Research on Compact Polarization GNSS-ReSAR Technology for Land Surface Remote Sensing

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Date: 2025-06-04T19:15:53+00:00

Abstract

GlobalNavigation Satellite System Reflectometry,GNSS-R is an effective Earth observation technique that retrieves land surface parameters by analyzing reflected navigation satellite signals. Historical studies indicate that conventional GNSS-R systems primarily employ a single polarization configuration (Right-Hand Circular Polarization (RHCP) transmission and Left-Hand Circular Polarization (LHCP) reception, hereinafter referred to as LR polarization), with relatively limited research on the scattering characteristics of other polarization combinations. With technological advancements, schemes utilizing RHCP antennas to receive surface-reflected signals have gradually gained attention. Meanwhile, the Delay-DopplerMap,DDM processing mode of conventional GNSS-R exhibits low efficiency in utilizing scattering features under varying observation geometries. In this context, developing GNSS-based SyntheticApertureRadar,GNSS-SAR technology capable of effectively receiving surface scattering signals across different geometric configurations has emerged as a promising research direction. This study focuses on remote sensing exploration of compact polarimetric GNSS-R and Synthetic Aperture Radar fusion technology (GNSS-ReSAR: GNSS-ReflectometryandSyntheticApertureRadar). Soil moisture retrieval studies were conducted based on dual-polarization (LR and RR (RHCP transmission and RHCP reception)) data acquired from the airborne GLORI experiment in Spain, with concurrent comparative validation using dual-polarization GNSS-R data from China's Tianmu (TM) commercial satellite. Both experiments consistently demonstrate that RR polarization reflectivity is approximately 10 dB lower than LR polarization, yet the soil moisture retrieval accuracy based on the two polarizations is comparable. Due to limitations in compact polarimetric data acquisition capabilities, this study employs the LAGRS (LandSurfaceGNSSReflection Simulator) model, constructed based on radiative transfer theory, to analyze other scattering characteristics of compact polarimetry. Through systematic analysis of the scattering mechanisms and development trends of the

GNSS-ReSAR mode, this study provides theoretical reference for the evolution of next-generation GNSS-R technology to a certain extent.

Full Text

Abstract

Objectives: Conventional Global Navigation Satellite System Reflectometry (GNSS-R) primarily relies on single-polarization, presenting key limitations. This research explores compact polarimetry potential by integrating GNSS-R and Synthetic Aperture Radar (SAR) techniques (GNSS-ReSAR), aiming to enhance soil moisture retrieval accuracy and expand observable land surface parameters.

Methods: Dual-polarization datasets from Spain's airborne GLORI experiment (LR, RR) and China's Tianmu satellite constellation were analyzed. A neural network incorporating coherent/non-coherent scattering components and auxiliary parameters (incident angle, roughness, leaf area index) was developed for soil moisture inversion. The Land surface GNSS Reflection Simulator (LAGRS) model characterized compact polarization scattering under varying geometries. Polarimetric ratio analysis and Stokes parameter synthesis resolved discrepancies between theoretical predictions and observed RR polarization characteristics.

Results: Soil moisture retrieval accuracy was comparable between RR and LR polarizations (RMSE: 0.0342–0.0681 RR vs. 0.0320–0.0700 LR), despite RR reflectivity being 5–10 dB lower. GLORI data showed non-coherent scattering contributed 15%–40% of total power; its inclusion with geometric/biophysical parameters improved RMSE from 0.0853 to 0.0348. Tianmu observations confirmed polarization-dependent reflectivity distributions (bare soil: -45 to 0 dB LR vs. -45 to -20 dB RR; vegetation cover), with normalized trends contradicting Fresnel predictions. LAGRS simulations revealed significant azimuthal variations (>70°) in compact polarization scattering, necessitating GNSS-SAR integration for multi-angle feature extraction.

