

Random Surface Scattering Models of RR Polarization for SoOp-R/GNSS-R Application

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Abstract

–LR polarization is commonly used for the corresponding geophysical parameters retrieval in GNSS#2; R (Global Navigation Satellite System-Reflectometry) or SoOP-R (Signal of Opportunity-Reflectometry) . However, the other polarization of the reflected signals has attracted more and more attention with the development . The popular used equation for RR polarization demonstrates that it decreases as the soil moisture content increase and this is in contradiction with the experiment data. Here, three new models have been developed: Spec4PolR (Specular reflectivity model for polarization GNSS#2; R), SPM4Pol (small perturbation model for polarization GNSS#2; R), and Umich4Pol (Umich model for polarization GNSS-R). The Mueller matrix of these three models has been presented and the wave synthesis technique is employed to calculate the reflectivity at RR polarization. Spec4polR employs only three elements in the Mueller matrix for the final reflectivity, while five elements for Umich4polR participate in the calculation and although all the elements of the SPM4Pol have constructed the Mueller matrix and only nine elements have been employed for calculation. Each elements' effects on the soil moisture content are presented and the final reflectivity at RR polarization has been illustrated. However, due to the simple formulations of Spec4Pol, its reflectivity at RR polarization still decreases as the soil moisture content increase. while the results of SPM4Pol and Umich4Pol are consistent with the measured data and the reflectivity at RR polarization increase as the soil moisture content increase. The accurate forward calculation of RR polarization is crucial for the subsequent retrieval algorithm of polarization GNSS-R/SoOP-R.

Full Text

Preamble

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Abstract

LR polarization is commonly used for geophysical parameter retrieval in GNSS-R (Global Navigation Satellite System-Reflectometry) or SoOp-R (Signal of Opportunity-Reflectometry). However, the other polarization of the reflected signals has attracted increasing attention with recent technological developments. The popularly used equation for RR polarization demonstrates that reflectivity decreases as soil moisture content increases, which contradicts experimental data. Here, we have developed three new models: Spec4PolR (Specular reflectivity model for polarization GNSS-R), SPM4Pol (Small Perturbation Model for polarization GNSS-R), and Umich4Pol (Umich model for polarization GNSS-R). The Mueller matrix of these three models has been presented, and the wave synthesis technique is employed to calculate reflectivity at RR polarization. Spec4PolR employs only three elements in the Mueller matrix for the final reflectivity calculation, while five elements participate in the calculation for Umich4PolR. Although all elements of SPM4Pol construct the Mueller matrix, only nine elements are employed for calculation. Each element's effects on soil moisture content are presented, and the final reflectivity at RR polarization is illustrated. However, due to the simple formulations of Spec4PolR, its reflectivity at RR polarization still decreases as soil moisture content increases, while the results of SPM4Pol and Umich4Pol are consistent with measured data and show that reflectivity at RR polarization increases as soil moisture content increases. Accurate forward calculation of RR polarization is crucial for subsequent retrieval algorithms in polarization GNSS-R/SoOp-R.

Index Terms—GNSS-R, RR polarization, SoOp-R, Specular reflectivity

I. Introduction

The retrieval of global geophysical parameters at large spatiotemporal scales is a critical requirement for the Earth science community, and Signals of Opportunity (SoOp)-based systems have recently emerged as a novel microwave remote sensing domain. The main principle of the SoOp-R approach is to receive and extract information from free illuminators after their signals reflect off the Earth's surface. In contrast to traditional microwave remote sensing, existing signal sources are used in a bistatic configuration with the transmitter and receiver separated by a considerable distance [?].

Since the 1990s, the SoOp-R concept has been extensively used for collecting and modeling Global Navigation Satellite System (GNSS) signal reflections over the ocean surface to estimate wind vectors [?]. Later, its applications on land surfaces have emerged and become increasingly promising, such as soil moisture or root zone soil moisture estimation [?, ?], vegetation water content [?, ?], and snow water content or biomass equivalent evaluation [?] using SoOp-R or GNSS-R. As an emerging remote sensing method, SoOp-R/GNSS-R essentially utilizes sensors to detect the scattering and reflection characteristics of electromagnetic waves from objects. Polarization is an important characteristic of electromagnetic waves, defined as the variation of the electric field trajectory over time at a certain position.

