

## Development of an Innovative Physical-Geometry-Based Soil Moisture Retrieval Method for CYGNSS Constellations

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**Date:** 2025-04-29T10:20:50+00:00

### Abstract

Global Navigation Satellite System-Reflectometry (GNSS-R) has evolved as an innovative remote sensing technique for Earth surface monitoring over the past three decades. While the Cyclone Global Navigation Satellite System (CYGNSS) constellation was initially designed to observe tropical cyclones, recent studies highlight its untapped potential for soil moisture retrieval. In this work, we first analyze the physical scattering mechanisms of bare soil and vegetation, focusing on their distinct interactions with GNSS signals. A novel soil moisture retrieval method is proposed based on a zero-order scattering model. Surface reflectivity (SR) derived from CYGNSS is influenced by vegetation cover, surface roughness, and soil texture. To mitigate these effects, roughness-vegetation (R-V) correction factors are introduced. By removing R-V contributions from the SR, Fresnel reflectivity—directly linked to soil dielectric properties—is isolated for moisture estimation. Additionally, simulations reveal that observation geometry significantly impacts SR variations; this geometric dependency is explicitly incorporated to refine retrieval accuracy. Validation demonstrates that integrating R-V correction and geometric adjustments reduces the root mean square error (RMSE) of soil moisture estimates from 0.0794 to 0.0357, marking a 55% improvement. This physics-based approach enhances CYGNSS-derived soil moisture precision and holds promise for advancing sustainable water resource management and meteorological studies through high-resolution, all-weather monitoring.

## Full Text

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Surface reflectivity (SR) derived from CYGNSS is influenced by vegetation cover, surface roughness, and soil texture. To mitigate these effects, roughness-vegetation (R-V) correction factors are introduced. By removing R-V contributions from the SR, Fresnel reflectivity—directly linked to soil dielectric properties—is isolated for moisture estimation. Additionally, simulations reveal that observation geometry significantly impacts SR variations; this geometric dependency is explicitly incorporated to refine retrieval accuracy. Validation demonstrates that integrating R-V correction and geometric adjustments reduces the root mean square error (RMSE) of soil moisture estimates from 0.0794 to 0.0357, marking a 55% improvement. This physics-based approach enhances CYGNSS-derived soil moisture precision and holds promise for advancing sustainable water resource management and meteorological studies through high-resolution, all-weather monitoring.

**Index Terms**— CYGNSS, GNSS-R, soil moisture, vegetation, roughness.

## I. INTRODUCTION

Global Navigation Satellite System-Reflectometry (GNSS-R) utilizes signal delay and Doppler Maps (DDM) to extract environmental data [?]. Unlike traditional methods, GNSS-R leverages existing GNSS satellites as transmitters, enabling real-time global reflected signal reception and quasi-continuous Earth monitoring with sufficient receiver sampling.

The UK-DMC satellite (launched 2003, decommissioned in 2011) demonstrated GPS Reflectometry (GPS-R) capabilities for sea state parameters (e.g., wind speed, wave height) and land parameter detection [?]. The UK's TDS-1 satellite (launched 2014 into a 635 km Sun Synchronous Orbit) hosts a Space GNSS Receiver Remote Sensing Instrument (SGR-ReSI), which generates DDM from multi-channel GPS reflections. These data have supported soil moisture and freeze/thaw cycle studies [?, ?]. In 2016, NASA's CYGNSS constellation advanced storm intensity prediction through sub-daily ocean wind monitoring,

later expanding to soil moisture, vegetation, and flood mapping [?]. This mission has significantly increased attention toward soil moisture retrieval using space-borne GNSS-R constellations.

