ABSTRACT

The Ament model is a practical and fast means to evaluate the forward radar propagation over the sea surface in coastal environment. Based on the Rayleigh roughness parameter, it calculates the total coherent power received by an on-board antenna. Here, by extending the Rayleigh roughness parameter to the case of a rough layer, the Ament model extended to the case of rough layers (in which the two rough surfaces are uncorrelated) is presented. This new model is applied to the case of thick oil spills on the sea surface, for which numerical simulations are presented in order to study the possibility of detecting this pollution.

Index Terms— Sea surface, Radar scattering, Overwater radio propagation, Water pollution, Sea coast

1. INTRODUCTION

For low grazing incidence angles, the classical asymptotic scattering models applied to natural surfaces or natural layers are not valid any more. Thus, the Ament model [1], which is a fast and simple model that describes the forward (i.e., in the specular direction) radar propagation over rough surfaces, can be used for such a configuration. For instance, this model is used in the Parabolic Wave Equation [2] to predict the forward propagation above a rough sea surface in the presence of ducts. As shown in the literature [3], this simple model enables one to obtain fast results which are consistent with rigorous methods for $R_a \leq 1.25$ ($R_a = k_1 \sigma_h \cos \theta_i$, with $\sigma_h$ the surface RMS height, $k_1$ the incident wave number, and $\theta_i$ the incidence angle). The model was then improved in [2] by taking the shadowing effect into account.

The interest of using this simple and efficient model is quite clear, because solving rigorously such an electromagnetic scattering problem for grazing incidence needs very long surfaces, and consequently very large computing time and memory space. As a result, the extension to rough layers would be quite difficult; it is not the aim of this paper, so it is not presented here. Then, the extension of the Ament model to the case of two rough surfaces separating homogeneous media is presented here, in order to deal with the forward propagation over rough layers. In section 2, the extension of the Rayleigh roughness parameter to the case of reflection from a rough layer is addressed. It is applied in section 3 to the forward radar propagation over a rough layer under the Ament model [4].

2. EXTENSION OF THE RAYLEIGH ROUGHNESS PARAMETER TO ROUGH LAYERS

The Ament model, which is based on a ray approach, uses the Rayleigh roughness parameter to describe the scattering from a rough interface for grazing incidence in a simple way. Indeed, it takes the surface roughness into account by multiplying the Fresnel reflection coefficient of a plane surface, $r_{12}$, by the term $\exp(-2R_a^2)$ (for Gaussian statistics, with $R_a$ the Rayleigh roughness parameter). Then, one can define the Ament reflection coefficient, $r_A$, as

$$r_A(\theta_i) = r_{12}(\theta_i) \times \exp(-2R_a^2), \quad (1)$$

the Rayleigh roughness parameter quantifying the degree of roughness of the surface.

For the case of a stack of two rough interfaces, it is possible to apply the same approach as for one rough interface to describe the scattering from a rough layer. Similarly, the
reflection from the rough layer can be split up into two components: the first one accounting for the reflection from two plane interfaces, and the second one accounting for the roughness of the interfaces.

Here, in the case of two rough interfaces, the scattering from such a system is composed of multiple successive reflections inside the rough layer. Then, the Ament equivalent reflection coefficient associated to the rough layer can be expressed from the summation of all these contributions (Fig. 1) and for Gaussian statistics, it is defined by

\[ r_{eq}^{\text{A}}(\theta_i) = r_{12}(\theta_i) e^{-R_{2,1}^2} + t_{12}(\theta_i) t_21(\theta_m) \times \sum_{k=0}^{\infty} r_{23}^{k+1}(\theta_m) r_{12}^{k}(\theta_m) e^{-j(k+1)\phi_{pl}} e^{-R_{2,k+2}^2}, \]

with \( r_{ij} \) and \( t_{ij} \) the Fresnel reflection and transmission coefficients from the medium \( \Omega_i \) to the medium \( \Omega_j \), respectively, \( \phi_{pl} = 2k_2 H \cos \theta_m \) the phase difference between two successive scattered fields, and \( R_{a,1} \) the Rayleigh roughness parameter of the upper interface \( \Sigma_A \). \( R_{a,1} = k_1 \sigma_{hA} \cos \theta_i \). For the case of uncorrelated surface points \( \{A_1, B_1, A_2, etc.\} \) and more generally for uncorrelated rough surfaces, one can show that [4]

