Frequency impact on the bistatic radar scattering from an ocean surface

Ahmad AWADA\textsuperscript{1,2}, Ali KHENCHAF\textsuperscript{1} and Arnaud COATANHAY\textsuperscript{1}

\textsuperscript{1}ENSIETA/E3I-Laboratory, 2 rue François Verny, Brest 29806, France
\textsuperscript{2}INP Grenoble GIPSA-Lab/DIS, 961 rue de la Houille Blanche, BP 46, 38402 St Martin d’Hres, France

Abstract—In this paper we study the frequency impact on the normalized bistatic cross section (NBCS) of the sea surface. Numerical simulations are presented and analyzed in the frequency range from 1 to 14 GHz (L- to K\textsubscript{u}-band). We treat this problem with the unifying scattering model denoted small slope approximation (SSA). The computations were made assuming the surface-height spectrum of Elfouhaily \textit{et al.} for fully developed seas. Numerical results are obtained and discussed in both forward and fully bistatic configurations for different sea states and polarizations.

I. INTRODUCTION

Bistatic polarimetric radars may potentially significantly increase the remote sensing radar data, as relatively cheap secondary receive-only systems, operating bistatically against a single transmitter can supplement several conventional monostatic systems [1]. Moreover, bistatic phenomena such as the Brewster effect can reveal target properties that are not revealed clearly in monostatic scattering.

Moreover, the frequency of radar signals represents a key parameter in remote sensing applications. The choice of its value depends on the target and the geometrical configuration of the imaging system. Usually, the majority of the common ocean remote sensing systems operate in the L, C-, X- and K\textsubscript{u}-bands [2], [3] since the magnitude wavelengths in these bands is of the same order as the sea surface wavelengths.

We can quote the ERS system operating at C-band [3] and the QuikSCAT system operating at K\textsubscript{u}-band [2]. Concerning the L-band, it is noteworthy that the use of Global Positioning System (GPS) (operating at L-band) as a forwardscatter remote sensing tool has lead to fruitful research in the last few years [4].

The major publications on the remote sensing of the sea surface present results in each band separately and usually in a monostatic configuration. Few studies have yet been presented to analyze the frequency influence particularly in a bistatic configuration. This is the main purpose of this paper. To treat this scattering problem, we adopted the approximate models categories. These methods are still a necessity owing to the insurmountable numerical complexity of realistic scattering problems [5]. We can refer to [5] which is the latest critical and up-to-date survey of the approximate models. These methods are still a necessity owing to the insurmountable numerical complexity of realistic scattering problems [5]. We can refer to [5] which is the latest critical and up-to-date survey of the approximate models categories. These methods are still a necessity owing to the insurmountable numerical complexity of realistic scattering problems [5]. We can refer to [5] which is the latest critical and up-to-date survey of the approximate models categories. These methods are still a necessity owing to the insurmountable numerical complexity of realistic scattering problems [5]. We can refer to [5] which is the latest critical and up-to-date survey of the approximate models categories. These methods are still a necessity owing to the insurmountable numerical complexity of realistic scattering problems [5]. We can refer to [5] which is the latest critical and up-to-date survey of the approximate models categories. These methods are still a necessity owing to the insurmountable numerical complexity of realistic scattering problems [5]. We can refer to [5] which is the latest critical and up-to-date survey of the approximate models categories. These methods are still a necessity owing to the insurmountable numerical complexity of realistic scattering problems [5]. We can refer to [5] which is the latest critical and up-to-date survey of the approximate models categories. These methods are still a necessity owing to the insurmountable numerical complexity of realistic scattering problems [5]. We can refer to [5] which is the latest critical and up-to-date survey of the approximate models categories. These methods are still a necessity owing to the insurmountable numerical complexity of realistic scattering problems [5].

