Analysis of simulated L-Band signals reflected from a sea surface using time-frequency representations

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***Abstract*—The study proposed in this paper deals with the analysis, in the time-frequency domain, of a L-band signal reflected by an time-evolving sea surface. The final goal of this project is to evaluate the technical potential of passive GNSS based systems to estimate oceanographic parameters. With this purpose in mind, this paper presents the experimental setup and describes the physical modeling applied to generate numerical simulations. We put more particular stress on the time-frequency representation of the signal received by an observer above the time-evolving sea surface. Finally, physical interpretations of the features obtained in the time-frequency domain from these simulated signals are proposed.**

I. Introduction

Passive remote sensing based upon electromagnetic sources of opportunity has become more and more popular for detection and characterization purposes. Among all the possible sources, the Global Navigation Satellite Systems GNSS (GPS, GALILEO, GLONASS,...) appears as one of the most relevant solution since the emitted signals (in L-Band) are reliable, available all over the world, deterministic and perfectly known (free civil signals). The use of these GNSS signals for passive observation has been significantly developed for oceanography purposes since the year 2000. The main estimated parameters are usually the wind velocity and direction, the surface roughness and its effects on the electromagnetic wave or the salinity (see for example [1], [2], [3]).

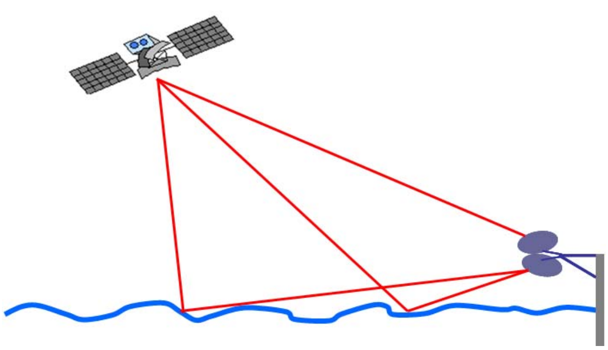

Fig. 1. Experimental setup.

The goal of this paper is to assess the possibility to observe the local movements and the temporal deformations of a sea surface from the reflected signals in L-Band. In this way, we investigate the connections between a time evolving surface and the time-frequency representation of the signal scattered by this surface. The idea is to take advantage of these representations to extract from Doppler and micro-Doppler signatures the oceanographic parameters of interest.

Figure 2 shows the location of possible measurements (Sainte Anne du Portzic - IFREMER site) and the picture of the antennas above the sea surface. The top antenna is for direct path reception (Right Hand Circular Polarization) and the bottom one is for the measurement of the signal reflected by the sea surface (Left Hand Circular Polarization).

Fig. 2. Experimental system and picture of the measurement area.

For a good understanding of the phenomena induced by time evolving sea surfaces upon the reflected signal, our study mainly consists in numerical simulations. Thus, our approach consists in generating time evolving surfaces and to compute the scattered field of a plane wave in L-Band by these surfaces. These numerical estimations are based upon the Method of Moment (MoM) which is a very standard approach to quantify the scattering by sea surfaces in L-Band. Then, the scattered signals received by an observer above the sea are analyzed in the Time-Frequency (TF) domain by using a Wigner-Ville transform. Finally, we provide interpretations of the obtained features in this domain.

It is important to stress that the final goal of our project is to evaluate the capabilities of such passive systems for remote

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sensing applications and more precisely to estimate oceanographic parameters such as wave height, wave orientation, roughness or the local sea state.

The paper is organized as follows. In section II, we briefly describe the method that can be used to model the moving sea surface and the electromagnetic field received by an observer above the sea. Then in section III the features obtained in the time-frequency domain are related to physical phenomena. Finally, section IV gives some concluding remarks.

II. Electromagnetic and Sea Surface Models

The GNSS signal can be considered as a plane Right Hand Circular Polarization (RHCP) incident wave. For the sake of simplicity, we assume one satellite at the Zenith position, so that the incident wave propagates in the Nadir direction, see figure 3.