In initial GNSS-R studies, it was believed that navigation satellites emitted right-handed circularly polarized (RHCP) signals. Due to the weak signal energy reflected from the surface, it was necessary to use left-handed circularly polarized (LHCP) signals to effectively isolate the impact of direct signals and study the reflection characteristics of ground objects [?]. Regardless of whether in ocean or land domains, the focus has been on LR polarization (the transmitted signals are RHCP while the received ones are LHCP), meaning researchers have inverted surface parameters using LR polarization reflected signals [?].

However, with the development of GNSS-R technology, exploration and analysis of other polarization characteristics have never stopped. For example, in monitoring land surface soil moisture, the receiver of the BAO tower in-situ measurement uses antennas with different polarizations to measure surface reflection signals and then analyzes the sensitivity of various polarizations to soil moisture. The receiver antenna includes a low-gain RHCP antenna pointing toward the zenith to receive direct signals and five receiver antennas pointing toward the ground: one low-gain LHCP and four high-gain (approximately 12 dB) antennas, i.e., V, H, RHCP, and LHCP [?]. One important point is that experimental results are inconsistent with theoretical model results due to simplistic model assumptions.

On satellite receivers, the antennas of UK-DMC (United Kingdom-Disaster Monitoring Constellation), CYGNSS (Cyclone Global Navigation Satellite System), and F3E GNOS-R (GNSS Occultation Sounder II-Reflectometry) are all LR polarization, and several results have been achieved in the inversion of wind

speed, SWH (Sea Wave Height), soil moisture, and vegetation biomass [?, ?, ?]. Using a combination of L-band radiometry and SAR, the Soil Moisture Active Passive (SMAP) mission was launched in 2015 with the objective of studying Earth's surface properties, with soil moisture and freeze/thaw being its primary objectives. Shortly after launch, the radar ceased normal activities while the SMAP radar receiver was adjusted to capture GPS L2 reflected signals, which we call SMAP-Reflectometry (SMAP-R)—a special polarimetric GNSS-R. Furthermore, computation of the signal's Stokes parameters allows for full reconstruction and a better understanding of the polarimetric properties of the received signal. With polarimetric SMAP-R data, reflectivity at not only LR polarization but also RR (the transmitted and received signals are both RHCP polarization), VR (the transmitted signals are RHCP while the received ones are vertical polarization), and HR (the transmitted signals are RHCP while the received ones are horizontal polarization) polarizations were used for final soil moisture or surface roughness estimation [?, ?].

Before the end of 2024, HydroGNSS, which has been selected as the second Scout small satellite mission, will be built and launched. Different from previous CYGNSS, one unique feature of HydroGNSS is its polarization. DDMs will be gathered from the antenna's left- and right-hand circular polarizations. The ratio of the two polarizations (RR/LR) can assist in distinguishing soil roughness effects from soil wetness, as well as in distinguishing biomass from ground reflections [?]. We can see that, unlike traditional research on LR polarization characteristics, using RR polarization to study ground features is an important research method, and the study of RR polarization characteristics is an inevitable trend for the development of polarimetric GNSS-R. Therefore, the study of the mechanism model of RR polarization is particularly important [?].

In this paper, we begin with the principles and formulas of three developed RR polarization models. The theoretical fundamentals are presented in Section II, numerical simulation results are provided in Section III, and conclusions are presented in Section IV.