A. The SSA model

The SSA proposed by Voronovich [7] is an analytical approach, appropriate for scattering from both large- (high-frequency regime), intermediate and small-scale (low-frequency regime) roughness scales within a single theoretical wave scattering by rough surfaces is an important issue in diverse areas of science such as measurements in medical, optics, acoustics, geophysics, communications, and terrestrial or extraterrestrial remote sensing. For this reason, the development of the scattering models is important. In this study, we choose to treat the scattering problem with the SSA model, which will be introduced in the following section.

II. THEORETICAL SCATTERING FORMULATION

The geometrical configuration adopted to resolve the wave-scattering problem from the sea surface is given in figure 1.
scheme. Thus it encompasses both the Bragg and the Kirchhoff mechanisms of scattering. It can be applied to an arbitrary wavelength, provided that the tangent of the grazing angles of incident/scattered radio waves sufficiently exceeds the RMS (root mean square) value of the surface slopes. It starts from an ansatz based on the invariance properties of the Scattering Amplitude (SA). Performing a horizontal or vertical translation $d$ affects the latter by a phase shift $\exp(-i(k - k_0) \cdot d)$ or $\exp(-i(q - q_0) \cdot d)$, so a solution is sought in the form [9]:

$$S(k, k_0) = \int \exp[-i(k - k_0) \cdot r - i(q - q_0)h(r)] \frac{d^r}{(2\pi)^2}$$

(1)

where $k_0, q_0$ are the horizontal and vertical projections of the wave vector of an incident wave, and $k, q$ are their equivalent for the wave vector of scattered wave. The unknown functional $\Phi$ is obtained by performing a Taylor development with respect to the Fourier transform of the surface height function $h$ and imposing coefficients that give consistency with the SPM as $h \rightarrow 0$. In practice, only the first two orders are tractable; the higher orders become far too intricate. At first order in the slope (SSA1) we have [7]:

$$S_1(k, k_0) = \frac{2(q q_0)^{1/2}}{q_k + q_0} B_1(k, k_0) \left(\frac{1}{2\pi}\right)^2 \times$$

$$\int \exp[-i(k - k_0) \cdot r - i(q - q_0)h(r)]dr$$

(2)

To avoid the computational complexity in the second order (SSA2) and accepting an error no more than about 1 dB [10], we will present numerical results by using the SSA model at its first order in the next section for different bistatic configurations.

B. Scattering dependence on the frequency value

To highlight the scattering dependence on the signals frequency, we write the scattering coefficient based on the SSA1 model for an isotropically rough surface [11]:

$$\sigma_{\alpha\alpha_0}(k, k_0) = 2 \left| \frac{2q_k q_0}{q_k + q_0} B_{\alpha\alpha_0}(k, k_0) \right|^2$$

$$\times \int \left\{ e^{-\kappa |\rho(0) - \rho(r)|} - e^{-\kappa \rho(0)} \right\} J_0(Kr) rdr$$

(3)

where $\kappa = (q_k + q_0)^2$. Values $\alpha$ and $\alpha_0$ correspond to the polarization of the scattered and the incident plane wave, respectively. To illustrate the effective parameters which can be selected under a given frequency value (for a fixed geometric condition), we plot the integrand evaluation in equation (3) for a scattering configuration along the specular direction at an incident angle equal to 60° and a wind speed of 4 m/s.

Figure 2 shows that the value of $r$ over which the integrand is significant is about 2 m for L-band signals (F=1.58 GHz). Under this condition, only points on the surface less than 0.3 m apart remain correlated in their scattering contribution. For signals in $K_u$-band (F=14 GHz), the significant integration range of $r$ is reduced to about 0.15 m. So, we can deduce that the effective surface parameters selected to explain the bistatic scattering problem at $K_u$-band cannot be used to explain scattering at $L$-band.

Figure 3 points out the wind dependence on the integration range of $r$ in $L$-band at an incidence of 50°. This figure shows that at 7 m/s, for an incidence angle of 50°, the convergence of the integral is achieved on about 1 m. For the same angle, at a wind speed of 4 m/s, the integration range increases to about 2 m. Indeed, when increasing the incident angle to 70°, a large surface is needed to be integrated over, up to about 4 m at a wind speed of 4 m/s. It follows that only a portion of the correlation function is contributing significantly to the scattering coefficient calculation. This portion is controlled by the frequency and how fast the correlation function decays (as a function of wind speed). We use the SSA scattering model and the Elfouhaily [12] sea surface spectrum to predict numerical NBCS of the sea surface, which is the subject of the next section.

