

A Simulation Study of GNSS-R Polarimetric Scattering from Bare Soil Surfaces Based on the AIEM Model

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Abstract

In the past two decades, Global Navigation Satellite System-Reflectometry (GNSS-R) has emerged as a new remote sensing technique for soil moisture monitoring. Some experiments showed that the antenna of V polarization is more favorable to receive the reflected signals, and the interference pattern technique (IPT) was used for soil moisture and other geophysical parameters retrieval. Meanwhile, the lower satellite elevation angles are most impacted by the multipath. However, electromagnetic theoretical properties are not clear for GNSS-R soil moisture retrieval. In this paper, the Advanced Integral Equation Model (AIEM) is employed using the wave synthesis technique to simulate different polarimetric scattering at the specular directions. Results show when the incidence angles are larger than 70° , scattering at RR polarization (The transmitted signal is Right Hand Circular Polarization (RHCP), while the received one is also RHCP) is larger than that one at LR polarization (The transmitted signal is RHCP, while the received one is Left Hand Circular Polarization (LHCP)), while scattering at LR polarization is larger than that at RR polarization for the other incident angles ($1^\circ \sim 70^\circ$). There is an apparent dip for VV and VR scattering due to the Brewster angle, which will result in the notch in the final receiving power and this phenomenon can be used for soil moisture retrieval or vegetation corrections. The volumetric soil moisture (vms) effects on their scattering are also presented. The larger soil moisture will result in lower scattering at RR polarization, and this is very different from the scattering of the other polarizations. It is interesting to note that the surface correlation function only affects the amplitudes of the scattering coefficients at much less level, but it has no effects on the angular trends of RR and LR polarizations.

Full Text

Preamble

A Simulation Study of GNSS-R Polarimetric Scattering from Bare Soil Surfaces Based on the AIEM Model

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Abstract

Over the past two decades, Global Navigation Satellite System-Reflectometry (GNSS-R) has emerged as a novel remote sensing technique for soil moisture monitoring. Experimental studies have demonstrated that V-polarized antennas are more effective for receiving reflected signals, and the interference pattern technique (IPT) has been employed for retrieving soil moisture and other geophysical parameters. Meanwhile, lower satellite elevation angles are most significantly impacted by multipath effects. However, the electromagnetic theoretical properties underlying GNSS-R soil moisture retrieval remain unclear. This paper utilizes the Advanced Integral Equation Model (AIEM) with wave synthesis techniques to simulate different polarimetric scattering components in specular directions. Results indicate that for incidence angles greater than 70° , scattering in RR polarization (where both transmitted and received signals are Right Hand Circular Polarization, RHCP) exceeds that in LR polarization (transmitted RHCP, received Left Hand Circular Polarization, LHCP), while the opposite trend holds for incidence angles between 1° and 70° . Notable dips occur in VV and VR scattering due to the Brewster angle, which produces notches in the final received power—a phenomenon that can be exploited for soil moisture retrieval or vegetation correction. The effects of volumetric soil moisture (vms) on scattering are also presented. Higher soil moisture leads to lower scattering in RR polarization, a behavior distinct from other polarizations. Interestingly, while the surface correlation function influences the amplitude of scattering coefficients to a limited degree, it has negligible effect on the angular trends of RR and LR polarizations.

Keywords: GNSS-R; Polarizations; Specular; AIEM

1. Introduction

Soil moisture serves as a critical link between surface water and groundwater, playing a vital role in terrestrial ecosystems and the water cycle. As a key determinant of terrestrial hydrosphere conditions, soil moisture largely controls evapotranspiration, water migration, and the land surface carbon cycle. It is also essential for understanding and predicting climate change, addressing global water cycle questions, managing water resources, and modeling basin hydrology. Furthermore, soil moisture is a necessary parameter for monitoring crop growth, drought, and flood conditions.

Soil moisture exhibits strong spatial and temporal heterogeneity, making traditional ground-based and meteorological monitoring approaches inadequate. Satellite remote sensing technology provides a new method for monitoring, and over the past two decades, GNSS-R has emerged as a promising technique due to its unique advantages [1]. Applications have expanded from mesoscale ocean remote sensing to snow, ice, and land surface parameter monitoring [2-4]. For land applications, soil moisture monitoring is the most important application. GNSS-R effectively complements existing radar and radiometer systems and offers potential for validating L-band soil moisture satellites such as SMOS (Soil Moisture and Ocean Salinity Mission) [5] and SMAP (Soil Moisture Active Passive Mission) [6].

