Simulation of a GNSS signal for a receiver near a time-evolving sea surface.

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I. INTRODUCTION

In marine environments, the GNSS systems (GPS, GALILEO,...) are well known to be increasingly important for military and commercial ship positionning. Yet, positionning is not the only application field for GNSS signals. For several years, the GNSS signals have been used for remote sensing application in ocean observations [1], [2]. The GNSS signal scattered from the sea, which is considered as a random rough surface, has been proved to be a significant source of information about the ocean behaviour. For example, the scattered GNSS signal is greatly influenced by the state of the sea and the wind direction. In this paper, we investigate the simulation of a GNSS signal above the sea surface and we take into account the evolution in time of this sea surface.

II. SEA SURFACE MODEL

First and foremost, a valuable simulation of GNSS 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. As a matter of fact, the roughness of the sea surface is usually determined using the sea surface spectrum, denoted $S(K, \phi)$, considering the sea surface as a random, ergodic and stationary process. In scientific literature [3], [4], [5], [6], many papers provides fully detailed description of various sea spectra, see Pierson and Moskovitz studies [7], [8] for instance. In this paper, we considered the Elfouhaily spectrum [9], called unified spectrum, that is very consistent with actual observations and presents no discontinuities at gravity and wind driven waves.

This sea spectrum is in the form:

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

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 (1) illustrates the spectrum behavior of the sea surface with the spatial wave number for different wind speeds.

III. SIMULATION FAR ABOVE THE SEA SURFACE

Most of the time, the GNSS signals, dedicated to remote sensing applications, are recorded by airborne systems and the observers are situated far above the ocean surface. In these conditions, the electromagnetic interactions with the ocean surface can be modeled using an asymptotic approach, for intance the Kirchhoff approximation, and the ocean is then only described by stationary statistical properties (slope probability density function,...).

A. Electromagnetic scattering

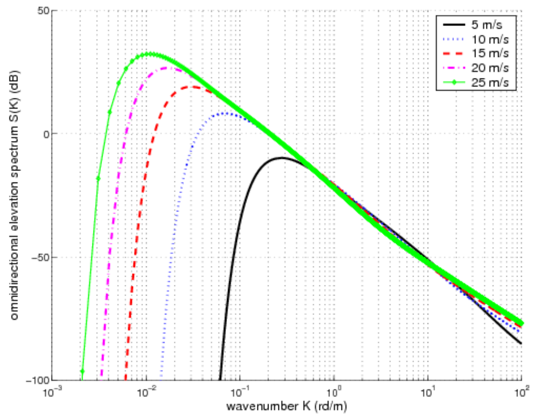
A plane wave impinging a rough surface is scattered in any direction. Indeed, the sea surface "reflection" of the incident wave, coming from the satellite, must be considered as a fully bistatic problem. For a given E^i incident wave, the S scattering matrix provides the scattered polarization and amplitude of the E^s scattered wave received in a given direction:

$$\begin{aligned} E^s = \begin{bmatrix} E^s_{v_r} \\ E^s_{h_r} \end{bmatrix} = \begin{bmatrix} S_{v_r v} & S_{v_r h} \\ S_{h_r v} & S_{h_r h} \end{bmatrix} \begin{bmatrix} E^i_v \\ E^i_h \end{bmatrix} \\ = [S] E^i \end{aligned} \tag{2}$$

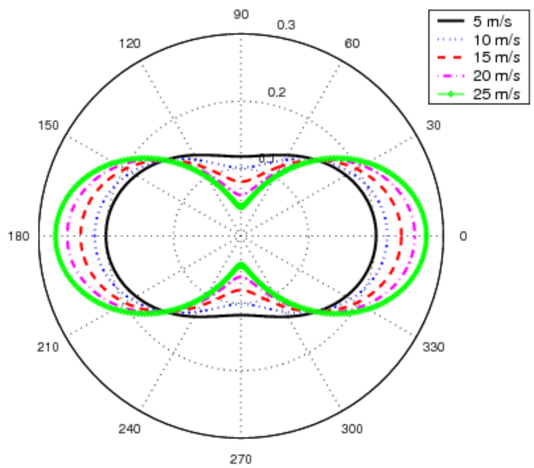
Many approaches were developed to evaluate this electromagnetic scattering matrix. Considering the GNSS Signal (L-Band), the most common approaches are: the Geometrical optics or physical optics methods, called Kirchhoff Approximations (KA) [10], the Small Perturbation Method (SPM) [11], [12] and the Two-Scale Model (TSM) [13], [14].