II. Theoretical Fundamentals

In this section, we present the theoretical fundamentals for random surface scattering models of RR polarization. For an ideal smooth surface, reflectivity is determined by the Fresnel reflection coefficient and the polarization mode of the incident signals [?]. The Fresnel reflection coefficients for horizontal and vertical polarizations are:

$$\Gamma_h = \frac{\cos \theta - \sqrt{\varepsilon_r - \sin^2 \theta}}{\cos \theta + \sqrt{\varepsilon_r - \sin^2 \theta}} \quad (1)$$

$$\Gamma_v = \frac{\varepsilon_r \cos \theta - \sqrt{\varepsilon_r - \sin^2 \theta}}{\varepsilon_r \cos \theta + \sqrt{\varepsilon_r - \sin^2 \theta}} \quad (2)$$

where θ is the incidence angle and ε_r is the complex dielectric constant; the subscripts h and v denote the polarization state. For completely smooth surfaces, cross-polarization can be ignored. For GNSS signals, the satellite transmission signal is RHCP, which can be understood as a linear combination of horizontal and vertical polarization components [?]:

$$\Gamma_{RR} = \frac{1}{2}(\Gamma_v - \Gamma_h) \quad (3)$$

Equation (3) is the commonly used formula to calculate specular reflectivity at RR polarization, and its relationship with soil moisture content is demonstrated in Fig. 1 [Figure 1: see original paper]. The variation of reflectivity at RR polarization versus soil moisture content at different incidence angles (10°, 20°, 30°, and 65°) is presented in Fig. 1. From the simulations, it can be seen that reflectivity simulated using (3) decreases with increasing soil moisture. However, both the BAO tower experiment and SOMOSTA (Soil Moisture Monitoring Station) in-situ measurements show that reflectivity of RR polarization increases with soil moisture content [?, ?]. Therefore, there is a contradiction between results obtained from (3) and in-situ measured data.

A. Wave Synthesis Technique

To solve this problem, we provide three models for evaluation in this section. Since we want to calculate specular reflectivity at RR polarization, we employ the wave synthesis technique to obtain polarization properties [?]. The electric field can be represented by an E-vector with components E_v and E_h , representing vertical and horizontal polarization components, respectively. One set of parameters for characterizing polarization state is the four Stokes representation, which consists of Stokes parameters I , Q , U , and V . I represents the total intensity of the wave, Q represents the difference between vertically polarized intensity and horizontally polarized intensity, and the last two (U and V) jointly represent the phase difference between the vertically and horizontally polarized components of the wave. Q , U , and V are functions of ellipticity angle χ and rotation angle ψ .

The definition of the modified Stokes vector is:

$$\mathbf{F}(\psi, \chi) = \frac{1}{2} \begin{bmatrix} 1 + \cos 2\chi \cos 2\psi \\ 1 - \cos 2\chi \cos 2\psi \\ \sin 2\chi \sin 2\psi \\ \sin 2\chi \end{bmatrix} \quad (4)$$

It should be mentioned that by changing the ellipticity angle and rotation angle, we can obtain reflectivity at any polarization combination. Table I presents the defined angles for commonly used polarization states, along with corresponding normalized Stokes parameters.

The scattered wave Stokes vector can be connected to the incident wave Stokes vector through the Mueller matrix:

$$\mathbf{F}_s(\theta_s, \phi_s) = \mathbf{M}(\theta_s, \phi_s; \theta_i, \phi_i) \cdot \mathbf{F}_i(\theta_i, \phi_i) \quad (5)$$

Because the scattered wave is spherical, the $1/r^2$ factor is required. For RR polarization calculation, after obtaining the modified Stokes vectors as shown in Table I, the other important step is calculating the Mueller matrix, which is presented in the next section.

B. Spec4PolR

We employ the specular reflectivity matrix to calculate reflectivity at RR polarization, and we name this model Spec4PolR. All elements in this model are based on horizontal and vertical polarization Fresnel reflectivity as shown in (1) and (2). The reflectivity matrix of a specular ground surface, which is directly related to the Mueller matrix, can be defined as follows [?]:

$$\mathbf{S} = \begin{bmatrix} S_{11} & S_{12} & 0 & 0 \\ S_{21} & S_{22} & 0 & 0 \\ 0 & 0 & S_{33} & S_{34} \\ 0 & 0 & S_{43} & S_{44} \end{bmatrix} \quad (6)$$

To simplify the final form and demonstrate the elements that constitute the Mueller matrix, we employ the following equation, where \mathbf{M} is a real 4×4 matrix:

$$\mathbf{M} = \begin{bmatrix} S_{11} & S_{12} & 0 & 0 \\ S_{21} & S_{22} & 0 & 0 \\ 0 & 0 & \text{Re}(S_{33}) & \text{Im}(S_{34}) \\ 0 & 0 & -\text{Im}(S_{43}) & \text{Re}(S_{44}) \end{bmatrix} \quad (7)$$

