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Research Status of GNSS-R/IR Remote Sensing of Soil Moisture

Authors: Wu Xuerui, Shuanggen Jin, Wang Feng, Wu Xuerui

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Abstract

GNSS-R/IR is a novel Earth observation approach utilizing reflected signals from navigation satellites, representing a hot research topic both domestically and internationally. Since the GNSS satellite constellation primarily operates in the L-band with relatively strong penetration capability, it is well-suited for surface soil moisture monitoring. This paper elaborates in detail on the development status of soil moisture monitoring using ground-based, tower-based, airborne, and spaceborne GNSS-R technology according to different remote sensing platforms, while also reviewing the development status of radiometer-GNSS-R combined technology for soil moisture monitoring and the development status of ground-based and spaceborne GNSS-R receivers, and discusses the key issues and challenges in soil moisture retrieval using GNSS-R/IR.

Full Text

Progress in GNSS-R/IR Remote Sensing of Soil Moisture

Wu Xuerui[1,2], Jin Shuanggen[1,2], Wang Feng[3]

[1]School of Electronic and Information Engineering, Beihang University, Beijing 100191, China

Abstract

GNSS-R/IR (Global Navigation Satellite System-Reflectometry/Interferometric Reflectometry) has emerged as a novel Earth observation technique using reflected navigation satellite signals, attracting significant research attention worldwide. Since GNSS constellations primarily operate in the L-band with strong penetration capabilities, this technology is particularly suitable for monitoring surface soil moisture. This paper provides a comprehensive review of soil moisture monitoring using GNSS-R across different platforms, including ground-based, tower-based, airborne, and spaceborne systems. Additionally, we examine the current state of integrated GNSS-R and microwave radiometer approaches for soil moisture retrieval, review the development status of GNSS-R receivers for both ground and space applications, and discuss key challenges and priorities in GNSS-R/IR soil moisture inversion.

Keywords: GNSS-R/IR, multipath, reflection/interference, soil moisture

1. Introduction

Soil moisture is a critical factor influencing global climate and environmental systems, playing a vital role in Earth’ s energy balance through its spatial distribution and transport mechanisms. As a key parameter controlling water and heat exchange between land and atmosphere, soil moisture is directly linked to atmospheric humidity, with research demonstrating strong feedback relationships between soil moisture anomalies and extreme climate events. Soil moisture serves as an essential indicator in hydrology, meteorology, and agricultural science, making large-scale monitoring and retrieval fundamental to agricultural research and ecological assessment. Furthermore, soil moisture acts as a crucial link between surface and groundwater, representing an integral component of terrestrial ecosystems and the water cycle. Consequently, soil moisture information is vital for improving regional and global climate model predictions, understanding global water cycle patterns, managing water resources, developing watershed hydrological models, monitoring crop growth, estimating crop yields, detecting environmental hazards, and addressing related natural and ecological issues [1].

Traditional observation methods rely primarily on discrete point measurements from monitoring stations or meteorological sites, which only represent limited areas (~10-100 cm), are time-consuming and labor-intensive, and cannot meet the requirements for large-scale, high-efficiency soil moisture observation. Moreover, these conventional approaches struggle to match the spatial and temporal scales required by weather and hydrological models (0.1-10 km), limiting their effectiveness for studying soil moisture impacts on environmental change.

Remote sensing offers an efficient means of acquiring soil moisture information over large areas. Optical, infrared, and microwave remote sensing constitute the primary Earth observation techniques, with sensors operating in the visible, infrared, and microwave portions of the electromagnetic spectrum, respectively. However, each approach has inherent limitations: optical and infrared remote sensing are restricted by weather conditions and cannot operate continuously under all-weather, all-day conditions. Microwave remote sensing overcomes these drawbacks, offering all-weather, all-day capabilities with strong penetration. Microwave wavelengths range from 1-100 cm, with commonly used bands including X (~0.8 cm), K (~3 cm), C (~5 cm), S (~10 cm), L (~20 cm), and P (~50 cm). The P-band (0.775 GHz, ~50 cm) and L-band (1.4 GHz, ~20 cm) are particularly advantageous for soil moisture observation due to reduced atmospheric attenuation and enhanced vegetation penetration [2].