Current soil moisture retrieval methods for space-borne CYGNSS data can be categorized into three types: empirical, semi-empirical, and physics-based models. Empirical methods rely on statistical relationships between GNSS-R observables (e.g., surface reflectivity, SNR) and in-situ soil moisture measurements. For example, Kim & Lakshmi (2018) established a linear regression between CYGNSS reflectivity and SMAP soil moisture data [?]. While simple, such methods lack generalizability across diverse surface conditions. Semi-empirical methods combine empirical relationships with physical considerations. Clarizia et al. (2019) proposed a ternary linear regression using CYGNSS reflectivity, SMAP vegetation optical depth, and roughness coefficients to mitigate vegetation/roughness effects [?]. This approach partially addresses surface complexities but still depends on ancillary datasets. Physics-based models leverage electromagnetic scattering theory to explicitly account for surface parameters. The Land Surface GNSS Reflection Simulator (LAGRS) framework [?], for instance, integrates vegetation and soil scattering mechanisms (e.g., zero-order vegetation attenuation, surface roughness effects). The proposed method in this paper falls into this category, utilizing Fresnel reflectivity corrected by R-V (Roughness-Vegetation) factors derived from physical models. Physics-based methods offer greater robustness across varying geometries and surface conditions but require precise modeling of scattering processes.

Emerging approaches include machine learning (e.g., neural networks trained on multi-source data) and hybrid methods merging GNSS-R with passive microwave or optical data. However, these remain exploratory and face challenges in interpretability and data fusion.

Section 2 introduces the theoretical framework underlying this study. Section 3 details the dataset construction and preprocessing methodology. Section 4 presents experimental retrieval results followed by comprehensive analysis. Finally, Section 5 summarizes key findings and concludes the paper.

## II. THEORETICAL FUNDAMENTALS

The accuracy of soil moisture retrieval using Global Navigation Satellite System-Reflectometry (GNSS-R) is critically influenced by vegetation canopy and surface roughness. Vegetation, ranging from dense forests to low canopies and grasses, attenuates reflected GNSS signals proportionally to its density, with higher attenuation observed in denser vegetation layers. For bare soil, surface roughness modifies scattering dynamics: rougher surfaces diminish coherent scattering intensity at the specular reflection point while enhancing diffuse scattering components, complicating signal interpretation. To address these challenges, physics-based models capable of explicitly characterizing vegetation attenuation and surface roughness effects are essential for robust soil moisture

inversion.

The Land Surface GNSS Reflection Simulator (LAGRS) provides a theoretical framework to model interactions between GNSS signals and land surface parameters [?]. The simulator integrates electromagnetic wave propagation from transmitter to receiver, incorporating surface scattering mechanisms driven by soil dielectric properties, vegetation structure, and roughness. The LAGRS framework comprises two core modules: the geometry module computes the relative positions and velocities of the transmitter and receiver to define observation geometry, while the bistatic scattering cross-section module simulates vegetation attenuation and volume scattering through canopy layer parameterization, and the soil layer is modeled as the random surface scattering layer with surface roughness consideration.

Applied to China's Fengyun GNOS-R payload, the LAGRS framework demonstrates robust performance in soil moisture retrieval by rigorously simulating coherent and diffuse scattering processes. Validation results highlight its capability to resolve complex interactions between navigation signals and heterogeneous land surfaces, outperforming empirical methods in scenarios with high vegetation density or significant surface roughness [?, ?]. The model's explicit treatment of scattering physics enables the development of inversion algorithms grounded in electromagnetic theory, offering superior generalizability across diverse terrain conditions compared to data-driven approaches [?, ?].

### **A. Impact of Vegetation and Surface Roughness on Surface Reflectivity**

The bistatic/multi-static scattering geometry of GNSS-R (illustrated in Fig. 1 [Figure 1: see original paper]) represents a fundamental configuration widely adopted in the GNSS-R community. This architecture employs spatially separated transmitters (GNSS satellites) and receivers (airborne/spaceborne platforms), enabling simultaneous multi-perspective Earth surface observations through opportunistic signal reflections.