\[ R_{a,2}^2 = 2R_{a,112}^2 + R_{a,r23}^2, \]

and \( \forall n \geq 2, \)

\[ R_{a,n}^2 = 2R_{a,112}^2 + (n-1)R_{a,r23}^2 + (n-2)R_{a,r21}^2, \]

with \( R_{a,112} = k_0 \sigma_{hA} |n_1 \cos \theta_i - n_2 \cos \theta_m|/2 \), \( R_{a,r23} = k_2 \sigma_{hB} \cos \theta_m \), and \( R_{a,r21} = k_2 \sigma_{hA} \cos \theta_m \).

### 3. APPLICATION TO FORWARD RADAR PROPAGATION OVER THICK OIL SPILLS ON SEA SURFACES

This extended Ament equivalent reflection coefficient is then applied to the forward radar propagation over sea surfaces covered in oil (called contaminated seas) and compared to clean sea surfaces. The radar source is located at a fixed height \( h_1 = 15 \) m above the origin \( (x_1 = 0) \). The target or receiver is at an arbitrary altitude \( h_2 \), and is located at a range \( x_2 = 2 \) km away from the source (see Fig. 2). The calculations are first led for a wind speed at 10 m over the surface \( u_{10} = 7 \) m/s, and for a radar frequency \( f = 3 \) GHz. The oil spill thickness is taken as \( H = 1 \) mm. For more details, one can refer to [4].

To quantify the forward propagation over sea surfaces, the propagation factor \( \eta \) is used. It is defined as the ratio of the field strength at the receiver reflected by the rough surface divided by the field strength at the receiver if it were in free space (direct field, Fig. 2). Then, the propagation factor \( \eta \) is given by the expression [3]

\[ \eta = \sqrt{1 + |r|^2 + 2|r| \cos(k_1 \delta + \angle r)}, \]

with \( \angle r \) the phase of the reflection coefficient, and \( \delta \) the path difference between the direct and reflected fields, which is given by

\[ \delta = \frac{h_1 + h_2}{\sin \varphi} - \sqrt{(h_2 - h_1)^2 + x_2^2}. \]

### 4. NUMERICAL RESULTS

The numerical results show a comparison between a clean sea surface and a contaminated sea, for the parameters quoted above. Results from [4] allowed to conclude that for the typical configurations studied here, concerning the contaminated sea, only the first-order contribution \( r_{12}(\theta_i) e^{-R_{2,1}^2} \) of the equivalent Ament reflection coefficient \( r_{eq}^{\text{A}}(\theta_i) \) contributes to the propagation factor \( \eta \). This corresponds to take into account the Ament reflection coefficient of the air-oil interface only. Then, the differences that appear between the clean and contaminated seas can be attributed only to the differences in the surface RMS height or in the Fresnel reflection coefficient \( r_{12}(\theta_i) \): they differ owing to the contrast of the relative permittivities of the sea and the oil media. In fact, for the typical configurations studied here, the main contribution comes from the difference in the Fresnel reflection coefficient, as observed in V polarization for which the Brewster effect significantly affects the propagation factor \( \eta \) of the clean sea in comparison with the contaminated sea. Here, additional numerical simulations are led so as to further investigate the model results.

The calculations are first led for a wind speed at 10 m over the surface \( u_{10} = 7 \) m/s, and for a radar frequency \( f = 3 \) GHz.
Fig. 3. Comparison between a clean sea surface and a sea covered in oil (called contaminated sea) for $H$ and $V$ polarizations: the horizontal range of the receiver from the source is $x_2 = 2$ km, the radar frequency $f = 3$ GHz, and the wind speed at 10 m above the surface is $u_{10} = 7$ m/s. For the contaminated sea, the oil layer thickness is $H = 1$ mm.