III. NUMERICAL RESULTS

In this section we present the numerical simulations to analyze the behavior of the NBCS of ocean surfaces especially as a function of the frequency of radar signals. Results will
be presented in the case of a forward scattering configuration (along the specular direction) and in a fully bistatic configuration one. We note that a detailed comparison between the SSA and TSM model in bistatic configuration was made in [10].

A. Forward scattering : comparison between different models

The forward configuration is a particular bistatic configuration where the z-axis, the incident wave vector and the scattered wave vectors are in the same plane ($\phi = \phi_s = 0^\circ$). Figure 4 compares the results yielded by the SSA with those of the geometric optics of the Kirchhoff approximation (KA-GO), the small perturbation model (SPM) and the two scales model (TSM). The emitter incident angle is equal to the small perturbation model (SPM) and the two scales model (TSM). The scattered wave vectors are in the same plane ($\phi = 0^\circ$).

As is apparent in figure 4, the maximum energy is received around the specular direction $50^\circ$ which is a logical result because this is the true specular direction as given by the law of reflection. Thus, there is a good agreement between the results obtained with SSA and those of the KA-GO near-specular directions, where it is well known that the last model works well. Also, the SSA results for VV-polarization present a higher concordance with those obtained with the TSM model than for the case of HH-polarization but the difference remains within about 2 dB. Therefore, graphs in figure 4 show the limit of the SPM model in this configuration.

B. Scattering along the specular direction

This configuration involves that incident emission and reception directions must be the same and the corresponding azimuth also must be equal. We present, in figure 5, the NBCS variations along the specular direction for $40^\circ$ incidence angle at three wind speeds $\{5, 10, 15\text{m/s}\}$, (a) VV-polarization and (b) HH-polarization direction by letting the incident angle vary between $0^\circ - 80^\circ$ for frequencies of $1.58, 5.5$ and $14$ GHz, corresponding to $L_\text{-}, C_\text{-}$ and $K_u$-band radar, respectively. The wind speed is fixed to 4 m/s and the upwind direction is under consideration.

When examining curves in figure 6, several items of importance may be deduced. First, for both VV- and HH-polarizations the NBCS values are quasi constant in the incidence region $[0^\circ - 60^\circ]$. This behavior can be an important tool in exploring the sea clutter. Second, for VV-polarization in part (a) beyond $60^\circ$, there is an important decrease in NBCS results. On the other hand, in part (b), the horizontally polarized scattering coefficient continues to rise with the incident angle up to $80^\circ$ except for $L$-band frequencies. Beyond $70^\circ$, in this particular case (F= 1.58 GHz), the coefficient turns back down. This is due to an integration into the negative correlation region [11].

C. Fully bistatic scattering dependence on the frequency

We present in figure 7 the numerical NBCS results in a fully bistatic configuration. It is defined with the following...
In the forward scattering configuration, we compared the SSA results with those of three other models. Whereas a good similitude is obtained with the KA-GO and TSM models, the limits of the SPM model are shown in this configuration. Analysis of the numerical results in a particular bistatic configuration (the specular direction) versus the frequency value, show that the NBCS decreases when the frequency increases which is unlike the backscattering configuration. For large scattering incident angles and at a small wind speeds, the low radar frequency (L-band) yields unexploitable signals in the specular direction which limits the use of the adopted theoretical model.

In a fully bistatic configuration, the NBCS variations versus the frequency value is the contrary of the scattering along the specular direction due to the fact of the Bragg mechanism. The recently proposed WCA model [8] seems to be promising to improve some particular bistatic cases predicted with the SSA model which will be exploited in our future work.

ACKNOWLEDGMENT
The authors would like to thank Mr. Andreas ARNOLD-BOS for his help.

REFERENCES