We can see that there are six elements in the final Mueller matrix. After multiplying modified Stokes vectors and their transformations on the left and right sides of the Mueller matrix, we obtain the following equation to calculate final reflectivity:

$$\sigma_{RR} = \mathbf{F}_{RR}^T \cdot \mathbf{M} \cdot \mathbf{F}_{RR} \quad (8)$$

After Spec4PolR calculation, it should be mentioned that only three elements of the Mueller matrix are used for the final calculation: S_{11} , S_{12} , and S_{21} . Elements S_{33} , S_{34} , S_{43} , and S_{44} are not employed. Different from previously used equations, in the modified equations, one quarter of the modulus of S_{12} and a half of the real part of S_{21} participate in the final calculations.

C. Umich4PolR

The Umich model is an empirical model developed based on polarimetric radar measurements [?]. Here, it has been employed for calculating specular reflectivity at RR polarization, and we name it Umich4PolR. The co-polarization and cross-polarization scattering coefficients at vv, hh, and hv are as follows:

$$\sigma_{vv} = \sigma_{vv}^0 \cdot f(\theta, \varepsilon_r, ks) \quad (9)$$

$$\sigma_{hh} = \sigma_{hh}^0 \cdot f(\theta, \varepsilon_r, ks) \quad (10)$$

$$\sigma_{hv} = \sigma_{vh} = \sigma_{hv}^0 \cdot f(\theta, \varepsilon_r, ks) \quad (11)$$

where θ , ε_r , and ks are the incidence angle, dielectric constant, and surface roughness, respectively. The formula for q can be expressed as:

$$q = 1 - \exp\left(-\frac{ks}{\cos\theta}\right) \quad (12)$$

The W matrix used to calculate the Mueller matrix is as follows, with its basic elements summarized based on σ_{vv} , σ_{hh} , and σ_{hv} :

$$\mathbf{W} = \begin{bmatrix} \sigma_{vv} & \sqrt{\sigma_{vv}\sigma_{hh}} & 0 & 0 \\ \sqrt{\sigma_{vv}\sigma_{hh}} & \sigma_{hh} & 0 & 0 \\ 0 & 0 & \text{Re}(\sigma_{hv}) & \text{Im}(\sigma_{hv}) \\ 0 & 0 & -\text{Im}(\sigma_{hv}) & \text{Re}(\sigma_{hv}) \end{bmatrix} \quad (13)$$

The final form for the Mueller matrix of the Umich4PolR model can be summarized as:

$$\mathbf{M}_{\text{Umich}} = \begin{bmatrix} U_{11} & U_{12} & 0 & 0 \\ U_{21} & U_{22} & 0 & 0 \\ 0 & 0 & U_{33} & U_{34} \\ 0 & 0 & U_{43} & U_{44} \end{bmatrix} \quad (14)$$

After multiplying modified Stokes vectors at both sides of the Mueller matrix, we obtain the final equations used to calculate specular reflectivity at RR polarization. Five elements in the matrix presented in (14) are employed for the final

calculation: U_{11} , U_{12} , U_{21} , U_{22} , and U_{44} . It should be mentioned that element U_{33} is not employed in the calculation.

D. SPM4PolR

The Small Perturbation Model (SPM) is a commonly used model for computing scattering from natural surfaces [?]. Here, it has been developed based on the wave synthesis technique to obtain specular reflectivity at RR polarization, and we name this model SPM4PolR. The average modified Mueller matrix of the SPM model can be written as a function of polarization-dependent factors:

$$\mathbf{M}_{\text{SPM}} = \begin{bmatrix} P_{11} & P_{12} & P_{13} & P_{14} \\ P_{21} & P_{22} & P_{23} & P_{24} \\ P_{31} & P_{32} & P_{33} & P_{34} \\ P_{41} & P_{42} & P_{43} & P_{44} \end{bmatrix} \quad (15)$$