The dielectric constant of water is approximately 80, while that of dry soil is only about 3.5. Increased soil moisture content leads to higher dielectric constants, resulting in lower emissivity or higher reflectivity. The fundamental principle of microwave remote sensing for soil moisture detection lies in this significant dielectric constant contrast between water and dry soil [2].

Conventional active and passive microwave techniques (microwave radiometers and radar) each have distinct advantages and disadvantages. Radiometers measure surface brightness temperature, enabling soil moisture retrieval through emissivity information. Radiometric measurements are relatively insensitive to surface roughness but susceptible to background brightness temperature and man-made radio frequency interference (RFI). While they offer high spatial resolution and simple data processing, their temporal resolution is low. In contrast, radar backscatter coefficients increase with soil moisture content, though monostatic radar shows lower sensitivity to soil moisture. Backscatter is significantly affected by surface characteristics such as roughness, soil dielectric constant, and vegetation structure, with complex data processing and lower spatial resolution.

Bistatic radar' s unique observation geometry has emerged as a novel approach for soil moisture and vegetation monitoring. However, conventional bistatic radar requires dedicated transmitters and receivers, suffering from high cost, heavy payload, and high power consumption limitations. GNSS-R technology leverages existing navigation satellite constellations as signal sources, requiring only specialized reflected signal receivers to achieve effective bistatic radar monitoring of soil moisture [3].

GNSS-R technology has attracted widespread attention over the past two to three decades. First proposed by Hall and Cordey in 1988 [4], Martin-Neira subsequently applied this technique to ocean altimetry [5]. GNSS-R can be categorized in various ways, including scatterometer and altimeter modes based on operational principles. Due to the homogeneous nature of ocean surfaces with less pronounced polarization characteristics, GNSS-R developed earlier and more maturely for ocean remote sensing, enabling studies of sea surface wind fields, wind speeds, and significant wave heights [6,7,8]. The technology has also been applied to monitoring oil spills and suspended matter [9,10] and detecting marine moving targets [11].

For land surfaces, soil moisture remote sensing represents the earliest and most extensively studied GNSS-R application, with most research conducted from an experimental perspective. The following sections summarize the current research status according to different remote sensing platforms.

2.1 BAO Tower-Based Experiment

The BAO (Boulder Atmospheric Observatory) tower experiment conducted seasonal GNSS-R soil moisture measurements using a modified GPS reflected signal receiver placed on a 300-meter tower (40°03 00.1 N, 105°00 13.8 W) [12]. The receiver, provided by NASA Langley Research Center, employed a low-gain zenith-pointing RHCP (Right-Hand Circular Polarization) antenna for direct signal reception. For reflected signal reception, multiple antenna types were used: a low-gain hemispherical LHCP antenna, and four high-gain (~12 dB) V, H, LHCP, and RHCP antennas. The high-gain antennas increased the receiver' s dynamic range while reducing surface multipath electromagnetic wave interference effects. Antennas were configured at a 35° incidence angle (from nadir) and 245° azimuth. This experimental design excluded surface roughness and vegetation effects, isolating signal variations to soil moisture changes alone. Results demonstrated correlation between reflected signals and rainfall, with good correlation between reflected signals and soil moisture under wet conditions. However, due to L-band penetration effects, the correlation between surface soil moisture and reflected energy weakened under dry conditions.