GHz. Fig. 3 presents the propagation factor $\eta$ in dB with respect to $h_2$ for both $H$ and $V$ polarizations of the line source. For $H$ polarization, the clean sea surface case is plotted in solid black line, and the contaminated sea case in dashed red line. For $V$ polarization, the clean sea surface case is plotted in dash-dot blue line, and the contaminated sea case in dotted green line. For $H$ polarization, the differences between the clean sea surface and the contaminated sea are observable only around the extrema of the propagation factor $\eta$, but they remain very weak. By contrast, for $V$ polarization, one can observe a significant difference between the clean sea surface and the contaminated sea around the extrema of $\eta$, the dynamics of the curves clearly differ. As explained in [4], this is mainly due to the Brewster effect in the Fresnel reflection coefficient, which occurs only in $V$ polarization. Thus, for this typical configuration, the detection of an oil slick is possible only for $V$ polarization, and around the extrema of $\eta$.

Fig. 4 presents numerical results in the same configuration as in Fig. 3, except from the horizontal range $x_2 = 2$ km and the wind speed $u_{10} = 7$ m/s.

Fig. 4. Same configuration as in Fig. 3 except from the horizontal range $x_2 = 2$ km and the wind speed $u_{10} = 7$ m/s.

the increase of the wind speed $u_{10}$ implies a lower dynamics of the curve. Indeed, as $u_{10}$ increases, the surface roughness increases, so that the amplitude of the field scattered by the rough surface or layer decreases, leading to a lower interference dynamics between the direct and the scattered fields. For $H$ polarization, similarly as in Fig. 3, differences between the clean and contaminated seas are observable only around the extrema of $\eta$. They are a bit higher than that in the preceding configuration, but remain weak. For $V$ polarization, the same qualitative conclusions as in Fig. 3 can be drawn.

Fig. 5 presents numerical results in the same configuration as in Fig. 3, but the radar frequency $f$ is ten times lower, i.e. $f = 300$ MHz. For $H$ polarization, comparatively to Fig. 3, the difference between the clean and contaminated seas is much higher, as significant differences appear around the extrema of $\eta$. Nevertheless, one can observe that comparatively to Fig. 3, the periodicity of the extrema of the propagation factor $\eta$ is ten times lower. Then, the observed differences are mainly due to the fact that the scale of $h_2$ is ten times larger, corresponding to a much larger range of the grazing angle $\varphi$, which implies a larger range of the Fresnel reflection coefficient. For $V$ polarization, the same qualitative comments can be done. Nevertheless, one can observe even more significant differences than in Fig. 3. Indeed, in addition to the differences in the amplitudes which are higher, it can be seen that the positions in the extrema of $\eta$ are different for this lower frequency. As explained in [4], it is due to the differences in the phase of the Fresnel reflection coefficient $\angle r_{12}$, owing to the Brewster effect. This phenomenon was not clearly observed in Fig. 3 because $h_2$ had a ten times lower range, leading to a ten times lower phase variation.
Fig. 5. Same configuration as in Fig. [3] except from the radar frequency $f = 300$ MHz.

Fig. 6. Same configuration as in Fig. [4] except from the radar frequency $f = 300$ MHz.

Fig. 5 presents numerical results in the same configuration as in Fig. 4 but the radar frequency $f$ is ten times lower, i.e. $f = 300$ MHz. The same general remarks and conclusions can be drawn in Fig. 5. Thus, the differences between the clean and the contaminated seas are much more significant for $V$ polarization than for $H$ polarization, allowing much easier detection of an oil slick.

5. CONCLUSION

In conclusion, the forward radar propagation over rough surfaces using the Ament model [3] has been extended to the case of rough layers. It is applied to a sea covered in oil (called contaminated sea) for the case of uncorrelated rough surfaces, which corresponds to thick oil spills. For the typical applications (microwave frequencies and coastal radar) presented, for $H$ polarization, a rather low contrast appears for grazing angles. This contrast is increased for lower ranges $x_2$ and higher heights $h_2$ of the receiver [4]. On the contrary, for $V$ polarization, a high contrast in the amplitudes together with in the positions of the extrema of the propagation factor appears, allowing easy oil slick detection. In future work, the model will be extended to a three-dimensional problem.

6. REFERENCES