For the SPM model, we can see that all elements in the 4×4 real matrix have their own definitions and values. To simplify expressions, we employ the P matrix to represent every element in the Mueller matrix, and the final form can be defined as:

$$\sigma_{RR}^{\text{SPM}} = \mathbf{F}_{RR}^T \cdot \mathbf{M}_{\text{SPM}} \cdot \mathbf{F}_{RR} \quad (16)$$

After multiplying the modified Stokes vectors at both sides of the Mueller matrix, we obtain the final form of specular reflectivity at RR polarization, shown in the equation below. It should be mentioned that nine elements in the modified Mueller matrix are employed for the final calculation: P_{14} , P_{24} , P_{11} , P_{21} , P_{41} , P_{12} , P_{22} , P_{42} , and P_{44} .

III. Numerical Simulation Results

Numerical simulation results based on Spec4PolR, Umich4PolR, and SPM4PolR are presented in this section. Each element that affects the final reflectivity is presented, and its effects on soil moisture content are illustrated.

A. Spec4PolR

From equations (6) to (8), we can see that only three elements of Spec4PolR are employed for the final RR reflectivity calculation: S_{11} , S_{12} , and S_{21} . The relationship between these three elements and soil moisture content is simulated here. From the numerical simulations presented in Fig. 2 [Figure 2: see original paper], we can see that S_{11} increases as soil moisture content increases. The real part of S_{12} increases as soil moisture increases when soil moisture content is below 0.3; however, if soil moisture content exceeds 0.3, the real part of S_{12} decreases as soil moisture content increases, while its imaginary part remains constant for different soil moisture contents. For the S_{21} element, its real part

increases as soil moisture content increases, while its imaginary part remains constant during soil moisture variation.

[Figure 2: see original paper]

The left figure in Fig. 3 [Figure 3: see original paper] presents the RR scattering coefficient in the specular direction versus soil moisture content. The soil moisture content for this simulation is 0.3, while the incidence angle is 30° . The final result from the three elements in the Mueller matrix shows that RR reflectivity decreases as soil moisture content increases, while RR reflectivity increases as specular incidence angle increases. From the simulation, we can see that only three elements employed in the specular reflectivity matrix cannot be used for accurate RR reflectivity calculation; that is, the Spec4PolR model cannot be used for RR calculations due to its simplistic utilization of modified Mueller matrix elements.

[Figure 3: see original paper]

B. Umich4PolR Model

Numerical simulation results of the Umich model for RR polarization GNSS-R application are presented in this section. From equations (9) to (14), we can see that five elements (U_{11} , U_{12} , U_{21} , U_{22} , U_{44}) are employed for the final RR reflectivity calculation. The five elements' effects on soil moisture content are the same: as soil moisture content increases, the five elements increase. Specular reflectivity at RR polarization is the result of the combined actions of these five elements.

[Figure 4: see original paper]

The relationship between specular reflectivity at RR polarization and soil moisture content is presented in the left figure of Fig. 5 [Figure 5: see original paper], and its relationship versus specular incidence angles is presented in the right figure. From the left figure, we can see that as soil moisture content increases, specular reflectivity at RR polarization increases. As incidence angle increases, specular reflectivity at RR polarization also increases. Both trends of Umich4PolR in Fig. 5 are consistent with measured data.

[Figure 5: see original paper]

C. SPM4PolR Model

The SPM model for RR polarization GNSS-R application (SPM4PolR) is presented in this section. The different element effects on soil moisture content are presented, and the final RR reflectivity versus soil moisture content and specular incidence angle are also illustrated.

From equations (15) and (16), we can see that nine elements in the modified Mueller matrix are employed, while their effects versus soil moisture content

are different. The trends for P_{14} , P_{24} , P_{41} , and P_{42} are almost the same, although their magnitudes differ. For the real parts of P_{11} , P_{21} , P_{12} , and P_{22} , they increase as soil moisture content increases (when soil moisture content is lower than 0.3), and the trends become opposite when soil moisture content exceeds 0.3, while the imaginary parts remain constant for these elements. The elements P_{44} and P_{14} are not complex numbers but real numbers, and their trends increase as soil moisture content increases. Elements P_{11} , P_{21} , P_{12} , and P_{22} are also complex numbers; their real and imaginary parts decrease as soil moisture content increases (when soil moisture content is lower than 0.3) and increase as soil moisture content increases (when soil moisture content exceeds 0.3). Element P_{24} is also a complex number, while its real part increases as soil moisture content increases and its imaginary part remains constant for different soil moisture contents.

