SIMULATION OF GNSS-R SIGNALS IN ARBITRARY VIEWING GEOMETRY WITH A CLOSED-FORM BISTATIC TWO-SCALE MODEL

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ABSTRACT

In this paper, we provide a link budget analysis of the Global Navigation Satellite System-Reflectometry (GNSS-R) signal scattered off the sea surface in arbitrary viewing geometries. The study is based on a recent electromagnetic scattering two-scale model for rough surfaces, named BA-PTSM, which is able to accurately describe the microwave scattering from sea surface at any acquisition geometry, including backscattering and forward-scattering, and on a simulator that accounts for geometrical and system parameters. Comparisons with Geometrical Optics (GO), whose validity is limited to specular and quasi-specular scattering, demonstrate that a reliable simulation of GNSS-R signals in configurations other than the conventional forward-scattering one calls for scattering models more accurate than GO, e.g., BA-PTSM.

Index Terms— ***GNSS-Reflectometry, two-scale model, bistatic radar, sea surface scattering***

1. INTRODUCTION

The exploitation of Global Navigation Satellite System (GNSS) signals of opportunity for remote sensing and Earth observation applications has been widely demonstrated in the last decades. GNSS signals scattered off the Earth' surface convey key information about the physical and geometric properties of the illuminated surface and have been exploited successfully in many fields such as oceanography, cryosphere and land [1].

More recently, GNSS-R observables are experiencing an increasing interest for maritime surveillance applications, e.g., ship detection, where it appears to be a prospective and attractive solution for global coverage and near real-time monitoring capabilities [2]. A number of theoretical analyses and simulation studies have been carried out in order to investigate the potentialities of GNSS-R for maritime surveillance purposes, see e.g., [3], [4], [5]. The main outcome of these works is that non-conventional geometries which are far enough from the forward scattering one typically adopted for sea surface analysis, are more suited to ship detection applications. This has been recently demonstrated in a simulation study based on a stochastic simulation of the delay-Doppler map (DDM) [6]. However, all previous works assume scattering from sea surface modeled through Geometrical Optics (GO) which is reliable in a limited angular region surrounding the specular reflection direction. Indeed, as it is well known, GO accuracy is poor when moving far from the specular direction.

To safely extend the analysis of sea surface scattering to arbitrary viewing geometries, the bistatic anisotropic polarimetric two-scale model (BA-PTSM) has been presented recently [7]. BA-PTSM is a closed-form electromagnetic scattering model that generalizes the polarimetric two-scale model (PTSM) first introduced in [8] to bistatic configuration and to anisotropic rough surfaces, as sea surface. It allows for computing the covariance matrix of sea surface scattering in an efficient and accurate way in a wide range of acquisition geometries.

In this paper, we exploit the BA-PTSM, in conjunction with a simulator that accounts for geometrical and system parameters, to provide a more accurate link budget analysis of the GNSS signal scattered off the sea surface and collected by both spaceborne and airborne GNSS-R receivers in arbitrary viewing geometries, including backscattering.

The paper is organized as follows: Section 2 briefly describes the BA-PTSM exploited for computing sea surface scattering. Section 3 introduces the link budget analysis for the evaluation of the signal-to-noise ratio (SNR). Numerical results comparing the BA-PTSM and the classical GO are then presented and discussed in Section 4, whereas concluding remarks are highlighted in Section 5.

2. SCATTERING MODEL FOR SEA SURFACE

Conventional GNSS-R systems operate in a forward-scattering configuration, where the delay and Doppler bins processed by the receiver are limited to a region surrounding the specular reflection point. Accordingly, over oceans, the received signal strength is typically modeled via GO assuming a bivariate normal distribution for local slopes in order to account for sea surface anisotropy. However, if acquisition geometries other than the forward-scattering one are of interest (e.g., in maritime surveillance applications), more accurate scattering models are required.

The BA-PTSM is based on the well-assessed TSM, which is a method to compute backscattering from rough surfaces [9]. According to TSM, the scattering coefficient of the sea surface is expressed as the sum of the scattering contributions from the small-scale roughness and large-scale roughness components of the scattering surface. The scattering contribution from the small-scale roughness is evaluated via the Small Perturbation Method (SPM) and mainly depends on the small-scale roughness spectrum, whereas scattering from the large-scale roughness is evaluated through GO and is mainly related to the large-scale roughness root mean square slopes. Additionally, the former dominates the scattering in far-from-specular directions, whereas the latter is the dominant term around the specular reflection direction. Differently from the original TSM, which can be expressed in closed form only for the co-polarized scattering coefficients, the PTSM provides closed-form expressions of the whole covariance matrix in backscattering so that cross-polarization and de-polarization effects can be analytically evaluated [8]. More recently, the PTSM has been further extended to deal with anisotropic surfaces (A-PTSM) [10] and bistatic geometries (BA-PTSM) [7].