Conclusions: RR polarization demonstrates operational feasibility for soil moisture monitoring. Compact polarimetry represents a transformative enhancement to GNSS-R. The GNSS-ReSAR framework synergistically utilizes polarization diversity and multi-angle scattering, addressing Delay-Doppler Map position ambiguity. Findings provide foundations for optimizing next-gen GNSS-R payloads (polarization-agile receivers, geometry-aware algorithms). Dual-polarization measurements and model-driven Stokes synthesis advance autonomous geophysical parameter retrieval without ancillary satellite data.

Keywords: GNSS-R, Simplified polarization, DDM, SAR

Introduction

Microwave remote sensing offers all-weather, day-and-night observation capabilities. GNSS-R, as a novel microwave remote sensing approach distinct from radiometers and radars, has gradually become a research hotspot in this field, with its polarization characteristics representing a key differentiator from traditional radiometers and radars. Unlike linear polarization in conventional microwave remote sensing, navigation satellites transmit Right-Hand Circular Polarization (RHCP) signals [1]. In early GNSS-R research, Left-Hand Circular Polarization (LHCP) receiver antennas were commonly employed to isolate direct signal interference [1-3].

In airborne experiments (as shown in), the early SMEX02 and SMEX03 experiments utilized a GPS bistatic radar receiver called the Delay Mapping Receiver (DMR) developed by NASA Langley Research Center. Its independent RF front-ends were connected to a zenith-pointing RHCP antenna (for direct signal reception) and a nadir-pointing LHCP L-band antenna (for surface reflected signal reception) [4]. This experiment marked the first attempt to utilize LR polarization reflectivity for surface soil moisture research, achieving favorable qualitative analysis results.

Subsequently, ESA's LEiMON (LAnd Monintoring with Navigation Signal) experiment also employed single-polarization (LHCP antenna) for soil moisture-related studies. The BAO (Boulder Atmospheric Observatory) tower experiment [5] and related experiments by the Universitat Politecnica de Catalunya (UPC) moved beyond LHCP polarized receiver antennas [6], beginning to explore using other polarized antennas to receive surface scattering information to improve soil moisture inversion accuracy. The SMIGOL reflectometer system obtained coherent waveform (IPT Interference Pattern Technique) information by receiving both direct and reflected GNSS signals, with its vertically and horizontally polarized antennas capable of measuring interference patterns in corresponding polarization states, enabling geophysical parameter retrieval through analysis of notch quantities and positions in the waveforms. The BAO tower experiment conducted during summer-autumn 2002 employed an improved DMR receiver provided by NASA Langley Research Center, where the RHCP antenna tracked direct signals while the surface observation antenna system comprised: (a) a low-gain hemispherical LHCP antenna; (b) four end-fire high-gain (~12 dB) antennas with vertical (V), horizontal (H), LHCP, and RHCP polarizations. The initial experimental design aimed to utilize four polarization types to mitigate soil roughness and vegetation effects, thereby improving soil moisture inversion accuracy. However, the experimental conclusions exhibited deviations from theoretical expectations due to overly simplified model assumptions [5]. In recent years, dual-polarization airborne experiments have become a hotspot for pre-research of spaceborne dual-polarization GNSS-R receivers. Spain's GLORI experiment [7] was the first to publicly provide a complete dual-polarization reflectivity observation dataset, which simultaneously quantified the proportion characteristics of incoherent components in total scattering signals. The ongoing

RONGOWAI (GLObal Navigation Satellite System Reflectometry Instrument) airborne experiment since October 2022 [8] has as its core scientific objective the enhancement of inland water detection capability under dense vegetation cover through polarimetric GNSS-R measurements (joint RHCP/LHCP dual-polarization observations).

Egido et al. conducted three experiments using airborne polarimetric measurement techniques, simultaneously acquiring RR and LR reflection data, finding that soil moisture and surface roughness significantly affected RR and LR reflectivity under low incidence angles. Polarization ratio analysis revealed low sensitivity to moderately rough surfaces, beneficial for soil moisture inversion; when roughness exceeded 3 cm, incoherent scattering became the dominant factor. Subsequent research employed a four-channel prototype for in-depth analysis of RHCP/LHCP dual-polarization reflection characteristics, focusing on eliminating incoherent reflection energy interference during data processing, ultimately confirming polarization ratio as an effective technical approach for soil moisture inversion [9].