[Figure 6: see original paper]

The final RR reflectivity is the combined action of these nine elements, and their trends versus soil moisture content and incidence angles are presented in Fig. 7 [Figure 7: see original paper]. We can see from Fig. 7 that RR reflectivity increases as soil moisture content and incidence angle increase. These trends are consistent with measured data.

[Figure 7: see original paper]

IV. Discussions and Conclusions

From the numerical simulations presented in Section III, we can see that based on the theory and methodology presented in Section II, three models have been developed: Spec4PolR, Umich4PolR, and SPM4PolR. The RR scattering coefficient of the Spec4PolR model decreases as soil moisture content increases, which is contrary to actual measurement situations. The reasons are due to overly simplistic assumptions during calculations, as presented by the commonly used Fresnel combination form.

In contrast, the two proposed models—Umich4PolR and SPM4PolR—show trends of RR scattering coefficients versus soil moisture content and specular incidence angles that are consistent with measurement data. The reasons are due to the more complex and detailed description of the Mueller matrix. One point that should be mentioned is that the incidence angles and soil texture information for the left figures in Fig. 5 and Fig. 6 are the same. However, the range of RR reflectivity for Umich4PolR is between -29 dB to -24.5 dB, while for SPM4PolR it is between -28.3 dB to -25.3 dB. The dynamic variation range for Umich4PolR and SPM4PolR differs by no more than 0.5 dB. The angle variation range for Umich4PolR and SPM4PolR are presented in the right figures of Fig. 5 and Fig. 6. From the simulations, we can see that the dynamic range of Umich4PolR is between -37 dB to -3 dB, while for SPM4PolR it is between -25 dB to -3 dB. The results show that the range for the Umich4PolR model appears larger than that of SPM4PolR. The reasons for this phenomenon

are perhaps due to the applicable range of surface roughness. The surface roughness parameters used in the SPM4PolR model are: RMS height equals 0.85 centimeter, and correlation length is 2.75 centimeters. The parameters employed for calculations of the Umich4PolR model are different: RMS height is 1.45 centimeters and correlation length is 1.75 centimeters. For different surface roughness conditions, they present different reflectivity properties at different incidence angles.

With the development of GNSS-R or SoOp-R remote sensing techniques, employment of polarization properties will become increasingly important, especially RR polarization, which is orthogonal to the presently commonly used LR polarization. The development of formulas for RR polarization calculation in this paper will benefit subsequent polarization studies and geophysical parameter retrieval based on RR polarization.

References

- [1] A. M. Balakhder, M. M. Al-Khaldi, and J. T. Johnson, "On the Coherency of Ocean and Land Surface Specular Scattering for GNSS-R and Signals of Opportunity Systems," *IEEE Trans. Geoscience and Remote Sensing*, vol. 57, no. 12, pp. 10426-10436, Dec. 2019, doi:10.1109/TGRS.2019.2935257
- [2] M. Kurum, M. Deshpande, A. T. Joseph, P. E. O' Neill, R. H. Lang, and Eroglu, "SCoBi-Veg: A Generalized Bistatic Scattering Model of Vegetation Signals of Opportunity Reflectometry Applications," *IEEE Trans. Geoscience and Remote Sensing*, vol. 57, no. 2, pp. 1049-1068, Feb. 2019, doi: 10.1109/TGRS.2018.2864631
- [3] C. D. Hall and R. A. Cordey, "Multistatic Scatterometry," in *International Geoscience and Remote Sensing Symposium*, 'Remote Sensing: Moving Toward the 21st Century' , Edinburgh, UK, 1988, pp.
- [4] M. C. Evans and C. S. Ruf, "Toward the Detection and Imaging of Ocean Microplastics With a Spaceborne Radar," *IEEE Trans. Geoscience and Remote Sensing*, vol. 60, pp. 1-9, 2022, doi: 10.1109/TGRS.2021.3081691.
- [5] D. Pascual, M. P. Clarizia and C. S. Ruf, "Spaceborne Demonstration of GNSS-R Scattering Cross Section Sensitivity to Wind Direction," *IEEE Geoscience and Remote Sensing Letters*, vol. 19, pp. 1-5, 2022, Art no. 8006005, doi: 10.1109/LGRS.2021.3049526.
- [6] E. Cardellach, Y. Nan, W. Li, R. Padullés, S. Ribó, and A. Rius, "Variational Retrievals of High Winds Using Uncalibrated CyGNSS Observables," *Remote Sensing*, vol. 12, no. 23, pp. 3930, 2020.
- [7] W. Li, E. Cardellach, F. Fabra, S. Ribó and A. Rius, "Assessment of Spaceborne GNSS-R Ocean Altimetry Performance Using CYGNSS Mission Raw Data," *IEEE Trans. Geoscience and Remote Sensing*, vol. 58, no. 1, pp. 238-250, Jan. 2020, doi: 10.1109/TGRS.2019.2936108.