B. GNSS simulation in far field conditions

The simulation of the GNSS signal consists to add the contribution of each elementary sea surface. In far field conditions, these elementary sea surfaces are assumed to be quite large (at least several dozens of thousand square meters). This is the reason why these elementary contributions are associated with a random phase (between 0 and 2π) and the estimation of the global reflection from the sea must be almost considered as an incoherent summation. Anyway, the electromagnetic signal scattered by each elementary sea surface is associated to a specific ray path. So, the scattered signal coming from a given elementary sea surface arrives with a specific delay. Then, we can simulated the (incoherent) signal coming from the sea as a function of the delay (in time or in distance), see for exemple the figure 2.



(a)



(b)

Fig. 1. Elfouhaily sea surface spectra with different wind speeds: a) omnidirectional elevation spectrum and, b) angular function

The distribution of the energy of this incoherent scattered signal as a function of the delay is highly connected with the state of the sea, see figure 3. This remarks highlight the fact that a GNSS receiver can be a great source of information for remote sensing applications (monitoring of the oceans).

IV. Time-evolving sea surface

In the present study, we assume that the observer is a few dozen meters above the ocean surface and the scattered signal is recorded for a quite long period (several minutes) at a fixed position. With these assumptions, the roughness of the ocean surface cannot be reduced to a simple statistical model and the movement of the sea must be taken into account.

In a very recent paper [15], Arnold-Bos et al. developed a reliable algorithm to estimate the signal scattered (in bistatic configurations) by a deterministic sea surface generated from a realistic sea spectrum, see figure 4. In the present study, we show that this approach can be adapted to time-evolving surfaces. More precisely, to get a time varying surface, we

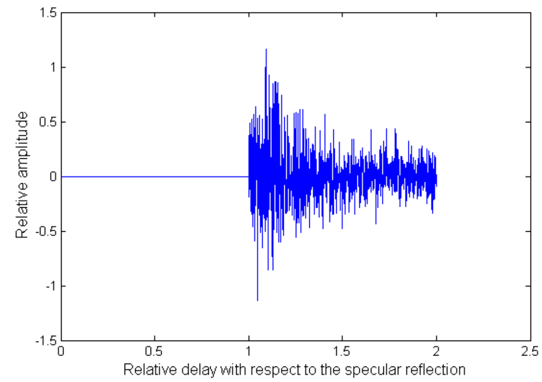


Fig. 2. Numerical simulation of the GPS signal (impulse response) received above sea surface (at 10km height) with Beaufort wind scale coefficients set to 5.5.

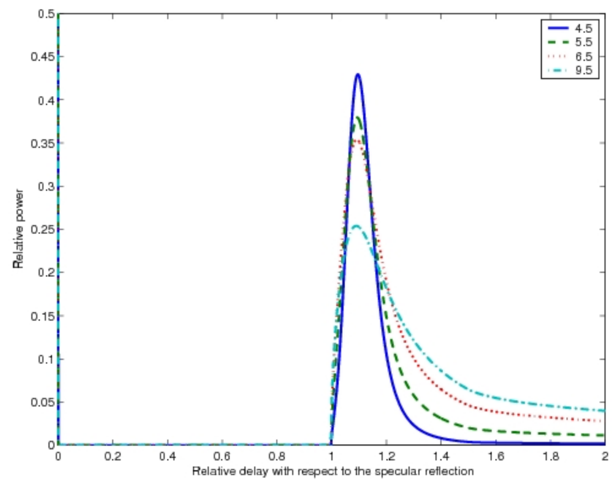


Fig. 3. Numerical simulation of the GPS signal power (impulse response) received above sea surface (at 10km height) with different Beaufort wind scale coefficients: 4.5,5.5,6.5 and 9.5.