In spaceborne GNSS-R payload design (as illustrated in [FIGURE:1]), early satellites including UK-DMC (United Kingdom-Disaster Monitor Constellation), TDS-1 (TechDemoSat), and CYGNSS (Cyclone Global Navigation satellite System) employed LHCP antennas to receive ocean/land reflected signals [10-12], while ESA's HydroGNSS satellite, commercial Muon satellite, China's commercial Tianmu (TM) satellite, and the land water resources satellite are equipped with dual-polarization (RHCP and LHCP) GNSS-R payloads [13,14]. For BeiDou GNSS scattering signal remote sensing, the transmitter polarization is definitively RHCP, while the receiver polarization can be arbitrarily varied, constituting a typical compact polarization mode. Currently, using SMAP-R as a data source, JPL researchers have investigated compact polarization surface remote sensing detection capabilities, obtaining RR, LR, VR, HR data through Stokes parameters for remote sensing research [15]. However, since SMAP-R (Soil Moisture Active and Passive-Reflectometry) was switched to GNSS reflected signal reception mode due to radar component damage, no specialized compact polarization receiver for BeiDou GNSS scattering signals currently exists domestically or internationally. This paper analyzes dual-polarization research results from airborne and spaceborne experiments and examines compact polarization characteristics from mechanism models. Notably, for effective inversion of land surface water cycle parameters focusing on soil moisture, both the airborne GLORI experiment and HydroGNSS design incorporate acquisition of incoherent scattering characteristics, aiming to utilize non-specular scattering for geophysical parameter inversion.

In mechanism model research, precise characterization and physical mechanism analysis of BeiDou GNSS scattering characteristics for land surface parameters constitute the core theoretical foundation supporting satellite observation data interpretation and modeling, multi-source data assimilation, quantitative land surface parameter inversion algorithm development, and new spaceborne sensor optimization design. Current physical models for GNSS-R land surface scattering characteristics research mainly include the SARVERS model [16], Scobi-Veg model [17], and LAGRS model [18-20]. SAVERS (Soil And VEgetation Reflection Simulator) integrates geometric, Delay-Doppler Map (DDM), and scattering coefficient calculation modules, employing electromagnetic models for bare soil/vegetation-covered soil, considering actual antenna polarization, mismatch, and crosstalk effects in polarization processing. This model accurately simulates ground conditions under LR polarization and low incidence angles, though RR polarization signal prediction accuracy requires improvement [16]. Scobi-Veg (Signals of opportunity Coherent Bistatic scattering model for Vegetation) focuses on dual-polarization characteristics in coherent/incoherent scattering, finding that LR polarization reflectivity exceeds RR polarization at low incidence angles during specular reflection, with divergent trends as incidence angle varies, and vegetation significantly affecting RR polarization reflectivity. Under diffuse scattering conditions, polarization characteristics are dominated by scattering mechanisms, with double-bounce scattering contributing most significantly, and LR polarization normalized radar cross-section response first increasing then decreasing with incidence angle [17]. The LAGRS (Land surface GNSS Reflection Simulator) system, based on microwave radiative transfer theory and polarization synthesis methods, can calculate scattering characteristics including compact polarization under specular/non-specular conditions. Simulation results indicate that GNSS scattering characteristics of ground objects are significantly affected by scattering zenith and azimuth angles, directly relating to inversion accuracy [18-20]. This model served as auxiliary theoretical support for soil moisture inversion algorithm development in CYGNSS and Fengyun GNOS-R [21], with its dual-polarization scattering characteristic research also contributing to the demonstration of dual-polarization GNSS-R payloads for China's planned 2028 land water cycle satellite.