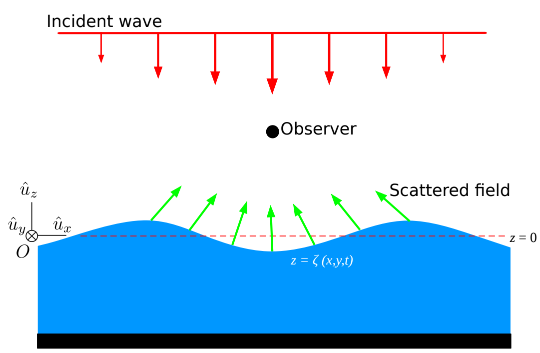

Fig. 3. Geometrical configuration.

Because of the high salinity of the sea water, the electromagnetic model assumes that the sea surface can be approximated by a perfect electric conductor interface. In addition, it worths mentioning that any RHCP wave can be decomposed into two components: TM and TE polarized waves. The scattering by a TM and TE polarized wave can be calculated from the boundary integral equation method and numerical estimations using functional basis: method of moments (see [4] for instance).

Once the electromagnetic model is known, it is necessary to introduce a realistic time evolving sea surfaces associated to a given weather condition (wind speed and wind direction). To achieve this, the Elfouhaily spectral sea model [5] combined with a phase dispersive equation is considered.

III. Time-Frequency Signature Analysis

From the simulated time-evolving surface and using the electromagnetic model, we can analyze the signal recorded by the receiver. In this paper, it is proposed to study this signal in the Time-Frequency (TF) domain using a Wigner-Ville Distribution. As time-frequency representations are well known, it is not proposed an overview of these methods here. However the readers can refer to [6] and to the free TFTB Matlab toolbox for more details.

A. *Surface made of three sinusoids*

By studying the obtained time-frequency features of the signals reflected from canonical moving sea surfaces (typically a sinusoid or the sum of two sinusoids), we found that the main contributors are the specular points. Their motions, see as Doppler frequencies from the receiver point of view, match the global features obtained in the TF domain.

In this paper, we propose to illustrate this fact by considering a surface made of three sinusoids. Each sinusoid s is defined as

$$s(t, x) = A_{sin} \sin(-\omega_{sin} t + k_{sin} x). \quad (1)$$

The main parameters of this surface are the amplitude A_{sin}, the velocity c_{sin}, the angular frequency $\omega_{sin} = 2\pi f_{sin}$ or the wavelength $\lambda_{sin} = c_{sin}/f_{sin}$ and the wavenumber $k_{sin} = 2\pi/\lambda_{sin}$. In (1), t stands for the time and x for the position. To come closer to a realistic sea model, the parameters of this sinusoidal model have been inferred from the sea surface spectral model introduced in Section II. Table I bring these parameters.

Scale	Description	wind speed (m/s)	Amplitude (m)	Wavelength (m)	velocity (m/s)
1	Light air	0.3-1.5	0.0-0.012	0.4-2.44	0.8-1.95
2	Light breeze	1.6-3.3	0.014-0.12	2.77-11.8	2.08-4.29
3	Gentle breeze	3.5-5.4	0.15-0.54	13.3-31.6	4.55-7.02
4	Moderate breeze	5.5-7.9	0.57-1.70	32.8-67.8	7.15-10.27
5	Fresh breeze	8-10.7	1.77-4.23	69.4-124.3	10.4-13.9

TABLE I. Sinusoidal sea surface parameters.

According to the spectral model of the sea surface, a sea is characterized by relevant physical phenomena at various scales: the surface with large wavelength and high amplitude stands for the gravity wave (large-scale roughness) and the surface with smaller wavelength and amplitude stands for the capillary and short gravity waves (small-scale roughness).

Thus, our surface can be defined as the sum of one sinusoid, which stands for the large-scale roughness, and two sinusoids, which stand for the small-scale roughness. Then, in what follows, each of the three sinusoids has a different wavelength, amplitude and velocity. The first sinusoid (large-scale) uses the parameters corresponding to Beaufort scale 3. The two others added sinusoids (small-scale) are fixed so that the wavelength is respectively divided by 3 and 5, the amplitude is divided by 2 and 5 and the velocity is multiplied by 1.25 and 1.6.