However, as an emerging Earth observation method, numerous open problems require resolution, particularly regarding the polarization properties of reflected signals. Polarization represents one of the most fundamental properties of electromagnetic waves, describing the shape and orientation of the trajectory formed by the tip of the electric field vector over time. Unlike traditional linear polarizations used in microwave remote sensing, GNSS signals are transmitted in RHCP. Upon reflection from a surface, their polarization state changes. Kavak et al. [7] noted that reflected signals consist of two components—circular and perpendicular polarization—dependent on elevation angle. Several experiments have investigated GNSS signal polarization. In one study [7], a modified GPS receiver with a horizontally positioned LHCP antenna was used to collect coherent energy from direct and reflected signals. During the SMEX 02/03 (Soil Moisture Experiment 2002/2003) campaigns [8], a different antenna configuration was employed using an airborne GPS-R receiver called DMR (Delay Doppler Maps Receiver) with two antennas: a standard zenith RHCP antenna for direct signals and a nadir LHCP antenna for surface-reflected signals, with incidence angles ranging from 15° to 35° [9].

As early as 2000, Zavorotny and Voronovich applied the GO (Geophysical Optics) scattering model [2] to study polarization reflections from soil moisture [10]. They simulated the sensitivity of polarization ratios (LR/RR and HR/VR) to soil moisture at large incidence angles (60° and 70°), theoretically concluding that these ratios could be used for soil moisture measurement, where LR, RR, HR, and VR denote RHCP transmission with LHCP, RHCP, horizontal

(H), and vertical (V) reception, respectively. In the BAO-Tower (Boulder Atmospheric Observatory Tower) experiment [11], a multi-polarization receiver from NASA Langley Research Center was used with a low-gain LHCP antenna and four high-gain antennas (V, H, LHCP, and RHCP polarizations) to collect surface-reflected signals at an incidence angle of 35° and azimuth angle of 245° . However, the BAO-Tower results did not support the original theoretical hypothesis [10].

Currently, the interference pattern technique (IPT) is used for soil moisture and vegetation retrieval [12], with V-polarized antennas preferred because angular information would be masked by the Brewster angle when using LHCP antennas [13]. LEiMON (Land Monitoring with Navigation Signals), a long-term GNSS-R campaign funded by the European Space Agency (ESA) [14], was conducted in 2009 using a SAM sensor. RHCP antennas collected direct signals, while RHCP or LHCP antennas collected reflected signals at elevation angles from 40° to 80° . However, their theoretical and experimental results indicated that both RR and LR reflectivity increased with incidence angle (0° - 80°), contradicting commonly used Fresnel theory for circular polarization in GNSS-R studies [2,4]. Unlike specialized GNSS-R receivers, multipath information from geodetic-quality GPS receivers can remotely sense soil moisture in the top 5 cm [15-17], with in-situ measurements showing elevation angles of 5° - 30° are most impacted by multipath [15-17].

Overall, most GNSS-R soil moisture monitoring relies on experimental studies [8,9,11,12,14-17], commonly using simple geometric combinations to convert between linear and circular polarization [2,4,14-17]. In these studies, RR polarization reflection increases with incidence angle while LR reflection decreases—a trend contradicting the LEiMON experimental report [14]. Notably, only amplitude changes are considered [2,4,14-17], while phase differences in linear-to-circular conversion are ignored [18]. However, as GNSS-R develops, greater attention should be paid to theoretical models, which assist in data interpretation, sensitivity analysis, and experimental design [19]. This paper focuses on polarization dependence (particularly circular polarization) of bare soil scattering using the AIEM model [20,21], with wave synthesis techniques for arbitrary polarization calculations presented in Section 2. Section 3 presents reflectivity of XR polarization and linear polarizations versus incidence angles, where XR denotes RHCP transmission with reception of any circular (RHCP, LHCP) or linear (V, H) polarization. Section 4 evaluates effects of volumetric soil moisture and surface roughness on different polarizations using the Mueller matrix. Section 5 provides conclusions.

2. AIEM Model

To mitigate ionospheric effects, GNSS signals are transmitted in RHCP, though polarization changes upon reflection from the soil surface. As discussed in Section 1, because reflected signals exhibit different polarizations, linear (vertical and horizontal) and circular (RHCP and LHCP) antennas are used to receive

them. Consequently, different polarization combinations require theoretical investigation. This section employs the widely used AIEM random rough surface bistatic scattering model, which calculates bistatic scattering coefficients for arbitrary polarization combinations (both linear and circular) through wave synthesis techniques, enabling full-polarization characterization of soil moisture.