Traditional GNSS-R applications commonly employ along-track scanning to form DDM waveforms, with land surface research primarily utilizing the DDM maximum at the specular point (Effective Surface Reflectivity, SR) as the inversion basis [22,23]. However, each grid in DDM waveforms corresponds to two positions, creating position ambiguity. Although researchers have attempted multi-satellite positioning solutions, current inversions only utilize grid maximum values without fully exploiting DDM data potential. Some studies have employed multiple delay-Doppler grids as incoherent data for inversion, yet position ambiguity prevents effective separation of observation geometry information, failing to truly utilize scattering characteristics across observation geometries for inversion [24], though these studies point toward future GNSS-R development directions. summarizes spaceborne GNSS-R development history: first-generation payloads (UK-DMC, TDS-1) validated that LR polarization surface reflected signals could be received; second-generation payloads (NASA CYGNSS, Fengyun GNOS-R, Spire GNSS-R) demonstrated that LR polarization scattering characteristics could be inverted for typical land surface water cycle parameters, though inversion algorithms relied on existing satellite data like SMAP; third-generation payloads (ESA HydroGNSS, China's land water resources satellite, and Tianmu commercial satellite GNSS-R) added dual-polarization information to eliminate surface roughness and vegetation effects, aiming to develop independent soil moisture inversion algorithms. All these GNSS-R systems employ DDM as observables, with inversion methods primarily extracting specular point reflectivity. Due to DDM data format limitations, scattering characteristics under other observation geometries (different scattering zenith/azimuth angles) have not been effectively exploited. Since GNSS satellite constellations serve as signal sources, mining compact polarization scattering characteristic information across different observation geometries while retaining the original DDM mode will facilitate effective extraction of additional land surface parameters such as vegetation biomass and freeze-thaw status. Therefore, in fourth-generation GNSS-R design, developing compact polarization GNSS-ReSAR (GNSS-Reflectometry and GNSS-SAR) mode receivers represents potential research content, where GNSS-Re refers to traditional DDM mode and GNSS-SAR represents bistatic or multistatic radar modes capable of separating scattering characteristics under different observation geometries. Utilizing GNSS-ReSAR mode to effectively mine polarization information (compact polarization) and scattering characteristics across different observation geometries from GNSS electromagnetic wave direct signals scattered by the surface will provide feasibility for obtaining sensitivity configuration parameters for different geophysical parameters and developing corresponding inversion algorithms [25].

2. Experimental Data Analysis

2.1 GLORI Airborne Data

The summer 2021 GLORI airborne experiment served as pre-research for ESA's planned 2025 HydroGNSS launch and other polarimetric GNSS-R satellite observation programs [26]. Conducted under the Global Energy and Water Exchanges Project (GEWEX-supported LIAISE international project), the experiment employed dual-polarization Global Navigation Satellite System Reflectometry (GNSS-R) technology to monitor and analyze soil moisture, surface roughness, and vegetation conditions in the Ebro River basin, particularly in the Urgell agricultural region of northeastern Spain. The core of the study involved collecting GNSS-R airborne data using the GLORI (GNSS Reflectometer) instrument installed on an ATR-42 aircraft. This experiment was the first airborne dual-polarization experiment to simultaneously include observations of coherent reflectivity and incoherent reflectivity ratios. These data, combined with ground truth and land use data, were used to evaluate dual-polarization characteristics and incoherent scattering energy intensity. One of the intended targets of the collected dataset was to provide valuable data resources for electromagnetic modeling research and validate related coherent and incoherent scattering components.

2.1.1 GLORI Dual-Polarization Characteristics Analysis The GLORI airborne flight test area featured rich land cover types, including alfalfa fields, orchards (apple and pear trees), cornfields, and post-harvest wheat fields [26].

When calculating reflectivity (gamma), the Interferometric Complex Field (ICF) method was employed. ICF is defined as the ratio of reflected waveform peak time series to direct waveform peak time series, with the calculation formula provided in [26]. Subsequently, incoherent contributions were eliminated from ICF to estimate reflectivity. The L1b dataset provides gamma_l and gamma_r variables. The incoherent ratio was calculated to estimate the percentage of incoherent components relative to total scattering power, with variables incoherent_{ratio}I and incoherent_{ratio}r provided in the L1b dataset.