To analyze polarization effects on retrieval accuracy, a first-order SSA (Small Slope Approximation) model was employed to calculate reflectivity for various polarization combinations with RHCP transmission. With fixed incidence angles (60°, 70°), simulations were performed using LR/RR ratio and HR/VR information under varying scattering angles and soil moisture conditions. The theoretical study indicated that received signal energy depends on two factors: a polarization-sensitive factor related to soil dielectric properties and a polarization-insensitive factor related to surface roughness. The orthogonal polarization ratio could effectively remove surface roughness effects while retaining soil moisture information. However, BAO tower experimental data could not validate this theoretical assumption, likely due to oversimplified initial assumptions of uniform soil moisture. Nevertheless, the BAO tower experiment provided important directions for subsequent research on angular and polarization information.

2.2 Airborne Experiments

The SMEX (Soil Moisture Field Experiment) campaigns conducted in Iowa during the summers of 2002 and 2003 integrated ground-based, airborne, and spaceborne observations [12]. The scientific objectives of SMEX02 included understanding land-atmosphere interactions, validating AMSR brightness temperature and soil moisture retrieval algorithms under vegetation cover, and assessing the feasibility of novel instruments such as GPS-R for soil moisture remote sensing [13].

Previous ocean surface GNEX-R studies used nadir-pointing hemispherical antennas. In SMEX02, antennas remained nadir-pointing but with increased gain to obtain better SNR data. Additional details about this experiment can be found in [14].

Experiments utilizing calibrated GPS reflected signals to estimate soil reflectivity and dielectric constants validated relationships between GPS reflected signals, soil dielectric constants, and volumetric soil moisture content. Dielectric constants derived from GPS data showed good agreement with Wang-Schmugge theoretical models, though both were lower than in-situ soil moisture measurements. These studies considered vegetation attenuation and explored various sources of discrepancy [15].

Domestic researchers simulated relationships between soil moisture, surface roughness, and single-frequency forward scattering coefficients using the AIEM model, and analyzed correlations between soil moisture and SNR at eight SMEX02 sites using airborne GPS-R experimental data [16].

Egido et al. conducted three airborne polarimetric measurement experiments, obtaining RL and RR polarization reflection information. Analysis indicated that at low altitudes, both RL and RR polarization reflectivities are sensitive to soil moisture and surface roughness. The polarization ratio becomes insensitive to roughness under moderate surface roughness conditions, facilitating soil moisture retrieval. However, when surface roughness exceeds 3 cm, incoherent scattering dominates [17].

On May 30, 2014, China conducted its first airborne GNSS-R experiment to validate the performance of a domestically developed GNSS-R receiver and to study soil moisture and altimetry retrieval algorithms. The study employed LR information for soil moisture retrieval while also receiving and testing RR polarization information [18].

In 2016, Jia and Savi used a 4-channel prototype to receive direct signals and both LHCP and RHCP reflected signals. Using dual-polarization antennas to simultaneously receive direct and reflected signals, the data processing aimed to remove incoherent reflection energy effects while normalizing reflected signals against direct signals. The study demonstrated that polarization ratios are suitable for soil moisture retrieval [19].

2.3 Ground-Based GPS-IR (GPS Interferometric Reflectometry)

This approach does not require specialized receivers, instead utilizing conventional geodetic or geophysical GPS receivers. For typical geodetic GPS receiver antennas, interference patterns between direct and reflected signals are most pronounced at elevation angles below 30°, enabling remote sensing of surface parameters through multipath information (coherent interference between direct and reflected signals). This remote sensing method offers spatial resolution of approximately 1 km, bridging the gap between traditional point sensors (<1 m^2) and spaceborne observations (>100 km^2). This means thousands of GPS stations can provide near-real-time soil moisture observations for environmental and hydrological research. Establishing soil moisture observation networks is crucial for hydrological studies, weather forecasting, and climate monitoring, and this method complements L-band spaceborne data well. Leveraging existing global GPS networks could enable establishment of a global soil moisture observation network for validating and calibrating other spaceborne soil moisture satellites [20].