Traditional electromagnetic scattering models for random rough surfaces [19] include the Kirchhoff Approximation (KA) and Small Perturbation Model (SPM). KA suits surfaces with small curvatures or high-frequency conditions, while SPM applies to slightly rough surfaces or low-frequency cases. The popular Integral Equation Model (IEM) bridges SPM and KA, though its assumptions limit accuracy, particularly for bistatic scattering. The subsequently developed AIEM model improves upon IEM [20,22]. Here we focus on polarization studies using this enhanced model for GNSS-R applications. Since received power primarily originates from the first Fresnel zone [23], only coherent scattering is considered in this study.

The bistatic scattering coefficient relates to the modified Mueller matrix as follows [19]:

where σ_{qp} is the bistatic scattering coefficient, subscripts q and p denote received and transmitted polarizations, A is the illuminated area, and the modified Mueller matrix M can be expressed in terms of scattering matrix S elements. Please consult reference [22] for detailed AIEM model information.

According to wave synthesis techniques [24], the scattering coefficient for arbitrary transmitted and received antenna polarizations can be expressed as:

where subscripts q and p represent received and transmitted polarizations, I is the normalized Stokes vector with unit amplitude, and Q is a rotation matrix. The normalized Stokes vector can be expressed in terms of ellipticity angle χ and orientation angle ψ :

The first element of I describes electromagnetic wave intensity in horizontal and vertical directions, the second represents intensity difference between horizontal and vertical wave vector components, the third indicates linear polarization intensity at $\pm 45^\circ$ azimuth in the polarization ellipse, and the fourth denotes circular polarization degree. This approach incorporates phase information from scattering matrix S .

For co-polarization, $q = p$ and $q = -p$, while for cross-polarization, $q = -p$ and $q = p + \pi/2$. Any transmitted and received polarization combination can be obtained by setting ellipticity χ and orientation angles ψ accordingly. For GNSS-R, scattering characteristics of σ_{XR} must be studied, where XR denotes RHCP transmission with reception of any circular (RHCP, LHCP) or linear (V, H) polarization.

3. Reflectivity of Different Polarizations Versus Incidence Angles

When a plane wave transmits across a planar boundary between non-destructive media, a specific angle exists where vertical polarization exhibits complete projection, known as the Brewster angle. The IPT method described in Section 1 uses notch position and count information from coherent waveforms of direct and reflected signals for geophysical parameter retrieval. In fact, waveform notches result from the Brewster angle, making this phenomenon particularly important for GNSS-R remote sensing inversion. Table 1 presents corresponding dielectric constants and Brewster angles for various soil moisture levels. Volumetric soil moisture (vms) expresses soil moisture as the percentage of water volume relative to total soil volume, reflecting water saturation degree and enabling calculation of solid, liquid, and gas ratios.

Figure 1 shows Fresnel reflectivity for r_v and r_h polarizations at different vms values, where r denotes Fresnel reflectivity and subscripts v and h represent vertical and horizontal polarization states. The Brewster angles from Table 1 are clearly visible in V polarization (left panel). For a given vms, r_v decreases with increasing incidence angle (before the Brewster angle) and increases afterward. Across different vms values, r_v is larger for higher vms (before 59°) but smaller for higher vms (after 82°). In contrast, r_h is larger for higher vms across all angles.

The real parts of r_v and r_h ($\text{Re}[r_v]$, $\text{Re}[r_h]$) are crucial for calculating XR and linear polarization scattering coefficients. Their variation with incidence angle is shown in Figure 2. Before reaching the Brewster angle, $\text{Re}[r_v]$ is positive; it becomes negative beyond the Brewster angle while increasing with incidence angle. $\text{Re}[r_h]$ remains negative across all angles and decreases as vms increases.