This model correspond to the fact that sea surface can be considered as a dispersive medium (speed of the sea waves depends upon the wavelength). This dispersion induces deformations over time in addition to the translation which act upon the TF features.

The Time-Frequency representation (TFR) obtained for the considered configuration is presented in Figure 4. This TF representation brings quite complex phenomena that deserve sustained analysis (in comparison with a simple sinusoidal surface). Thus Figure 5 shows zooms of two areas of interest in Figure 4: from $t = 2$s to $t = 3$s and from $t = 6$s to $t = 7.5$s.

In addition, Figures 6 and 7 show the shape of the sea surface with the corresponding specular points at several successive times in these two periods.

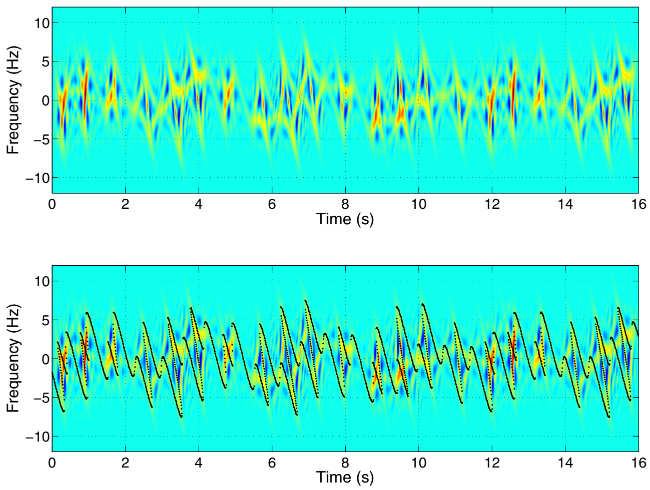

Fig. 4. TF representation of the signal reflected from a surface made of the sum of three sinusoids with different velocities. In the bottom image the Doppler frequency due to the specular points is added (black dots).

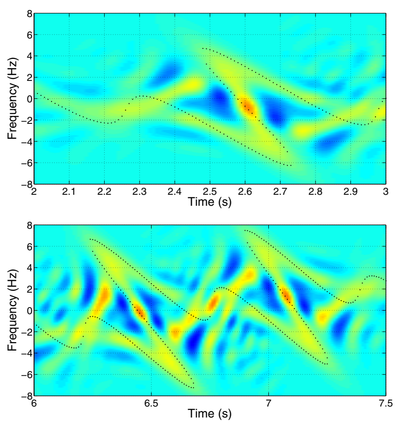

Fig. 5. Zoom on an area of interest in Figure 4.

Between $t = 2.13$s and $t = 2.39$s there is only one specular point inducing a Doppler curve that appears to be oscillating. In Figure 6, we can see that in a first step ($t = 2.13$s/2.14s) the specular point moves away from the receiver with a speed greater than the global sea movement. Then Doppler frequency is negative and lower than that obtained for a harmonic sea surface. In a second step ($t = 2.25$s/2.26s) the specular point locally tends to move closer to the receiver. The Doppler frequency increases and even reaches a positive maximum. In the last step ($t = 2.38$s/2.39s), the specular point speeds up the shift to the right, and the Doppler frequency returns to the negative domain. This oscillation cannot be explained by a global translation of the sea surface but must be seen as the consequence of the local sea surface deformations related to dispersion.

