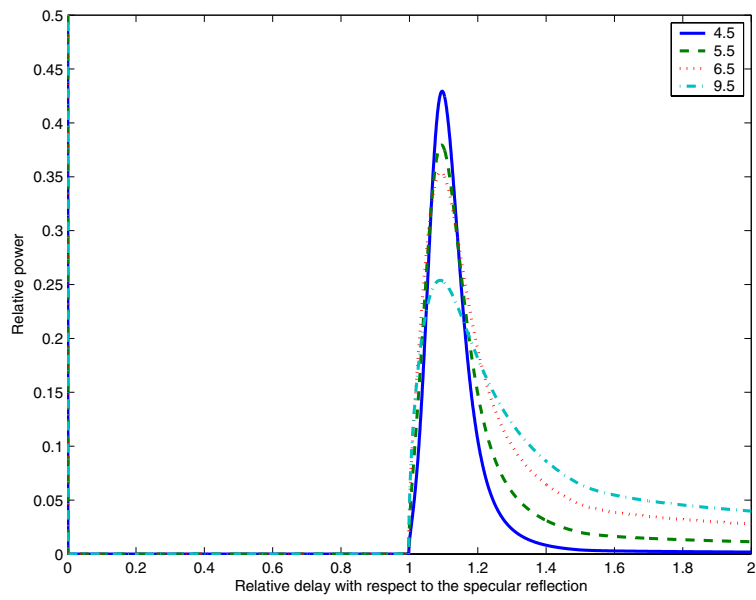


Fig. 11. Numerical simulation of the GALILEO signal power (impulse response) received above sea surface (with different Beaufort wind scales: 4.5, 5.5, 6.5 and 9.5)