Larson et al. analyzed data from a Colorado site, demonstrating linear correlation between phase and near-surface soil moisture [21-24]. Zavorotny developed a GPS reflection model explaining the underlying physical mechanism. Chew et al. built upon this model to develop a bare soil retrieval algorithm [26,27]. Vey applied this algorithm to create a multi-year soil moisture time series for South Africa, though the study found a root-mean-square error (RMSE) of 0.05 cm^3/cm^3 between measured and GPS-IR retrieved soil moisture, representing relatively large retrieval errors that limit certain applications [28].

Chew et al. noted that vegetation effects cannot be ignored in soil moisture retrieval [20], suggesting use of SNR amplitude information to remove vegetation effects while employing SNR phase information for soil moisture retrieval. Vegetation information can also be corrected using frequency information from SNR interference patterns [29]. Factors affecting soil moisture retrieval include surface roughness, vegetation cover, terrain, and seasonal variations. Vegetation effects are significant when soils are very dry, while terrain slope effects become prominent when surfaces are very wet.

2.4 IPT (Interference Pattern Technique) Method

The IPT method utilizes coherent interference between direct and reflected signals to retrieve surface parameters including terrain slope, soil moisture in vegetated areas, and vegetation height [30]. Experimental studies show that when receivers employ LHCP polarization antennas, H-polarization can mask angular information due to null reflectivity at the Brewster angle for V-polarization [31].

This research approach utilizes the ground-based SMIGOL reflectometer (Soil Moisture Interference-pattern GNSS Observations at L-band), developed in 2008, operating at GPS L1 frequency (1.57542 GHz). The SMIGOL reflectometer points horizontally, with its footprint defined by the antenna pattern. To improve retrieval accuracy, the dual-polarization IPT method employs PSMIGOL (two antennas: H-polarization and V-polarization) [32]. The receiver records coherently 叠加干涉信号 (superimposed interference signals) within the same GPS code chip interval, with each sampling point corresponding to different GPS satellite elevation angles. Consequently, received interference power is a direct function of elevation angle, where notch positions, amplitudes, and quantities relate to surface parameters.

The SMIGOL retrieval process for each satellite's raw data follows this sequence: (1) Surface slope information is retrieved as a function of satellite elevation angle θ and azimuth ϕ during overpass; (2) Vegetation height information is obtained based on notch positions and numbers, which can be retrieved independently of soil moisture and surface roughness; (3) With known vegetation height and measured surface roughness, soil moisture is retrieved using interference power amplitude information as a function of satellite elevation angle θ and azimuth ϕ.

2.5 Spaceborne GNSS-R Soil Moisture Monitoring

UK-DMC (UK Disaster Monitoring Constellation), launched in 2004, represented the first spaceborne GNSS-R observation program, successfully receiving reflected signals from Earth’ s surface [33]. Following UK-DMC’ s success, Surrey Satellite Technology developed an enhanced spaceborne GNSS-R sensor launched on TechDemoSat-1 on July 8, 2014 [34]. This instrument, also carried on CYGNSS, tracks L1 C/A code reflections and generates Delay-Doppler Maps (DDMs) while pioneering the detection and recording of GPS L2 reflected signals, marking the maturation of spaceborne GNSS-R programs.

While airborne, ground-based, and tower-based GNSS-R have proven effective for soil moisture studies, spaceborne GNSS-R research remains in its initial stages. Camps et al. analyzed soil moisture and vegetation effects on TechDemoSat-1 (TDS-1) data [35]. Without direct signal measurements for calibration, TDS-1 data were processed using 1 ms coherent integration and 1000 ms non-coherent integration to compute DDM SNR, establishing strong correlations between TDS-1 data and SMOS soil moisture across different land cover types (evergreen needleleaf forest, grassland, evergreen broadleaf forest).