The deformations due to dispersion increase the complexity of the local curvature observed at the sea surface. Between $t = 6.21$s and $t = 6.26$s, the number of specular points changes

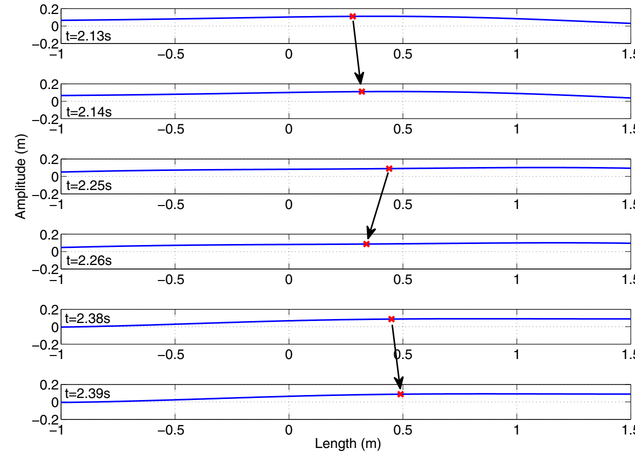

Fig. 6. Three sets of two (zoom) successive surfaces (blue line) and the evolving positions (shown by the black arrows) of the specular point (red star).

over time. Figure 7 shows that there is only one specular point from $t = 6.21$s to $t = 6.22$s. Then, a new specular point appears at $t = 6.23$s. Finally this new point forks into two new specular points. One of them moves closer (locally) to the observer and the other moves away.

In the same way, we can see that dispersion and the local deformations of the sea surface periodically lead to the disappearance of one or more specular points. Somehow we must highlight the fact that the Doppler curves associated to each specular points still form a continuous Global Doppler curve.

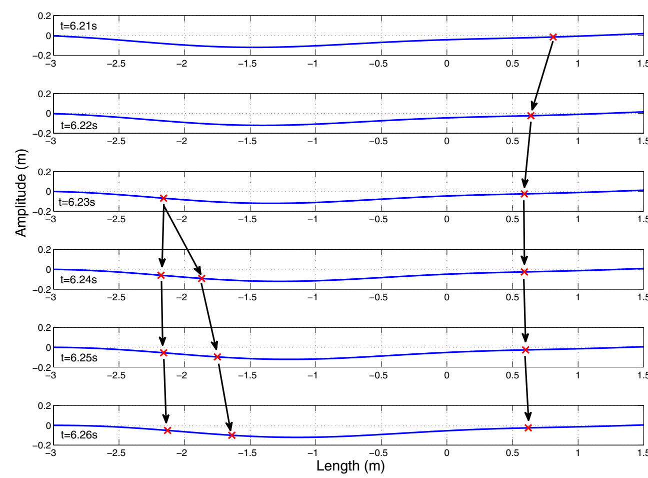

Fig. 7. Example showing (zoom) six successive surface shapes (blue line) and the evolving positions (shown by the black arrow) of the specular points (red star).

B. Sea surface

Figures 8 shows the TFR obtained from the signal reflected from sea surfaces with respectively Beaufort scale 2, 2.5, 3 3.5, 4 and 4.5. For the sea surface with Beaufort scale 2, from the receiver point of view, the surface is almost flat which is why the time frequency feature is mainly focused upon the zero-Doppler frequency line. The oscillations around this strip, called micro-Doppler phenomena, are linked with the small oscillation of the surface.

For the other sea states, the surface can no longer be considered to be almost flat and then the TF feature appears as a far more structured geometry.