The vegetation module of the LAGRS framework (LAGRS-Veg) was employed to simulate and analyze the impact of vegetation parameters on left-right (LR) polarized scattering, as documented in [?]. These simulations—summarized in [?—quantify the contribution of individual vegetation components to total scattering power, with detailed mechanisms described therein. Notably, simulations of dense Aspen forests demonstrate that vertical trunks dominate specular-direction scattering due to their alignment with the incident wave front. Surface scattering from bare soil also contributes significantly to total scattering, particularly in the specular direction. Surface roughness critically modulates specular scattering, which predominantly occurs on flat surfaces and diminishes with increasing roughness. The LAGRS model, grounded in microwave scattering theory, rigorously resolves these dynamics through physics-based parameterization [?]. Accurate interpretation of these scattering mechanisms—vegetation

structure, soil roughness, and their interplay—is essential for refining soil moisture retrieval algorithms. Addressing these variables enhances both the precision and reliability of remote sensing-derived soil moisture estimates, advancing applications in environmental monitoring and sustainable resource management [?].

## B. Impact of Observation Geometry on GNSS-R Scattering Signals

The interaction of GNSS-R signals with different surface features results in a diverse range of scattering phenomena, influencing the overall signal response. Factors such as surface roughness, vegetation cover, soil moisture content, and the geometric properties of scattering significantly affect the behavior of GNSS-R signals. As can be observed from the simulations [?], the final scattering properties of vegetation are significantly influenced by the observation geometry. A companion paper [?] that utilized observation geometry information for Fengyun 3E GNOS-R soil moisture retrieval has given a detailed demonstration on these effects.

From the corresponding theoretical simulations in [?], we can see that the observation geometry parameters—including incidence angle and satellite elevation—critically modulate GNSS-R scattering signals through three primary mechanisms: 1) Scattering mechanism sensitivity: Specular scattering dominates at low incidence angles ( $<35^\circ$ ), whereas diffuse scattering intensifies with surface roughness and elevation. Geometry governs the coherent/incoherent component ratio, necessitating angular-dependent modeling. 2) Fresnel reflectivity dependence: Fresnel reflectivity exhibits pronounced angular dependence; angle-agnostic formulations introduce systematic errors in roughness-vegetation (R-V) factor estimation and subsequent soil moisture inversion. 3) Vegetation attenuation: Vegetation attenuation demonstrates geometric modulation—elevated angles enhance canopy opacity ( $\tau$ ), mandating geometry-adaptive correction schemes.

## C. Process and Steps

The proposed soil moisture retrieval methodology comprises seven sequential steps: 1) Data Quality Control: Input data undergo validation filtering, excluding samples with elevation  $>600$  m or Signal-to-Noise Ratio (SNR)  $<55$  dB. 2) SMAP Data Integration: Concurrent Soil Moisture Active and Passive (SMAP) observations—including soil moisture, surface roughness, and vegetation optical depth—are integrated as auxiliary inputs. 3) Theoretical Modeling: Dominant error sources impacting inversion accuracy are identified through physical scattering model analysis. 4) Zeroth-Order Model Application: Vegetation attenuation and surface roughness factors (R-V factors) are derived using the zero-order radiative transfer model. 5) Reflectivity Correction: Retrieved R-V factors are applied to compensate vegetation/roughness effects on CYGNSS effective reflectivity. 6) Fresnel Coefficient Extraction: Corrected reflectivity values are converted to Fresnel reflection coefficients via dielectric modeling. 7) Soil Mois-

ture Inversion & Validation: Final moisture estimates are retrieved through dielectric-to-moisture conversion, followed by quantitative accuracy assessment.