- [8] S. Leidner, B. Annane, B. McNoldy, R. Hoffman, and R. Atlas, "Variational Analysis of Simulated Ocean Surface Winds from the Cyclone Global Navigation Satellite System (CYGNSS) and Evaluation using Regional OSSE," *Atmos. Oceanic Technol.* doi:10.1175/JTECH-D-17-0136.1, to be published, 2018.
- [9] H. Kim and V. Lakshmi, "Use of Cyclone Global Navigation Satellite System (CyGNSS) Observations for Estimation of Soil Moisture," *Geophysical Research Letters*, vol. 45, no. 16, pp. 8272-8282, Aug. 2018.
- [10] D. R. Boyd et al., "Cramer-Rao Lower Bound for SoOp-R-Based Root-Zone Soil Moisture Remote Sensing," *IEEE Journal of Selected Topics. Applied Earth Observations and Remote Sensing*, vol. 13, pp. 6101-6114, 2020, doi: 10.1109/JS-TARS.2020.3029158.
- [11] S. H. Yueh, R. Shah, M. J. Chaubell, A. Hayashi, X. Xu and A. Colliander, "A Semiempirical Modeling of Soil Moisture, Vegetation, and Surface Roughness Impact on CYGNSS Reflectometry Data," *IEEE Trans. Geoscience and Remote Sensing*, vol. 60, pp. 1-17, 2022, Art no. 5800117, doi: 10.1109/TGRS.2020.3035989.
- [12] F. Chen, F. Guo, L. Liu and Y. Nan, "An Improved Method for Pan-Tropical Above-Ground Biomass and Canopy Height Retrieval Using CYGNSS," *Remote Sensing*, vol. 13, no. 13, pp. 2491, Jun. 2021.
- [13] V. Zavorotny, and A. Voronovich, "Constellations of CubeSats to exploit Signals-of-Opportunity for Earth System Science," *SPIE Conference on CubeSats and NanoSats for Remote Sensing*, vol. 10769, Sep. 2018, doi:10.1117/12.2319863.
- [14] V. U. Zavorotny and A. G. Voronovich, "Scattering of GPS signals from the ocean with wind remote sensing application," *IEEE Trans. Geoscience and Remote Sensing*, vol. 38, no. 2, pp. 951-964, Mar. 2000, doi: 10.1109/36.841977.
- [15] S. Zhang, Z. Pu, D. J. Posselt, and R. Atlas, "Impact of CYGNSS Ocean Surface Wind Speeds on Numerical Simulations of a Hurricane in Observing System Simulation Experiments," *Journal of Atmospheric and Oceanic Technology*, vol. 34, no. 2, pp. 375-383, Feb. 2017.
- [16] F. Huang et al., "Spaceborne GNSS Reflectometry With Galileo Signals on FY-3E/GNOS-II: Measurements, Calibration, and Wind Speed Retrieval," *IEEE Geoscience and Remote Sensing Letters*, vol. 20, pp. 1-5, 2023, Art no. 3501505, doi: 10.1109/LGRS.2023.3241358.
- [17] C. Chew and E. Small, "Description of the UCAR/CU Soil Moisture Product," *Remote Sensing*, vol. 12, no. 10, pp. 1558, 2020.
- [18] B. Liu et al., "Statistical Analysis of CyGNSS Speckle and Its Applications to Surface Water Mapping," *IEEE Trans. Geoscience and Remote Sensing*, vol. 60, Art no. 5803915, pp. 1-15, 2022, doi: 10.1109/TGRS.2022.3196012.
- [19] V. Zavorotny et al., "Seasonal polarimetric measurements of soil moisture