According to BA-PTSM, the scattering surface is described as a superposition of randomly rough facets, whose roughness is the small-scale roughness; then, the facets are randomly tilted according to the slope of the large-scale roughness. The overall surface is then defined by the power spectral density (PSD) of the small-scale roughness and the probability density distribution of the facets' slopes. The PSD of the facet roughness is modeled according to the high-frequency part of the Elfouhaily spectrum. The surface slopes of the large-scale roughness, s_x and s_y, are described as zero-mean jointly Gaussian random variables. Both the PSD and the slopes' variances and correlation depend on the wind speed and direction as illustrated in [7].

The elements of the covariance matrix $R_{pq,rs}$ are then evaluated as

$$R_{pq,rs} = R_{pq,rs}^{GO} + \langle R_{pq,rs}^{SPM} \rangle_{s_x,s_y} \quad (1)$$

where the subscripts p, q, r, and s may each refer to horizontal and vertical polarization and the symbol $\langle \cdot \rangle_{s_x,s_y}$ represents the statistical mean with respect to the random variables s_x and s_y. The SPM contribution from the tilted rough facet $R_{pq,rs}^{SPM}$ is evaluated via a second-order power-series expansion with respect to the slopes s_x and s_y. The bistatic scattering coefficients σ_{sea}^0 in linear polarization coincide with the diagonal terms of the covariance matrix. Finally, results in circular polarizations, which are of interest in GNSS-R, are obtained through a basis change [7].

BA-PTSM has been proved to offer much wider validity limits and more accurate predictions with respect to GO. As a matter of fact, BA-PTSM showed a good agreement with much more complex and computationally-demanding scattering models such as the second-order small-slope approximation (SSA2) [7].

3. LINK BUDGET ANALYSIS

The power of the received signal at the output of the GNSS-R receiver is evaluated as

$$P_{r,sea} = P_t G_t G_r \frac{1}{(4\pi)^3} \left(\frac{\lambda \cos\vartheta \cos\vartheta_s}{h_t h_r} \right)^2 A_{sea} \sigma_{sea}^0 . \quad (2)$$

In (2), the scattering coefficient of sea surface is evaluated via BA-PTSM. The scattering model takes as input viewing geometry parameters –viewing and scattering angles–, sensors parameters –radar frequency, polarization–, and scene parameters –dielectric constant (complex) of seawater, wind speed U_{10} and wind direction φ_w.

Noise power at the output of the receiver front-end is evaluated as

$$P_n = k_B (T_a + T_e) B_W . \quad (3)$$

Then, SNR at the output of the incoherent integration can be computed as

$$SNR = B_W T_c \sqrt{\frac{T_i}{T_c}} \frac{P_{r,sea}}{P_n} . \quad (4)$$

In (2) and (3) k_B stands for the Boltzmann constant; all other symbols are defined in Table I assuming Global Positioning System as the transmitting GNSS and SGR-ReSi and GOLD-RTR as the spaceborne and airborne GNSS-R receivers, respectively [6]. Viewing and scattering angles are defined according to the reference system shown in Fig. 1.

TABLE I: LIST OF SYMBOLS AND VALUES.

Symbol	Parameter	Value
P_t	Transmitted power	26.61 W
G_t	Transmitting antenna gain	13 dBi
G_r	Receiving antenna gain	13.3 dBi (spaceborne) 15.05 dBi (airborne)
λ	GNSS wavelength	0.19 m
ϑ	Viewing angle	Varying
ϑ_s	Zenith scattering angle	Varying
h_t	Transmitter altitude	20200 km
h_r	Receiver altitude	540 km (spaceborne) 10 km (airborne)
A_{sea}	Scattering area	Varying
σ_{sea}^0	Sea scattering coefficient	Evaluated according to [7]
T_a	Receiving antenna noise temperature	99.4 K
T_e	Receiver noise temperature	374.35 K (spaceborne) 161.23 K (airborne)
B_W	Receiver bandwidth	2.5 MHz (spaceborne) 24 MHz (airborne)
T_i	Incoherent integration time	1 s
T_c	Coherent integration time	1 ms (spaceborne) 10 ms (airborne)
τ_c	Chip length	977.52 ns

