A simulator of sea clutter from X-band radar at low grazing angles

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Abstract—Sea-return signals from X-band radar contain back-scattering signals from the sea surface called sea clutter, due to the interaction between electromagnetic waves and the sea surface. In this paper, we will present a simulator that calculates the sea clutter spectrum from a coastal radar. This implies that sea clutter characteristics should be computed for low-grazing angles. The goal of this simulator is to implement models for all the components involved in the radar chain from the emission of electromagnetic waves to their reception. In order to be able to simulate back-scattering signals from a quite large area, the computation time is considered with care as part of the design of the simulator.

I. INTRODUCTION

In the context of a low grazing angle X-band radar, back-scattering signals contain targets and the sea clutter. Spectral characteristics of the sea clutter affect the performance of detectors of targets such as moving target indicator filter or constant false alarm techniques. In order to quantify its influence on detectors, the first part is to simulate the sea clutter from environmental parameters, which is the purpose of this paper.

Low grazing angle radar spectra can be explained by the coexistence of two kinds of back-scatters: “slow” and “fast” scatterers. First ones can be explained by the Bragg resonance, the others ones are produced by breaking waves ([1]) and give spikes as results. Although the breaking waves phenomenon is still an open problem, one hydrodynamic criteria to explain breaking waves is the curvature of waves. Therefore, in order to localize breaking waves, we choose to simulate the sea surface. To provide information on the sea state, the directional spectrum is used. One way to simulate sea surface from a directional spectrum is to compute an inverse fast fourier transform of it and to affect random phase to each sinusoid. This operation gives a linear sea surface. The non-linearities are due to phase rearrangement and give steeper waves which is interesting for us to simulate fast scatterers.

Therefore we split the directional spectrum in two part: a bare spectrum and a dressed one as in [2], [3]. Hence each elementary wave are expressed as:

\[ \eta_w(t) = a \cos(\omega t + \theta) + \alpha \cos(2(\omega t + \theta)) + \beta \sin(2(\omega t + \theta)) \]  

(1)

where the first term in the sum is provided by the bare spectrum and the two other term are provided by the dressed spectrum. In this equation, \( \omega \) represents the pulsation of the wave and \( \theta \) its phase. This expression allows us to produce waves with asymmetries as shown on the figure 1. In the equation (1), the parameter \( \alpha \) (resp. \( \beta \)) controls the amount of horizontal (resp. vertical) asymmetry in the final wave profile. In our implementation, the ratio between \( \alpha \) and \( \beta \) is modified according to the wave direction and to the wind direction. If the wave moves in the same way as the wind direction, then this wave will only have vertical asymmetry. Horizontal asymmetry appears when the wave direction deviates from the wind one.

Once the surface is simulated, it is analysed to detect and localize breaking waves. All parts of the surface whose slope exceeds a threshold are considered to break. Nevertheless, the final localization of breaking waves can be modified to appear at the top of waves.

This part of the simulator provides a sea surface. In the next chapter, we will present how this surface will be involved in the computation of the back-scattering signal with the electromagnetic model.

II. THE MODELS

As explained previously, we will describe models implemented in the simulator.

A. The hydrodynamic model

Low grazing angle radar spectra can be modeled as the result of two kinds of scatterers: “slow” and “fast” scatterers. Slow scatterers appeared near the Bragg frequency resonance and fast scatterers are associated with breaking waves. Although the breaking waves phenomenon is still an open problem, one hydrodynamic criteria to explain breaking waves is the curvature of waves. Therefore, in order to localize breaking waves, we choose to simulate the sea surface. To provide information on the sea state, the directional spectrum is used. One way to simulate sea surface from a directional spectrum is to compute an inverse fast fourier transform of it and to affect random phase to each sinusoid. This operation gives a linear sea surface. The non-linearities are due to phase rearrangement and give steeper waves which is interesting for us to simulate fast scatterers.

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B. The electromagnetic model

This paragraph will be divided in two parts, the first will deal with “low” scatterers and the second part with “fast”
The speed vector is given in the figure 2. Moreover the sea surface is considered to be a given area, with a distribution on each facet. Let the slope and orbital velocity be a given area, with a distribution on each facet. A tilted facet is described by a slope vector for receding (-) waves. \( \sigma_0(x, y, t) \) is frequency of the incident electromagnetic wave, and \( \omega^\pm_1(\mathbf{u}) \) describes the Doppler shift of the back-scattering signal. This latter takes into account the speed of the Bragg resonant wave and the current. The expression of all these parameters can be found in [4].

Concerning the “fast” scatterers, we have implemented the model presented in [1]. In this paper, the back-scattering signal from breaking wave are considered to result from a large numbers of elementary isotropic scatterers. Hence each elementary scatterer sends back a fixed portion of the incident electromagnetic signal. The relevant speed use to estimate the shift of the back-scattering signal in the Doppler spectrum is the local phase speed of the breaking facet. With an Hilbert transform we can estimate the local wave frequency and the local wavenumber. The ratio of this two parameters gives us an estimation of the local phase speed. Finally, for each elementary scatterer, a randomly deviation from the mean value of the Doppler shift is performed according to a lorentzian distribution (5).

In the next part, we will deal with the attenuation of the electromagnetic wave due to its propagation from the emission to the sea surface.