2.1.2 GLORI Dual-Polarization Inversion Results presents soil moisture inversion results using the neural network method with LR polarization coherent and incoherent scattering [27]. When utilizing coherent scattering components for inversion, with only SRLR (LR polarization effective reflectivity) as input, the RMSE was 0.0700. Adding specular incidence angle , root-mean-square height rms, and leaf area index LAI as neural network training layers improved RMSE to 0.0650, 0.0468, and 0.0320 respectively. Using LR polarization incoherent scattering characteristics for inversion yielded RMSE of 0.0821, which improved to 0.0728, 0.0422, and 0.0293 when adding observation geometry ( ) and physical parameters (rms and LAI). This demonstrates that LR polarization incoherent scattering can achieve comparable inversion accuracy to coherent scattering.

For RR polarization, the study [27] first utilized it for soil moisture inversion. Using RR polarization coherent scattering alone yielded RMSE of 0.0681, improving to 0.0650, 0.0402, and 0.0342 when adding incidence angle , rms, and LAI. Using RR polarization incoherent scattering yielded RMSE of 0.0853, lower than coherent scattering, but improved to 0.0741, 0.0569, and 0.0348 when adding auxiliary data (, rms, LAI). Compared to RR polarization coherent scattering, the accuracy was slightly lower but still within acceptable ranges. Therefore, [27] first confirmed that RR polarization can be used for soil moisture inversion and demonstrated that incoherent scattering energy can also be used for soil moisture inversion in both LR and RR polarizations, with accuracy slightly lower than coherent scattering but both acceptable for soil moisture inversion.

2.2 Tianmu Satellite Data

The Tianmu commercial satellite constellation, independently developed by China Aerospace Tianmu (Chongqing) Satellite Technology Co., Ltd., employs BeiDou/GNSS remote sensing technology for BeiDou/GNSS occultation detection and GNSS reflectometry (GNSS-R) detection. The constellation is compatible with signals from four major navigation systems: BeiDou, GPS, Galileo, and GLONASS. Currently, the Tianmu-1 constellation comprises multiple satellites.

2.2.1 Tianmu Dual-Polarization Characteristics Analysis The GNSS-R payload on Tianmu satellites was developed by the same institution as the GNSS-R payload (GNOS-R) on China's Fengyun series satellites (Fengyun E/F/G), with identical data format design. When using GNSS-R data for inversion under the assumption of specular reflection, effective reflectivity at the specular angle is calculated as follows [21]:

where Γ is effective reflectivity, distances from specular point to receiver and transmitter are represented, DDM peak power is denoted, and DDM bistatic radar cross-section factor is included. GNSS effective isotropic radiated power (EIRP) and receiver antenna pattern are also incorporated.

2.2.2 Tianmu Dual-Polarization GNSS-R Data Analysis Specular reflection point trajectories plotted using Tianmu-12 dual-polarization GNSS-R data from DOY071 2024 are shown in [FIGURE:2], where different colors represent Surface Reflectivity (SR) values. Subplot (a) shows LR polarization reflectivity from a single satellite day, while subplot (b) shows corresponding RR polarization reflectivity. Comparison reveals that RR polarization data can be received in spaceborne GNSS-R, but its magnitude is approximately 5-10 dB lower than LR polarization reflectivity.

Using global land use and land cover maps to categorize land types into bare soil, low vegetation, and tall forest regions, [FIGURE:3] presents histogram statistical analysis of effective reflectivity values for satellite-12 across three land types. Subplots (a), (b), and (c) show LR and RR polarization effective reflectivity distribution histograms for bare soil, low vegetation, and tall forest regions respectively. LR polarization values primarily distribute between -45 dB and 0 dB, while RR polarization values range from -45 dB to -20 dB. Bare soil and tall forest regions exhibit similar histogram distributions for LR and RR polarizations, but low vegetation regions show distinct distribution differences between LR and RR polarization histograms.

In the Tianmu GNSS-R satellite constellation, satellites 12 through 22 are dual-polarization satellites. [FIGURE:4] shows LR and RR polarization reflectivity distributions for these 11 dual-polarization satellites on DOY 071. LR polarization primarily distributes between -45-0 dB, while RR polarization mainly distributes between -45–10 dB.