Figure 3, reproduced from reference [25], shows scattering coefficients for linear and XR polarizations versus incidence angles. For smaller incidence angles ($< 70^\circ$), LR polarization scattering exceeds RR polarization scattering ($RR < LR$), where LR and RR denote RHCP transmission with LHCP and RHCP reception, respectively. However, for larger incidence angles ($85^\circ > > 70^\circ$), the trend reverses, with RR polarization scattering coefficients exceeding those of LR polarization. For large incidence angles ($85^\circ > > 70^\circ$), RR polarization scattering coefficients also exceed those of VR polarization, where VR denotes RHCP transmission with vertical reception. RR polarization scattering coefficients increase with incidence angle for $< 55^\circ$ but decrease for other angles. LR polarization scattering coefficients decrease monotonically with incidence angle. Scattering coefficient trends for VV, VR, HH, and HR versus incidence angle are similar, where VR and HR denote RHCP transmission with vertical and horizontal reception, and VV and HH denote co-polarized vertical and horizontal reception. This similarity occurs because they depend only on $M(1,1)$ and $M(2,2)$, respectively (Equations 2,5). HH and HR polarization scattering coefficients decrease with incidence angle, while VV and VR polarization scat-

tering coefficients exhibit dips around 70° due to the Brewster angle defined in Equation 8 [19], decreasing initially (before the Brewster angle) then increasing with incidence angle (after the Brewster angle).

4.1 Effects of Volumetric Soil Moisture on Polarizations

Figure 4 presents linear and circular polarization scattering coefficients at various soil moisture levels (vms) versus incidence angles. HR polarization scattering trends closely resemble those of HH polarization, while VR polarization trends are similar to VV polarization, as shown in Figure 1. Dips in VV and VR polarization are vms-dependent due to Brewster angle variations (Table 1). Higher vms shifts the dip position to larger incidence angles. Notably, RR polarization scattering coefficients are larger for smaller vms values. For other polarizations (LR, HR, HH), higher vms corresponds to larger scattering coefficients. For VV and VR polarizations, higher vms yields larger scattering coefficients at incidence angles below the Brewster angle, while lower vms produces larger scattering coefficients at angles above the Brewster angle.

4.2 Effects of Surface Roughness on Different Polarizations

Since soil moisture affects GNSS reflected signals, soil geometric characteristics—specifically surface roughness—also influence these signals. Removing surface roughness effects poses a significant challenge in soil moisture inversion. Surface roughness can be characterized by two parameters: root mean square height (s) and surface correlation length (l), which define vertical and horizontal roughness scales, respectively. Alternatively, surface autocorrelation functions such as Gaussian or exponential functions describe random surface roughness.

This section presents surface roughness effects on final scattering at RR and LR polarizations. Figure 5 shows roughness effects for different correlation functions. With fixed root mean square height (s), larger correlation length (l) yields larger scattering coefficients (both RR and LR). With fixed l , larger s produces larger scattering coefficients (both RR and LR), where k is the wavenumber.

Scattering from exponential correlation functions exceeds that from Gaussian functions (both RR and LR) (Figure 6 [Figure 6: see original paper]). Interestingly, unlike in the backscattering direction, the surface correlation function only affects scattering coefficient amplitudes with minimal impact on angular trends.

5. Conclusions

For GNSS-R remote sensing, transmitted signals are RHCP, and received power is commonly assumed to originate from the first Fresnel zone. This study simulates coherent scattering for different polarizations using a modified AIEM model with wave synthesis techniques. Results show that for incidence angles below 70° , RR polarization scattering is lower than LR polarization scattering;

between 70° and 80° , LR polarization scattering exceeds RR polarization scattering. For larger incidence angles, VV and VR polarization exhibit dips due to Brewster angles, which are soil moisture-dependent. Therefore, V-polarized antennas are recommended because Brewster angle-induced dips at different soil moisture levels provide useful information for soil moisture monitoring, and VR polarization offers larger scattering dynamic ranges than other polarizations. Meanwhile, VR polarization provides effective information for vegetation correction. Notably, higher soil moisture corresponds to lower RR polarization scattering, while the opposite trend occurs for other XR polarizations (LR, HR, VR, HH, VV). Additionally, unlike in the backscattering direction, the surface correlation function only affects scattering coefficient amplitudes without influencing angular trends.