using tower-based GPS bistatic radar,” *IGARSS 2003. 2003 IEEE International Geoscience and Remote Sensing Symposium. Proceedings* (IEEE Cat. No.03CH37477), Toulouse, France, Jul. 21-25, 2003, pp. 781-783.

[20] N. Rodriguez-Alvarez, S. Misra and M. Morris, “The Polarimetric Sensitivity of SMAP-Reflectometry Signals to Crop Growth in the U.S. Corn Belt,” *Remote Sens.*, vol. 12, no. 6, pp. 1007, 2020.

[21] H. Carreno-Luengo, S. Lowe, C. Zuffada, S. Esterhuizen, and S. Oveisgharan, “Spaceborne GNSS-R from the SMAP Mission: First Assessment of Polarimetric Scatterometry over Land and Cryosphere,” *Remote Sens.*, vol. 9, no. 4, pp. 362, 2017.

[22] M. J. Unwin et al., “An Introduction to the HydroGNSS GNSS Reflectometry Remote Sensing Mission,” *IEEE Journal of Selected Topics. Applied Earth Observations and Remote Sensing*, vol. 14, pp. 6987-6999, 2021, doi: 10.1109/JS-TARS.2021.3089550.

[23] X. Wu, S. Jin, “Models and Theoretical Analysis of SoOp Circular Polarization Bistatic Scattering for Random Rough Surface,” *Remote Sensing*, vol. 12, no. 9, pp. 1506, 2020.

[24] X. Wu, Y. Song, J. Xu, Z. Duan and S. Jin, “Bistatic scattering simulations of circular and linear polarizations over land surface for signals of opportunity reflectometry,” *Geoscience Letters*, vol. 8, no. 1, doi:10.21203/rs.3.rs-117659/v1.

[25] X. Wu and S. Jin, “GNSS-Reflectometry: Forest canopies polarization scattering properties and modeling,” *Advances in Space Research*, vol. 54, no. 5, pp. 863-870, 2014.

[26] A. Fung and Hyo Eom, “Coherent scattering of a spherical wave from an irregular surface,” *IEEE Trans. Antennas and Propagation*, vol. 31, no. 1, pp. 68-72, Jan. 1983, doi: 10.1109/TAP.1983.1142979.

[27] C. Yin, “Soil Moisture Remote Sensing with Global Navigation Satellite System Reflectometry,” Ph.D. dissertation, Nju of tech, Nanjing, 2019

[28] C. Elachi, and F. T. Ulaby, et al., “Radar Polarimetry for Geoscience Applications,” Apr. 1, 1990.

[29] Pan Liang, L. E. Pierce and M. Moghaddam, “Radiative transfer model for microwave bistatic scattering from forest canopies,” *IEEE Trans. Geoscience and Remote Sensing*, vol. 43, no. 11, pp. 2470-2483, Nov. 2005, doi: 10.1109/TGRS.2005.853926

[30] Y. Oh, K. Sarabandi and F. T. Ulaby, “An empirical model and an inversion technique for radar scattering from bare soil surfaces,” *IEEE Trans. Geoscience and Remote Sensing*, vol. 30, no. 2, pp. 370-381, Mar. 1992, doi: 10.1109/36.134086.

[31] J. A. Kong, R. T. Shin and L. Tsang, “Theory of Microwave Remote Sensing”, vol. 2, Wiley-Interscience, Jul. 3, 1985.

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Note: Figure translations are in progress. See original paper for figures.

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