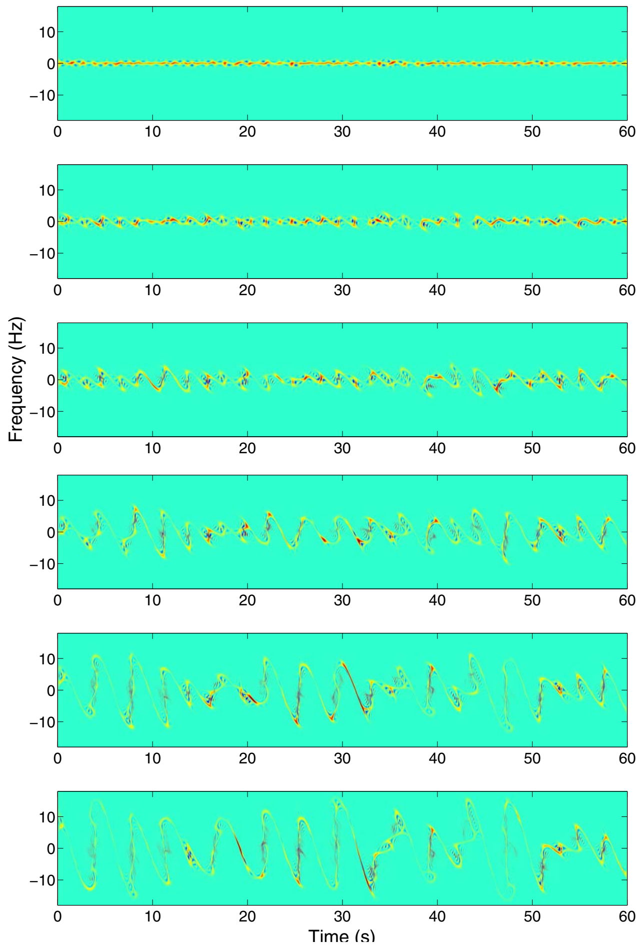

Fig. 8. TF representation of the reflected signals from sea surface with Beaufort scales (top to buttom) 2, 2.5, 3, 3.5, 4, 4.5.

These TF representations suggest that there is great potential for feature extraction and remote sensing applications. At first glance, we can see that the spreading of the Doppler frequency is in close conjunction with the sea state. This is illustrated in figure 9 which shows the (normalized) power distribution according to the Doppler frequency obtained from the pictures in figure 8. It can also be notated that the micro-Doppler signature is directly related to the surface roughness and the fluid dynamics of the sea surface.

Let us consider now the sea surface with Beaufort scale 2.5. Figure 10 shows the corresponding TF of the reflected signal. It also shows the Doppler evolutions, according to the time, of the specular points.

Figure 12 shows the shape of the sea surface and the position of the specular points for several times highlighted in figure 11 by a vertical black line.

If we take a closer look at the shape of the surface and

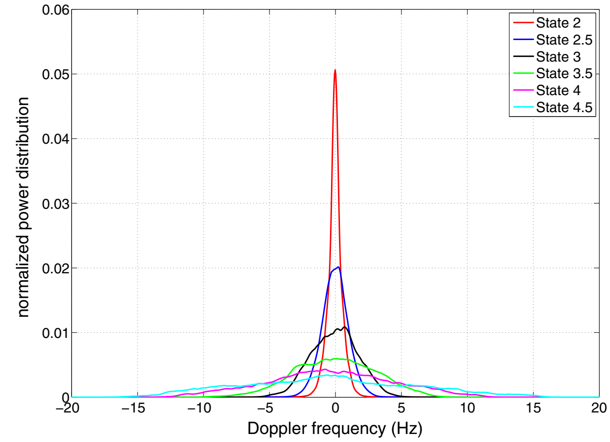

Fig. 9. Normalized power distribution for several sea states.

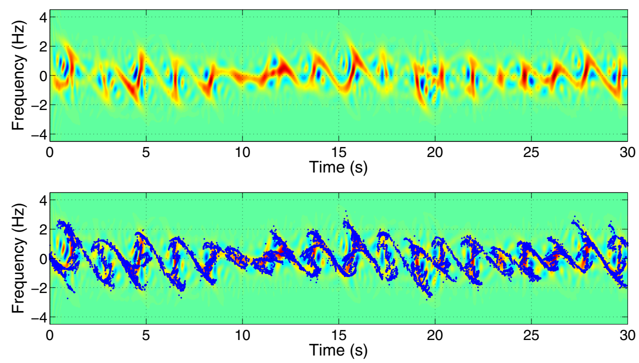

Fig. 10. (a) TF representation of the reflected signal from a sea surface and (b) superposed with blue dots the Doppler frequency of the specular points according to the time.