calculate the spatial Fourier components as a function of t:

$$\zeta(K_n,t) = \frac{2\pi}{\sqrt{2\Delta K}} \cdot \Big\{ \gamma_n \sqrt{W(K_n)} e^{j\omega(K_n)t} + \gamma_{-n}^{*} \sqrt{W(-K_n)} e^{-j\omega(-K_n)t} \Big\}$$

where W is the realistic sea spectrum, K_n are the discrete values of the spatial wave number and γ_n are independant Gaussian unitary random values. Then, using an inverse Fourier transform, the spatial Fourier components induce the actual sea surface:

$$\zeta(x,t) = \frac{\Delta K}{2\pi} \sum_n \zeta(K_n,t)\, e^{-jK_n x}$$

A. Semi-deterministic scattering model

In few words, the approach developed by Arnold-Bos et al. consider the simulated sea surface as a height map of $n \times m$ facets (each facet is about one square meter). Then, to obtain the contribution of a single facet, the authors introduce

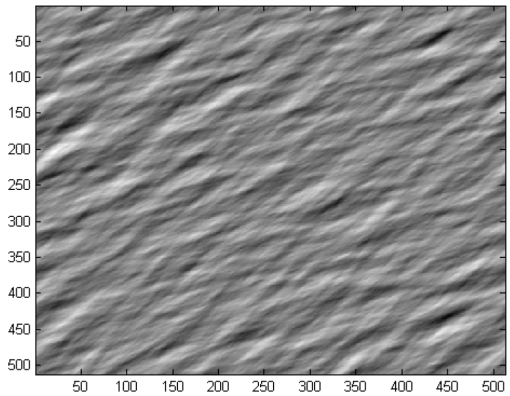


Fig. 4. Deterministic sea surface generated with a realistic sea spectrum at a given time (over an area of 500x500 square meters).

a modified version of the two scaled method [13], [14]. The main difference is that, due to the small size of the facet, the mean slope of each facet is not equal to zero and must considered as deterministic value. Then, the facet is now assumed to be a rough surface with a small scaled roughness and with a deterministic slope. Finally, using ray tracing methods, the authors developed an algorithm adapted to estimate the electromagnetic field received quite near the sea surface and that takes into account the sea movement.

In these conditions, this new agorithm can provide an estimation of the GNSS signal above the sea based on a coherent summation of the contribution coming from each facet. In figure 5, we can see an example of the contributions associated to each facet.

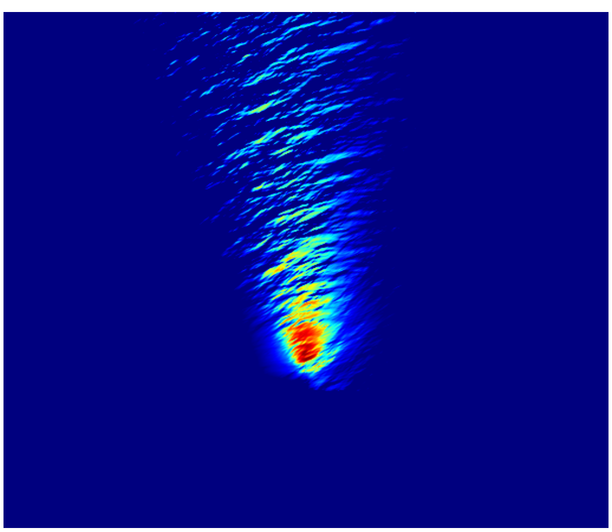
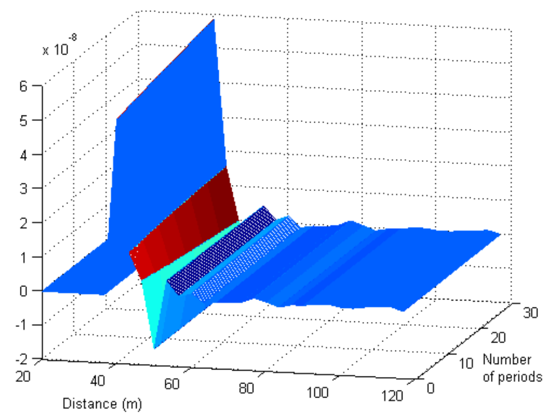


Fig. 5. Map of the contributions associated to each facet cooresponding to a deterministic sea surface.