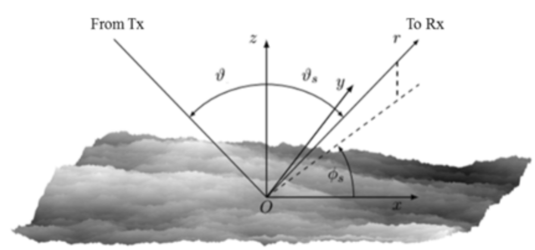

Figure 1: Coordinate system.

In (4) it is assumed that the incoherent integration typically performed on board GNSS-R instruments leads to an integration gain equal to the square root of the number of incoherently integrated DDMs.

4. NUMERICAL RESULTS

In this section, we provide some numerical results of the link budget analysis described in Section 3. The SNR is evaluated according to (2)-(4) with parameters values reported in Table I. The evaluation of the scattering area A_{sea} is performed via a simulator that accounts for the acquisition geometry, i.e., the viewing and scattering angles and the receiving antenna beamwidth. In particular, in order to compute A_{sea}, first the GNSS-R delay-Doppler resolution cell $A_{cell} = \Delta\tau\Delta f_d$ is projected onto a geographical coordinate system, $\Delta\tau$ and Δf_d being the widths of the Woodward Ambiguity Function along the delay and Doppler axes, respectively, i.e., $\Delta\tau = 2\tau_c$ and $\Delta f_d = 2/T_c$. Then, A_{sea} is computed as the portion of A_{cell} falling within the receiving antenna footprint. In this study, a beamwidth of 30° has been considered. Additionally, here we assume that the ambiguity problem which affects GNSS-R systems (see [1]) has been solved through, e.g., a proper pointing of the receiving antenna.

Results comparing our BA-PTSM with GO are shown in Fig. 2 and Fig. 3, where the SNR is plotted as a function of the zenith scattering angle ϑ_s for both right-hand (R) and left-hand (L) circular polarization channels and for different azimuth scattering angle φ_s. Viewing angle ϑ = 15°, wind speed U_{10} = 10 m/s and wind direction φ_w = 0° have been assumed. As it is expected, *i)* the RL channel provides larger SNR values regardless of the acquisition geometry; *ii)* largest SNR is achieved around the forward-scattering direction ($\vartheta_s = \vartheta$ and φ_s = 0°) as both the scattering coefficient and the resolution cells attain their maximum. It is also evident that BA-PTSM reduces to GO in directions around the specular reflection direction where GO contribution dominates. However, when moving far from the typical forward-scattering configuration, GO becomes inaccurate as it severely underestimates the received signal strength. This is crucial for simulation of airborne GNSS-R signals even with standard receivers, e.g., GOLD-RTR, as, in this case, the departure of GO from BA-PTSM begins at SNR values still significantly larger than 0 dB. Conversely, it emerges that for the simulation of sea surface returns with standard spaceborne GNSS-R receivers such as SGR-ReSi, GO can be safely adopted regardless of the acquisition geometry, because it diverges from BA-PTSM when both models predict a very low SNR.

5. CONCLUSION

In this paper, a link budget analysis of the GNSS signal scattered off the sea surface is carried out in order to estimate the SNR at the receiver output in arbitrary acquisition geometries. The BA-PTSM is used for an accurate and efficient evaluation of sea surface scattering. Numerical results have shown that when simulation of airborne GNSS-R signals in acquisition geometries other than the conventional forward-scattering one is of interest –e.g., in maritime surveillance applications –, GO is no longer appropriate to describe surface scattering as it would significantly underestimate the received signal strength. Indeed, a reliable and fast simulation of airborne GNSS-R observables, e.g., DDM, in arbitrary viewing geometry calls for scattering models more accurate than GO and more efficient than SSA2. In this direction, BA-PTSM proved to be a good solution. The results presented in this study might be exploited for a more accurate assessment of the potentialities and limits of GNSS-R for maritime surveillance purposes.

6. REFERENCES

[1] V. U. Zavorotny, S. Gleason, E. Cardellach, and A. Camps, “Tutorial on remote sensing using GNSS bistatic radar of opportunity,” *IEEE Geoscience and Remote Sensing Magazine*, vol. 2, no. 4, pp. 8–45, 2014.