[FIGURE:5] shows corresponding effective reflectivity distribution histograms: (a) bare soil region, (b) low vegetation region, and (c) tall forest region. Analysis of 12 satellites on DOY 071 2024 reveals that LR polarization effective reflectivity primarily distributes between -45 dB and 0 dB, while RR polarization effective reflectivity concentrates between -45 dB and -10 dB.

Normalization was performed by extracting the top 20 maximum and bottom 20 minimum values from land data, calculating their averages as max and min respectively. Each data point was then normalized using the formula: data_{normalized} = (data - min) / (max - min). [FIGURE:6] shows normalized LR (a) and RR (b) polarization effective reflectivity distributions, demonstrating similar trends after normalization. In traditional GNSS-R remote sensing, RR polarization reflectivity is calculated using Fresnel reflection coefficients for horizontal and vertical polarizations. However, observed normalized reflectivity patterns from Tianmu satellite show that LR and RR polarization effective reflectivity trends are actually identical, contradicting traditional Fresnel predictions. SMAP-R data similarly confirms that RR polarization reflectivity increases with soil moisture [30]. Therefore, for dual-polarization GNSS-R satellites, using traditional Fresnel reflection coefficient combinations for RR polarization reflectivity analysis and inversion algorithm development shows certain inapplicability, necessitating mechanism model-based research on RR polarization scattering characteristics.

2.2.3 Tianmu Dual-Polarization GNSS-R Data Inversion This study conducted soil moisture inversion using observation data from DOY071 to DOY181 2024. Analysis of Fengyun satellite GNOS-R payload data [31] revealed that observation angle significantly affects soil moisture inversion accuracy. Therefore, this study employed random sampling, selecting 80% of sample data for multi-angle training based on AI algorithms, with the training method referencing the airborne GLORI data processing scheme and using the remaining 20% as validation set.

Inversion accuracy results based on LR and RR polarization dual-polarization effective reflectivity are shown in [FIGURE:7]. When 30°-40° data were divided into two parts (30°-34° and 35°-40°), inversion RMSE values were 0.056 and 0.053. When inverting at each degree interval, corresponding RMSE results were 0.063, 0.061, 0.065, and 0.060. Comprehensive inversion using all angles yielded final RMSE of 0.041. Thus, dual-polarization spaceborne data similarly demonstrates capability for soil moisture inversion with acceptable accuracy.

3. Compact Polarization Mechanism Model Analysis

Contrary to traditional views requiring LHCP reception of surface reflected signals and RHCP signal isolation, both airborne GLORI and spaceborne Tianmu data have proven that RR polarization reflectivity from land surfaces can be effectively received. When using linear combinations of horizontal and vertical polarization Fresnel reflectivity to obtain RR polarization Fresnel reflectivity, its trend with soil moisture changes opposite to LR polarization. However, normalized Tianmu data and SMAP-R research show RR polarization trends identical to LR polarization [30], with RR polarization reflectivity achieving soil moisture inversion accuracy comparable to LR polarization. Therefore, in-depth research on RR polarization mechanism models is urgently needed. Meanwhile, adding polarization information and analyzing other compact polarization BeiDou GNSS scattering characteristics will facilitate development of inversion algorithms for different geophysical parameters and become a potential research hotspot. Limited by compact polarization observation data, this paper employs mechanism models to analyze land surface compact polarization BeiDou GNSS scattering signal characteristics.