**C. The propagation model**

The attenuation of the electromagnetic field is obtained by resolving the parabolic equation. This equation was formerly use in sonar application, and became in the radar field in the middle of the 20th century with the growth of calculation capacity ([6]). In two dimensions, where \( r \) represents the distance and \( z \) the altitude, the parabolic equation can be written as below:

\[
\frac{\partial^2 \Psi(r, z)}{\partial z^2} + 2jk_0 \frac{\partial \Psi(r, z)}{\partial r} + k_0^2(n^2(x, z) - 1)\Psi(r, z) = 0 \tag{4}
\]

In this equation, \( k_0 \) is wavenumber of the electromagnetic wave, \( \Psi \) is the complex attenuation and \( n \) is the refractive index over the air column. In order to resolve this equation we use the split step Fourier algorithm ([7], [8]). From a solution at \( r \), this method calculates the solution at \( r + \Delta r \).
Hence we can propagate a solution with this method. The initial solution is given by the characteristic of the antenna. Moreover we consider that the sea is a perfect conductor. The figure 3 presents two examples of attenuation calculated with the split step Fourier algorithm in two different contexts: the figure 3(b) show the result of the attenuation of the electromagnetic field on a flat surface with a constant refractive index and on the figure 3(b) is shown the attenuation over a flat surface but with a variable refractive index. Besides, in [7], a way to integrate rough terrain in the calculation process is presented. This modification is also implemented in our propagation model. This last improvement avoids us to compute the shadow parts on the sea surface due to its elevation. Indeed the shadow parts are directly obtained with the attenuation. The figure 4 presents an example of our implementation on a simple uneven surface.

In the previous paragraph, we have presented the parabolic equation and some results for one horizontal dimension. However the sea surface generated by the hydrodynamic model provide surface with two horizontal dimensions. In order to get attenuation information over the sea surface, it is computed for different azimuths. We consider that the computation from one azimuth to another is independent. With all this information we are able to generate a map of the attenuation just over the sea surface.

Another difficulty encountered is the link between the propagation model and the electromagnetic model. Indeed as we have seen previously, the electromagnetic field is considered as a “ray” that interacts with the sea surface. Therefore we have to determine the incident angle which is not well defined with our propagation model. Hence we compute the mean incident angle of the incident electromagnetic field. This is done by considering a small part of the complex attenuation over the surface. The Fourier transform produces theoretically the field distribution according to the variable $p = k_0 \sin \theta$, with $k_0$ the wave number of the radar and $\theta$ the incident angle ([8]). Hence with this decomposition and with a weighted mean according to the field distribution, an incident angle is estimated.

In this section, we have described the model use in our simulator. In the next section we will focus on the structure of the simulator and how the computation is performed.

### III. Structure of the Simulator

The figure 5 presents the structure of the simulator. In order to comment this schematic, we will explain how the computation process progresses. We will consider that the system is a radar with an rotating antenna. The first step in the computation process is an initialization step. In this step, all the operations that we have to do just once are performed. It begin with the formatting of parameters in order to be usable in the different models. This can also be the re-gridding of data such as the directional spectrum. We also discretize the time dimension, and calculate instant where simulation of the back-scattered signal have to be done.

The elementary computation element is the simulation of Doppler spectra at different range for a given azimuth of the antenna. This begin by the generation of the sea surface with the hydrodynamic model. The surface is then send to the propagation model in order to get the attenuation just over the surface and to estimate the incident angle. Before the electromagnetic model computes the back-scattering cross-section, an analysis of the surface is performed to detect and to localize breaking waves. This analysis will produce a map sent to the electromagnetic model. This map indicates the localization of “fast” back-scatterer which is required by the electromagnetic model. At the end all the Doppler spectra at each range by the electromagnetic model are mixed to produce the final Doppler spectra at a given instant. This is repeated for each relevant moment found in the initialization step.

### IV. Some Results

In this section, some examples will be presented. The simulator can produce the energy of the Doppler spectrum for different meteo-oceanographic environment. Its phase is not computed. The integration of Doppler spectra over frequencies provides the energy of the back-scattered signal. The figure 6 presents this kind of result near the radar. In a second example, we present the Doppler spectrum of the simulated
In this paper, a simulator of sea clutter is presented. In a first part we have presented, the models used to generate the sea surface, to calculate the cross-section of a small sea surface area and to compute the attenuation of the electromagnetic signal. The goal of this simulator is to aggregate all this model and to manage to make them work together. As a result we expect to have realistic sea clutter.

This simulator is designed to accept different meteorological and oceanographic environment. This can make this simulator an interesting tool to evaluate sea clutter before the installation of a radar according to typical environmental characteristics of the area of interest.

In the actual version, the simulator is in a validation phase. Actually the simulated Doppler spectra should be compared to real data, which has not been done yet.

Moreover different parts of the simulator could be improved. At first the sea surface can be modified to generate more realistic surface, and we are indeed developing a new model of non-linear sea surface. This is quite important in the simulator structure as it is used to distinguish “slow” and “fast” scattered and it is involved in the computation of the cross-section for “slow” scattered. Besides, we also think to modify the propagation model in order to integrate the fact that sea surface is not a perfect conductor.
REFERENCES