### III. DATASET DESCRIPTION

#### A. Overview of CYGNSS

On December 15, 2016, NASA’s Cyclone Global Navigation Satellite System (CYGNSS) achieved a critical milestone through successful deployment of its pioneering constellation. The CYGNSS constellation comprises eight microsattelites, each equipped with four Delay Doppler Mapping Instruments (DDMIs). Each DDMI incorporates two left-hand circular polarization (LHCP) L-band antennas and one right-hand circular polarization (RHCP) L-band antenna. These antennas are respectively coupled with low-noise amplifiers (LNAs) and delay mapping receivers (DMRs), where each DMR contains three radio frequency (RF) front-ends and a digital processing unit. The downward-pointing LHCP antennas capture GNSS signals undergoing specular reflection from Earth’s surface and diffuse scattering from distributed targets, while the zenith-oriented RHCP antenna receives direct GNSS signals for precise orbit determination. This configuration enables each satellite to simultaneously acquire four specular reflection measurements, collectively providing 32 concurrent reflection point observations across the constellation.

The CYGNSS data products comprise four processing levels, with Level 1 data being utilized for soil moisture retrieval in this study. As the foundational dataset, Level 1 products undergo systematic calibration of raw onboard measurements to generate calibrated Delay-Doppler Maps (DDMs) with associated metadata. The calibration pipeline implements two sequential stages: L1a processing converts raw DDM counts to digital/analog signal power units, while L1b processing applies geometric corrections (satellite location, specular point position) and antenna gain compensation to derive bistatic radar cross-section (BRCS) values from the power-calibrated DDMs.

Assuming coherent reflections across flat terrain, the extraction of surface reflectivity (SR) from L1 data requires the utilization of the following equations [?, ?]:

$$\Gamma = \sigma(R_t + R_r)^2 / 4\pi(R_t R_r)^2 \quad (1)$$

Where  $R_t$  and  $R_r$  are the distances from the transmitter and receiver to specular point, respectively.  $\sigma$  is the definition of the surface scattering coefficients, and it will be utilized to represent SR in this paper.

#### B. SMAP Ancillary Data Products

SMAP (Soil Moisture Active and Passive) is one of the Earth observation satellites launched by the United States on January 31, 2015 [?]. The primary

scientific objective of SMAP is to monitor soil moisture. Operating within the L-band signal spectrum, SMAP data covers land areas globally within  $\pm 45^\circ$  latitude, with a revisit cycle of 2 to 3 days. Observations are conducted in ascending (6:00 am) and descending (6:00 pm) orbits, providing excellent spatiotemporal coverage worldwide. In equatorial regions, SMAP delivers global coverage data within three days, while in higher latitudes (areas above  $45^\circ\text{N}$ ), global coverage data is provided within two days. The global passive L-band microwave radiometer products at SMAP Level 3 provide surface soil moisture data at a 0 to 5 cm depth on the EASE-Grid 2.0 grid, and global composite products at resolutions of 9 km and 36 km. The ancillary dataset incorporates SMAP Level 3 products with 36-km spatial resolution, comprising four critical parameters: soil moisture, vegetation optical depth (VOD), surface roughness and soil texture.

#### IV. RESULTS AND ANALYSIS

The histograms of the incidence angles with their temporal distribution over a 21-day observation period (July 10-30, 2021) are presented in Fig. 2 [Figure 2: see original paper]. The distribution of SR is between -40dB and 0dB, while the incidence angle covers from lower  $10^\circ$  to higher  $60^\circ$ .

In Fig. 3 [Figure 3: see original paper], we have classified incidence angle distributions into three groups. Panel (a) corresponds to observations at incidence angles below  $35^\circ$ , panel (b) covers the intermediate range of  $35^\circ$ - $60^\circ$ , and panel (c) characterizes the distribution patterns for angles exceeding  $60^\circ$ .

To account for acquisition geometry variations, the SR measurements were also stratified into three angular regimes (Fig. 4 [Figure 4: see original paper]). Panel (a) displays observations with incidence angles  $<35^\circ$ , panel (b) illustrates the intermediate angular range ( $35^\circ$ - $60^\circ$ ), while panel (c) presents the distribution characteristics at higher incidence angles ( $>60^\circ$ ).

As demonstrated in Fig. 4, the incidence-angle-dependent SR distribution exhibits significant variability, aligning with the theoretical framework established in Section 2. This angular dependence necessitates geometry-specific soil moisture inversion schemes.