[2] A. Di Simone, *et al.*, “Sea target detection using spaceborne GNSS-R delay-Doppler maps: Theory and experimental proof of concept using TDS-1 data,” *IEEE J. Sel. Topics Appl. Earth Observ. Remote Sens.*, vol. 10, no. 9, pp. 4237–4255, 2017.

[3] A. Di Simone, A. Iodice, D. Riccio, A. Camps, and H. Park, “GNSS-R: A useful tool for sea target detection in near real-time,” *2017 IEEE 3rd International Forum on Research and Technologies for Society and Industry (RTSI)*, pp. 1–6, 2017.

[4] A. Di Simone, P. Braca, L. M. Millefiori and P. Willett, "Ship detection using GNSS-reflectometry in backscattering configuration," *2018 IEEE Radar Conference (RadarConf18)*, Oklahoma City, OK, 2018, pp. 1589-1593.

[5] B. J. Southwell, J. W. Cheong and A. G. Dempster, "A Matched Filter for Spaceborne GNSS-R Based Sea-Target Detection," *IEEE Trans. Geosci. Remote Sens.*, vol. 58, no. 8, pp. 5922-5931, Aug. 2020.

[6] T. Beltramonte, *et al.*, "Simulation-Based Feasibility Analysis of Ship Detection Using GNSS-R Delay-Doppler Maps," *IEEE J. Sel. Topics Appl. Earth Observ. Remote Sens.*, vol. 13, pp. 1385-1399, 2020.

[7] G. Di Martino, A. Di Simone, A. Iodice and D. Riccio, "Bistatic Scattering From Anisotropic Rough Surfaces via a Closed-Form Two-Scale Model," *IEEE Trans. Geosci. Remote Sens.*, vol. 59, no. 5, pp. 3656-3671, May 2021.

[8] A. Iodice, A. Natale, and D. Riccio, “Retrieval of Soil Surface Parameters via a Polarimetric Two-Scale Model”, *IEEE Trans. Geosc. Remote Sens.*, vol. 49, no. 7, pp. 2531-2547, July 2011.

[9] G. R. Valenzuela, “Scattering of Electromagnetic Waves from a Tilted Slightly Rough Surface”, *Radio Sci.*, vol. 3, pp. 1057-1066, 1968.

[10] G. Di Martino, A. Iodice, D. Riccio, “Closed-Form Anisotropic Polarimetric Two-Scale Model for Fast Evaluation of Sea Surface Backscattering”, *IEEE Trans. Geosc. Remote Sens.*, vol. 57, no. 8, pp. 6182-6194, 2019.