The LAGRS model is a GNSS-R scattering model specifically developed for typical land surface parameters, integrating random rough surface scattering models and radiative transfer equation models from microwave scattering theory. The model systematically incorporates sub-model systems for key land surface water cycle parameters, including the LAGRS-Soil model characterizing soil properties, LAGRS-Veg model describing vegetation characteristics, and LAGRS-FT model reflecting surface freeze-thaw states [18-20]. The model's core advantage lies in its ability to accurately characterize the complex electromagnetic scattering physical process where navigation satellite direct signals interact with surface parameters and are captured by GNSS-R receivers. Implementation involves constructing full-polarization scattering matrices, employing polarization synthesis techniques, and adjusting ellipticity and tilt angles in the Mueller matrix to achieve scattering characteristics in various polarization modes. The LAGRS model flowchart is shown in

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For GNSS-ReSAR mode development, the model can output not only traditional DDM waveforms containing coherent and incoherent scattering but also bistatic radar cross-sections under different observation geometries (GNSS-SAR mode). The model's full-polarization calculation capability enables compact polarization characteristic calculation in GNSS-ReSAR mode. For typical land surface water cycle parameters, the model can analyze DDM waveforms and bistatic radar cross-sections for bare soil, surface freeze-thaw, and vegetation-covered soil in GNSS-ReSAR mode. Compact polarization functionality is achieved through interaction between full-polarization scattering matrices and modified Stokes vectors, using variations in ellipticity angle c and tilt angle y in the modified Stokes vector (Equation 9) to obtain various compact polarization scattering characteristics [32].

For BeiDou GNSS scattering signal remote sensing, LAGRS compact polarization calculation capability enables arbitrary receiver polarization state changes for navigation satellite transmitted RHCP signals, allowing calculation of RR, LR, VR, HR, and $±$45°R polarizations. Preliminary simulations of bare soil and vegetation by researchers show different polarization scattering characteristics, with VR and HR polarizations within effective receiver ranges, though compact polarization scattering characteristics vary significantly with observation geometry.

Regarding RR polarization models, researchers constructed three novel polarimetric GNSS-R reflectivity models [29]: Spec4PolR, SPM4Pol, and Umich4Pol. Mueller matrix expressions for all three models were derived, with RR polarization reflectivity calculated using wave synthesis techniques. Spec4PolR uses only 3 Mueller matrix elements for final reflectivity calculation, Umich4Pol requires 5 matrix elements, while SPM4Pol is built on full matrix elements but