Under zero-order conditions, GNSS signals attenuate the vegetation layer from both the incident and reflection directions. The formula for a zero-order model is as Eq. 2 and Eq. 3 [?]:

$$\gamma(\theta) = \exp(-\tau \csc(\theta)) \quad (3)$$

Where the transmissivity  $\gamma$  accounts for the attenuation of signal propagation by vegetation layer and it can be presented by the exponential term for vegetation opacity  $\tau$  and incidence angles  $\theta$  (Equation (3)).

The effects of surface roughness and vegetation as shown in the above two equations are called as R-V factor (Roughness-Vegetation factor), and it should be get rid of due to its effects that affect the final soil moisture retrieval accuracy. The final R-V factor according to the above equation is shown in Figure 5 [Figure 5: see original paper]. It should be mentioned that the R-V factor that is shown in Fig. 5 have not considered the effects of incidence angles [?].

The corresponding SR values were retrieved from CYGNSS Level-1 data products, with their temporal distribution over a 21-day observation period (July 10-30, 2021) presented in Fig. 4. The R-V factor that is related to the incidence angles is presented in Fig. 6. While the left panel in Fig. 6 [Figure 6: see original paper] is the R-V factor whose incidence angle is lower than  $35^\circ$ , the R-V factor for the incidence angle between  $35^\circ$  and  $60^\circ$  is shown in the middle panel, while the one when the incidence angle is larger than  $60^\circ$  is shown in the right panel. With this information, these three factors are employed to get rid of the vegetation surface roughness effects with the considerations of incidence angles.

After removing the R-V factor from the SR, we can get the mask Fresnel reflectivity information. As shown in Fig. 7 [Figure 7: see original paper], here mask Fresnel reflectivity means these values are no longer related to surface roughness and vegetation information. The corresponding mask Fresnel reflectivity with the consideration of incidence angles are presented in Fig. 8 [Figure 8: see original paper].

After obtaining the mask Fresnel reflectivity, we can retrieve the corresponding soil moisture information by employing the fixed relationship between dielectric constant of soil and the Fresnel reflectivity. The final retrieval result is shown in Fig. 9 [Figure 9: see original paper]. By incorporating geometry (e.g., grouping data by incidence angle bins in Fig. 3–8), our method reduces RMSE by 55% ( $0.0794 \rightarrow 0.0357$  as shown in Fig. 9). This demonstrates that geometry-aware modeling is essential for accurate soil moisture retrieval. And this method is also applicable to Fengyun 3E GNOS-R and has achieved acceptable accuracy tolerance [?, ?].

## V. DISCUSSION

This study presents a soil moisture retrieval algorithm grounded in physical modeling principles. The integration of precise physical models is crucial for achieving accurate soil moisture retrieval from CYGNSS data. The proposed methodology demonstrates inherent extensibility to spaceborne GNSS-R missions, with particular applicability validated on Fengyun GNOS-R systems. The LAGRS model, originally architected for Fengyun GNOS-R, features parameterized modules that facilitate system-specific customization (e.g., adjustable platform descriptors including antenna gain characteristics and orbital dynamic parameters) through the generalized R-V formulation. The algorithm has been successfully implemented on Fengyun-3E GNOS-R datasets, demonstrating measure-

ment consistency with soil moisture retrieval errors constrained within 0.04–0.05 RMSE ranges. As the zeroth-order scattering formulation establishes a physical correction scheme independent of mission specifications, this approach is readily adaptable to other GNSS-R missions such as CYGNSS and HydroGNSS. Notably, Fengyun’s multi-angular observational geometries provide enhanced error mitigation through angular diversity exploitation.

## ACKNOWLEDGMENT

The authors wish to extend their sincere gratitude to the anonymous reviewers for their insightful feedback and constructive suggestions, which have significantly enhanced the clarity and academic rigor of this manuscript. This research was funded by the National Natural Science Foundation of China (No. 42061057) and Key Laboratory of Satellite Navigation Technology.

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