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References

- [1] S. Jin and A. Komjathy, "GNSS reflectometry and remote sensing: New objectives and results," *Adv. Space Res.*, vol. 46, pp. 111–117, July 2010.
- [2] V. U. Zavorotny and A. G. Voronovich, "Scattering of GPS signals from the ocean with wind remote sensing application," *IEEE Trans. Geosci. Remote Sensing*, vol. 38, no. 1, pp. 951–964, Mar. 2000.
- [3] E. Cardellach, F. Fabra, A. Rius, S. Pettinato, and S. D' Addio, "Characterization of dry-snow sub-structure using GNSS reflected signals," *Remote Sensing Environ.*, vol. 124, pp. 122–134, Sept. 2012.
- [4] Masters, D., P. Axelrad, and S. Katzberg, "Initial results of land-reflected GPS bistatic radar soil moisture measurements in SMEX02," *Remote Sensing Environ.*, vol. 92, pp. 507–520, Sept. 2004.
- [5] M. Berger, A. Camps, J. Font, Y. Kerr, J. Miller, J. Johannessen, J. Boutin, M. R. Drinkwater, N. Skou, N. Floury, M. Rast, H. Rebhan, E. Attema, "Measuring ocean salinity with ESA's SMOS mission," *ESA Bull.*, 111(113f):113–121, 2002.
- [6] D. Entekhabi, E. Njoku, P. O' Neill, et al., "The Soil Moisture Active Passive (SMAP) mission," *Proc. IEEE*, 98(5):704–716, 2010.
- [7] A. Kavak, G. Xu, and W. J. Vogel, "GPS multipath fade measurements to determine L-band ground reflectivity properties," in *Proc. 20th NASA Propagation Experimenters Meeting*, 1996.
- [8] Masters, D. 2005. "SMEX02 Airborne GPS Bistatic Radar Data", Iowa. Boulder, Colorado USA: University of Colorado, Colorado Center for Astrodynamics Research.
- [9] Masters, D., P. Axelrad, and S. Katzberg, "Initial results of land-reflected GPS bistatic radar soil moisture measurements in SMEX02," *Remote Sensing of Environment* 92, 507–520, 2004.

- [10] V. U. Zavorotny and A. G. Voronovich, "Bistatic GPS signal reflections at various polarizations from rough land surface with moisture content," in *Proc. IEEE Int. Geoscience Remote Sensing Symp.*, Honolulu, HI, 2000, vol. 7, pp. 2852-2854.
- [11] Zavorotny, V., Masters, D., Gasiewski, A., Bartram, B., Katzberg, S., Axelrad, P., Zamora, R., "Seasonal polarimetric measurements of soil moisture using tower-based GPS bistatic radar," in *Geoscience and Remote Sensing Symposium, IGARSS' 03. Proceedings. 2003 IEEE International*, 2:781-783.
- [12] N. Rodriguez-Alvarez, A. Camps, M. Vall-llosera, X. Bosch-Lluis, A. Moneris, I. Ramos-Perez, E. Valencia, J. F. Marchan-Hernandez, J. Martinez-Fernandez, G. Baroncini-Turricchia, C. Pérez-Gutiérrez, and N. Sánchez, "Land geophysical parameters retrieval using the interference pattern GNSS-R technique," *IEEE Trans. Geosci. Remote Sensing*, vol. 32, no. 1, pp. 47-61, Jan. 2011.
- [13] N. Rodriguez-Alvarez, X. Bosch-Lluis, A. Camps, M. Vall-llossera, E. Valencia, J. F. Marchan-Hernandez, and I. Ramos-Perez, "Soil moisture retrieval using GNSS-R techniques: Experimental results over a bare soil field," *IEEE Trans. Geosci. Remote Sensing*, vol. 47, no. 11, pp. 3616-3624, Nov. 2009.
- [15] K. M. Larson, E. E. Small, E. D. Gutmann, A. D. Bilich, J. J. Braun, and V. U. Zavorotny, "Use of GPS receivers as a soil moisture network for water cycle studies," *Geosci. Res. Lett.*, vol. 35, no. 24, p. L24405, 2008.
- [16] K. M. Larson, J. Braun, E. E. Small, V. Zavorotny, E. Gutmann, and A. Bilich, "GPS multipath and its relation to near-surface soil moisture content," *IEEE J. Select. Topics Appl. Earth Observ. Remote Sensing*, vol. 3, no. 1, pp. 91-99, 2010.
- [17] Chew, C. C., Small, E. D., K. M. Larson, V. Zavorotny, "Effects of Near-Surface Soil Moisture on GPS SNR Data: Development of a Retrieval Algorithm for Soil Moisture," *IEEE Transactions on Geoscience and Remote Sensing*, vol. 9, pp. 1-7, 2013.
- [18] Ruck G., Barrick D., Stuart W., et al. *Radar Cross Section Handbook*, Vol II. New York, NY: Plenum, 1970.
- [19] A. K. Fung, *Microwave Scattering and Emission Models and Their Applications*. Norwood, MA: Artech House, 1994.
- [20] Chen K S, Wu T D, Tsang L, et al. "Emission of rough surfaces calculated by the integral equation method with comparison to three-dimensional moment method simulations," *Geoscience and Remote Sensing, IEEE Transactions on*, vol. 41(1), pp. 90-101, 2003.
- [21] Wu, Xuerui, and S. Jin. "Characteristics of GNSS-R bare soil based on advanced integral equation model (AIEM) and interference patterns," *General Assembly & Scientific Symposium IEEE*, 2015.
- [22] T. D. Wu, K. S. Chen, J. C. Shi, H. W. Lee and A. K. Fung, "A study of AIEM Model for Bistatic Scattering from Randomly Surfaces," *IEEE Trans. Geoscience and Remote Sensing*, vol. 46, no. 9, pp. 2584-2598, 2008.
- [23] Beckmann, P., Spizzichino, A. *The Scattering of Electromagnetic Waves from Rough Surfaces*. Artech House, Norwood, MA, 1963.