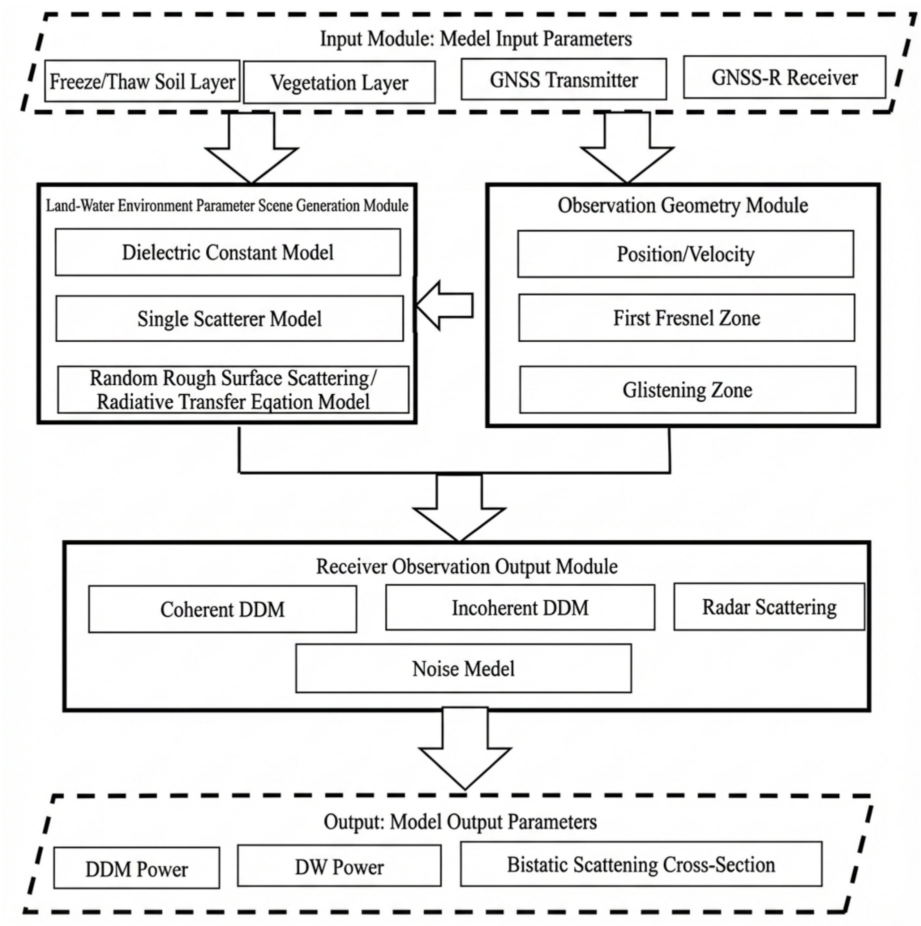

Figure 1: Figure 8

only requires selection of 9 core elements in practice. Systematic quantification of each matrix element's sensitivity to soil volumetric water content and clarification of its contribution mechanism to RR polarization reflectivity revealed that Spec4Pol's simplified model leads to negative correlation between RR polarization reflectivity and soil water content (reflectivity decreasing with increasing water content), contradicting measured data. SPM4Pol and Umich4Pol simulation results agree with measured data, showing significant positive correlation between RR polarization reflectivity and soil water content.

LAGRS model geometry observation module analysis results for different observation angles are shown in [FIGURE:9]. During simulation, GPS L1CA code was used for GNSS satellite signal orbit parameters, with GNSS signal transmission power of 13.4 dBW, receiver chip interval of 0.25 chips, coherent integration time of 1 ms, incoherent integration count of 1000, Doppler frequency range of 5000 Hz, Doppler interval of 500 Hz, and spatial integration range interval of 1000 m. When transmitter and receiver incidence angles range from 8° to 9°, corresponding scattering zenith angles range from 5° to 13°, showing 9° differences. Scattering azimuth angle dynamic variation range is approximately 70°. [FIGURE:10] shows bare soil compact polarization scattering characteristics varying significantly with scattering azimuth angle. However, existing research has paid insufficient attention to scattering characteristics under such angular distribution conditions, resulting in low observation data utilization. In response, future GNSS-ReSAR receivers will simultaneously acquire coherent and incoherent scattering components to effectively capture scattering characteristic differences under multi-observation geometry conditions [33].

4. Discussion and Conclusions

In GNSS-R remote sensing technology for geophysical parameter inversion, current methods primarily utilize waveform characteristic parameters (including peak, leading/trailing edges, and bistatic radar cross-section BRCS) for inversion. Among these, inversion methods based on specular point effective reflectivity have become the most effective approach for spaceborne GNSS-R soil moisture inversion. However, when GNSS systems serve as opportunistic illuminators, the bistatic radar system formed with GNSS-R receivers exhibits dynamic characteristics derived from the time-varying nature of GNSS signal sources. Even with constant incidence angles, this time-varying property causes scattering zenith and azimuth angles to change with observation time. Through forward modeling of GNSS-R Delay-Doppler Map (DDM) waveform formation, it is evident that different surface features exhibit significantly different scattering characteristics under varying scattering geometries, with observation area integration grids containing not only specular reflection components but also incoherent scattering contributions. Current single-polarization or dual-polarization DDM (GNSS-Re) modes have limitations in capturing scattering characteristic differences and polarization features under different observation geometries. Therefore, next-generation GNSS-R payloads (GNSS-ReSAR) adopt Synthetic

Aperture Radar (SAR) mode to simultaneously acquire coherent and incoherent scattering information, enabling comprehensive utilization of surface target scattering characteristics under different observation geometries. Furthermore, GNSS-ReSAR mode with compact polarization capability provides multi-dimensional data containing both polarization and observation geometry dimensions. This enhanced dataset establishes an important foundation for developing independent inversion algorithms and expanding invertible geophysical parameters, particularly for AI-based inversion algorithms that rely on massive data, where added polarization and geometry information facilitates deep mining of physical information contained in surface target scattering characteristics.

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