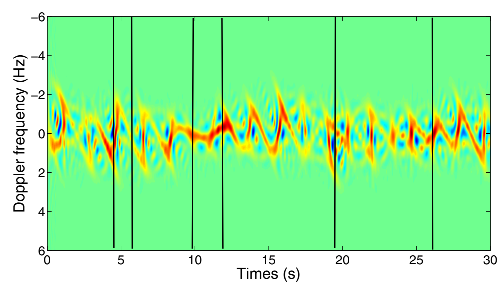

Fig. 11. TF representation same as figure 10.a with highlightes times (vertical black line) corresponding to the sea surface snapshot in figure 12.

the motion of the specular points, one can see specular points which are moving away from the receiver, in the receiver direction, or combining successively both motions. One can also observe the evolution of the number of specular points in a given (small) area. All these motions have an influence upon the reflected electromagnetic waves according to the sea surface deformations and, consequently, on the TF features. This shows that from the TF representation one can expect to estimate some parameters of the sea surface (which will be the focus of the forthcoming works) like for example the (global) height, the direction and velocity of the waves, or the sea roughness...

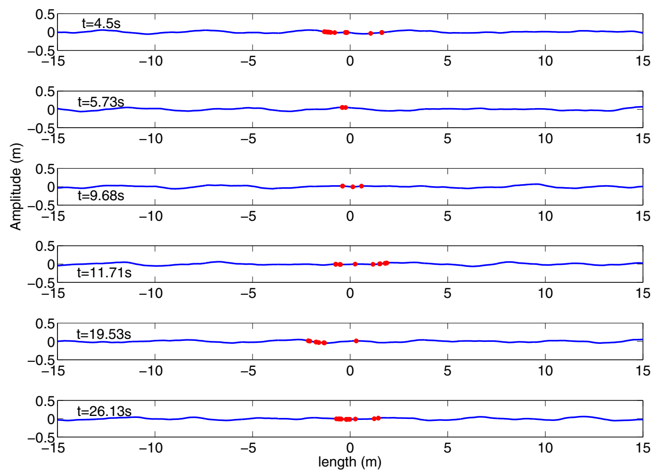

Fig. 12. Shape of the sea surface at several times and the corresponding speculare points (red stars).

IV. Conclusion

In this work, the features obtained in the Time-Frequency (TF) domain due to L-band signals reflected from moving sea surfaces are described and interpreted. It has been shown that the signatures in the TF domain are linked to physical phenomena that occur in the considered measurement systems. The main features can be explained by the motion of the specular points. However the multiple interactions also induce some features but with a lower extent. Finally, one can note that future works will deal with the estimation of oceanographic parameters from these TF features.

References

[1] A. Komjathy, V. U. Zavorotny, P. Axelrad, G. H. Born, and J. L. Garrison, “GPS signal scattering from sea surface: Wind speed retrieval using experimental data and theoretical model,” *Remote Sensing of Environment*, vol. 73, no. 2, pp. 162–174, 2000.

[2] J. L. Garrison, J. K. Voo, S. H. Yueh, M. S. Grant, A. G. Fore, and J. S. Haase, “Estimation of sea surface roughness effects in microwave radiometric measurements of salinity using reflected global navigation satellite system signals,” *IEEE Geoscience and Remote Sensing Letters*, vol. 8, no. 6, pp. 1170–1174, 2011.

[3] J. F. Marchan-Hernandez, M. Vall-llossera, A. Camps, N. Rodriguez-Alvarez, I. Ramos-Perez, E. Valencia, X. Bosch-Lluis, M. Talone, J. M. Tarongi, and M. Piles, “Ground-based GNSS-R measurements with the PAU instrument and their application to the sea surface salinity retrieval: First results,” in *IEEE International Geoscience and Remote Sensing Symposium (IGARSS)*, vol. 4, 2008, pp. 530–533.

[4] L. Tsang, J. A. Kong, K.-H. Ding, and C. O. Ao, *Scattering of electromagnetic waves. Numerical simulations*, J. A. Kong, Ed. John Wiley & Sons, 2001.

[5] T. Elfouhaily, B. Chapron, K. Katsaros, and D. Vandemark, “A unified directional spectrum for long and short wind-driven waves,” *J. of Geophysical Research*, vol. 102, no. C7, pp. 15 781–15 796, 1997.

[6] B. Boashash, *Time-Frequency Signal Analysis and Processing. A Comprehensive Review*. Elsevier, 2003.