- [24] Ulaby, F. T., and C. Elachi, 1990. *Radar Polarimetry for Geoscience Applications*. Norwood, MA, USA: Artech House Publishers.
- [25] Wu, Xuerui, and S. Jin. *Sensing Bare Soil and Vegetation Using GNSS-R—Theoretical Modeling*. Satellite Positioning - Methods, Models and Applications, InTech-Publisher, Rijeka, Croatia, 2015.

Appendix

Abbreviations:

- **AIEM:** Advanced Integral Equation Model
- **DDM:** Delay-Doppler Maps
- **DMR:** Delay Doppler Maps Receiver
- **GNSS:** Global Navigation Satellite System
- **GNSS-R:** GNSS-Reflectometry
- **GO:** Geophysical Optics Model
- **GPS:** Global Positioning System
- **HR, VR, +45R, -45R polarizations:** Transmitted RHCP with received H (horizontal), V (vertical), +45° linear, and -45° linear polarizations, respectively
- **IEM:** Integral Equation Model
- **IPT:** Interference Pattern Technique
- **KA:** Kirchhoff Approximation model
- **LEiMON:** Land Monitoring with Navigation Signals
- **LHCP:** Left Hand Circular Polarization
- **LR:** Transmitted RHCP, received LHCP
- **RHCP:** Right Hand Circular Polarization
- **RR:** Transmitted RHCP, received RHCP
- **SMAP:** Soil Moisture Active and Passive Mission

- **SMEX:** Soil Moisture Experiments
- **SMIGOL:** Soil Moisture Interference pattern GNSS Observations at L-band Reflectometer
- **SMOS:** Soil Moisture and Ocean Salinity Mission
- **SPM:** Small Perturbation Model
- **Z-V model:** Zavorotny-Voronovich model

Table 1: Dielectric constants and Brewster angles for different volumetric soil moisture values

vms	Dielectric Constant	Brewster Angle (°)
0.01	2.814 - 0.127i	[value]
0.05	3.965 - 0.241i	[value]
0.25	13.175 - 1.021i	[value]
0.45	26.99 - 2.19i	[value]
0.60	40 - 3.3i	[value]

Figure Captions:

- **Fig. 1:** Fresnel reflectivity vs. incidence angles (left: rv; right: rh) for different vms values
- **Fig. 2:** Real parts of Fresnel reflectivity vs. incidence angles (left: Re[rv]; right: Re[rh])
- **Fig. 3:** Scattering coefficients of linear polarization and XR polarization vs. incidence angles (vms = 0.15). AIEM model parameters: rms = 0.45 cm, cl = 18.75 cm, Gaussian correlation function
- **Fig. 4:** Scattering coefficients of different vms values vs. incidence angles. AIEM model parameters: rms = 0.45 cm, cl = 18.75 cm, Gaussian correlation function
- **Fig. 5 [Figure 5: see original paper]:** Surface roughness effects on RR and LR scattering. AIEM model parameters: rms = 0.45 cm, cl = 18.75 cm, vms = 0.15
- **Fig. 6 [Figure 6: see original paper]:** Correlation function effects on RR and LR scattering. AIEM model parameters: rms = 0.45 cm, cl = 18.75 cm, vms = 0.15

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

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