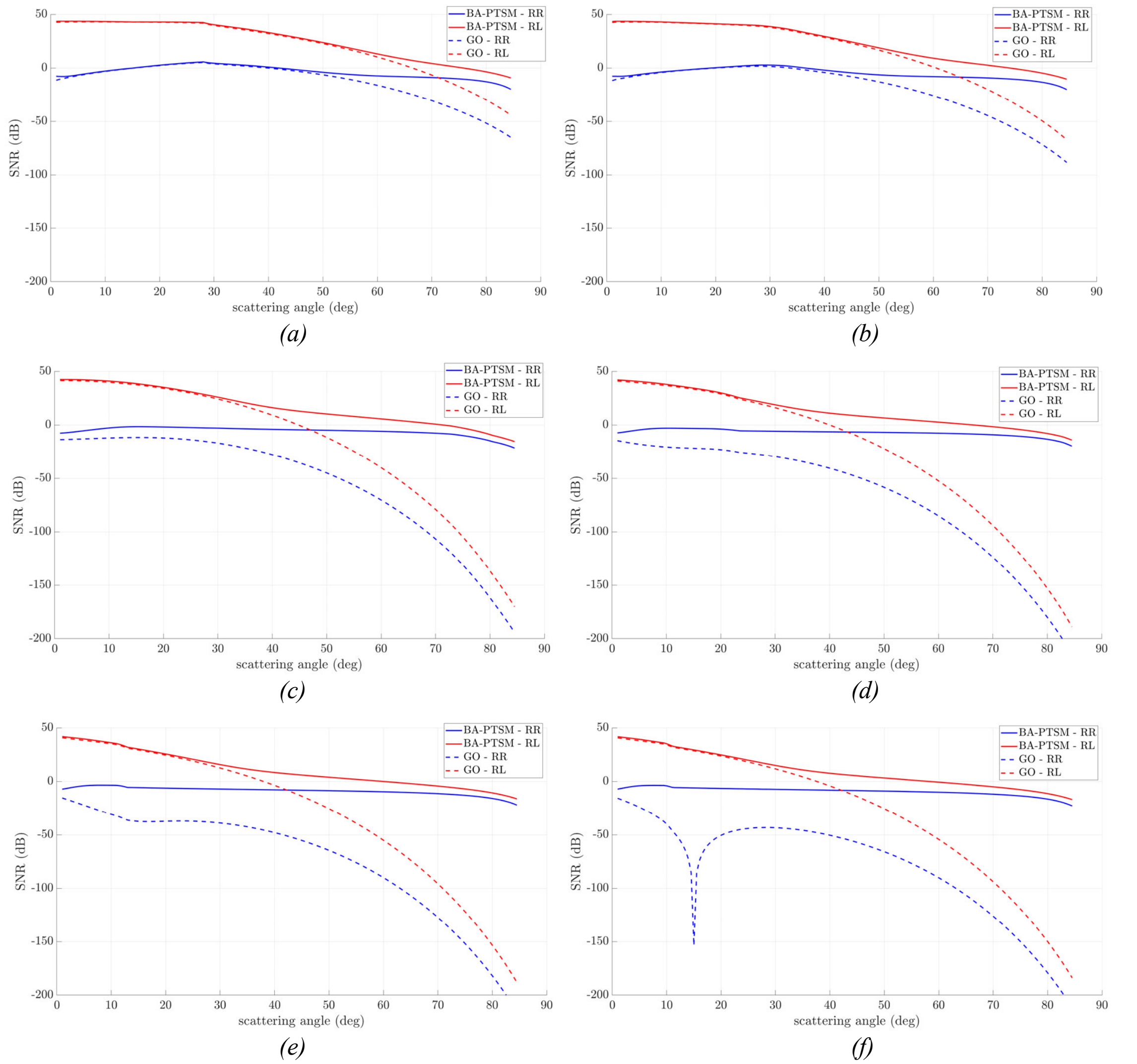

Figure 2: SNR as a function of the scattering angle ϑ_s in RR (blue lines) and RL (red lines) for an airborne GNSS-R receiver. Viewing angle is $\vartheta = 15°$. BA-PTSM (solid lines) is compared with GO (dashed lines). (a) $\varphi_s = 0°$; (b) $\varphi_s = 30°$; (c) $\varphi_s = 90°$; (d) $\varphi_s = 120°$; (e) $\varphi_s = 150°$; (f) $\varphi_s = 180°$.

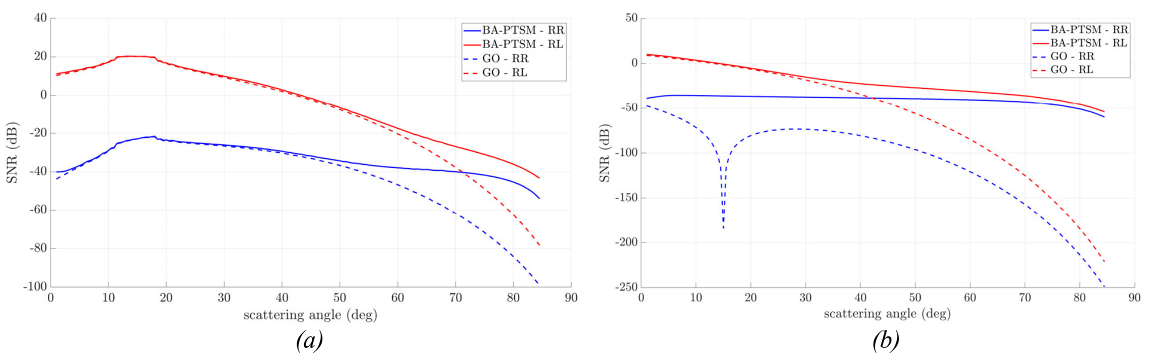

Figure 3: SNR as a function of the scattering angle ϑ_s in RR (blue lines) and RL (red lines) for a spaceborne GNSS-R receiver. Viewing angle is $\vartheta = 15°$. BA-PTSM (solid lines) is compared with GO (dashed lines). (a) $\varphi_s = 0°$; (b) $\varphi_s = 180°$.