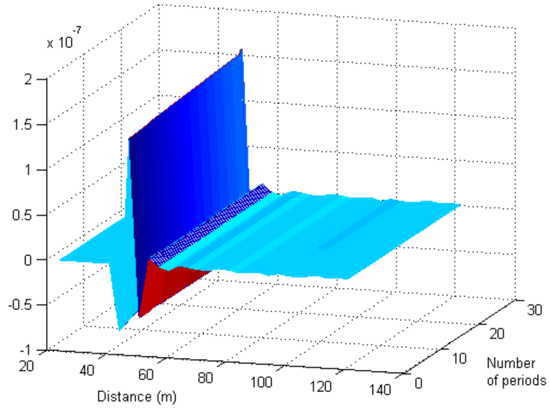
B. GNSS simulation quite near the sea surface

Based on the Arnold-Bos et al. algorithm, we can simulate the GNSS received quite near the sea surface. Moreover, this simulation can be obtained at any time and for any duration. In the present paper, we assume the observer is situated at 20 meters above the sea surface. At $t = 0$ A GPS satellite (L1-Band) is at the zenith related to the observer. The satellite altitude is $20200\,km$ and its orbital speed is $5475\,m/s$.

In figure 6, we simulate the GPS signal for 30 periods of 1ms. The simulations respectively start at $t = 0s$ and $t = 1s$. In fact, it is noteworthy that the phase shift between two periods, due to the movement of the satellite, is estimated using the integration of the doppler shift recorded by the observer in direct signal coming from the satellite. The figure 6 that eliminate the phase shift between different periods, shows that the time-evolution for 30ms is almost negligeable.



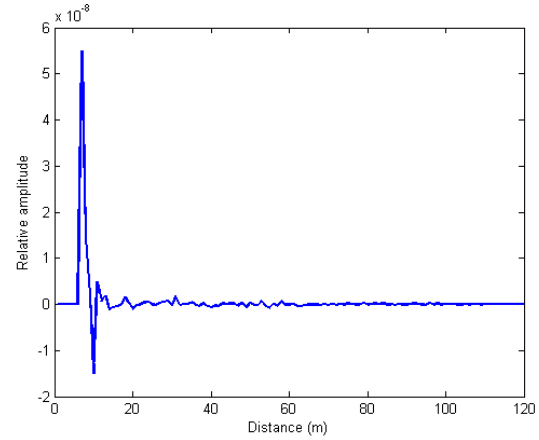
(a) t=0s



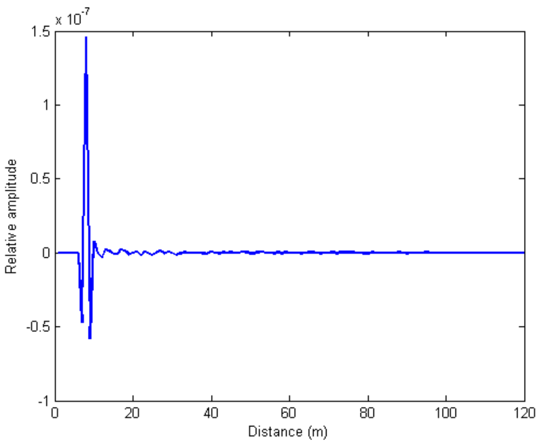
(b) t=1s

Fig. 6. Simulation of the GPS impulse response for 30 periods (30x1ms) at $t = 0s$ and $t = 1s$

Unlike very short periods, a comparision between the averaged curves at $t = 0s$ and $t = 1s$ shows that the evolution during one second is quite significant. This evolution is due to the movement of the satellite (modification of the angles of incidence) and the movement of the sea surface. However, if the satellite is situated at the more than $20000\,km$, the modification of the angles of incidence during one second can be assumed as very weak, and the main contribution to the time-evolution is due the movement of the sea.



(a) t=0s



(b) t=1s

Fig. 7. Average curve of the GPS impulse response for 30ms at t=0s and t=1s.

V. Conclusion

Our numerical results point out the influence of the sea movement upon the scattered GNSS signals, and we underline the fact that an inverse problem approach, dedicated to time-evolving sea surface, could provide many information for ocean monitoring.

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