Chew et al. used 19 days of TDS-1 data to demonstrate 7 dB sensitivity between reflected signals and soil moisture [35]. However, this study did not consider vegetation effects on surface soil moisture. Data analysis was restricted to incidence angles of 0°-35° (mirror antenna gain >5 dB). Since onboard specular point prediction software was designed for ocean reflections, land applications excluded reflection points above 3000 m altitude. Recalculated specular point positions were used, analyzing only DDM peak power. Results aligned with Master et al. (2004), showing that increased surface roughness reduces peak power while increased dielectric constant raises peak power.

Beyond surface characteristics, DDM peak power is affected by antenna gain, distance, and incidence angle. Effective peak power is therefore corrected using the bistatic radar equation [36]: $P_{r,eff}$ represents effective reflected power on TDS-1, normalized by noise (equivalent to DDM SNR), where P_r is peak reflected power per DDM, N is noise, R_{sr} and R_{ts} are distances from receiver/transmitter to surface specular point, θ is incidence angle, and G is antenna gain.

3. GNSS-R and Microwave Radiometry

Microwave radiometers measure natural microwave emission using brightness temperature data. Radiometers are insensitive to surface roughness, with spatial resolution increasing with antenna size. GNSS-R operates as a passive bistatic radar with spatial resolution dependent on coherent or incoherent scattering. Under coherent scattering dominance, resolution corresponds to the first Fresnel zone; under incoherent dominance, it relates to the glistening zone, forming the GNSS-R scatterometer mode that produces DDMs. Consequently, in incoherent mode, retrieval accuracy is inferior to microwave radiometry due to higher sensitivity to surface roughness.

Zavorotny et al. first qualitatively compared microwave radiometer and GNSS-R data [27]. Alonso-Arroyo et al. examined this relationship both qualitatively and quantitatively [28]. From September to November 2013, researchers conducted joint flights of the LARGO (Light Airborne Reflectometer for GNSS Observations) scatterometer and PLMR (Polarimetric L-band Microwave Radiometer) to compare GNSS-R and L-band microwave radiometer observations. LARGO is a dual-channel, low-power passive GNSS-R receiver with a zenith-pointing RHCP antenna for direct signals and a nadir-pointing LHCP antenna for reflected signals. PLMR operates in the L-band (1400-1426 MHz).

Three airborne experiments demonstrated that for large incidence angles (>30°), coherent scattering dominates according to Rayleigh criteria, with correlation coefficients of 0.74-0.8 for crop areas and 0.51-0.61 for grasslands. For incidence angles <30°, increased incoherent scattering reduces coherence, with correlation coefficients of 0.64 for crop areas.

4. Receiver Development

Ground-based receiver development has followed three main approaches: (1) Direct use of geodetic or geophysical GPS receivers, exploiting low-elevation multipath data for parameter retrieval; (2) SMIGOL receivers used in IPT methods, employing V-polarization Brewster angle information for monitoring, with PSMIGOL receivers adding H-polarization antennas to improve accuracy; (3) Specialized GNSS-R receivers for dedicated campaigns.

The earliest spaceborne receiver was the GPS-R receiver on UK-DMC (2004), comprising two zenith-pointing antennas for direct signals and one nadir-pointing LHCP antenna for reflected signals. The next-generation GNSS-R receiver SGR-ReSI (Space GNSS Receiver Remote Sensing Instrument) launched on UK-TDS-1 in 2014 supports both raw data collection and onboard real-time processing, marking GNSS-R technology maturation. GEROS, deployed on the International Space Station with larger volume, mass, and power, primarily measures sea surface height and RMS slope using GNSS reflections, while also validating GNSS-R land applications. PAU/GNSS-R is an FPGA-based GPS reflectometer designed to improve sea surface salinity retrieval accuracy by combining radiometer and GNSS-R RF frontends to reduce mass and power. PYCARO, flown on a 3×2U CubeSat for land and atmospheric remote sensing, uniquely employs codeless processing of P(Y) codes and dual-frequency observations to correct ionospheric altimetry errors.

5. Summary

GNSS-R/IR technology has emerged over the past two decades as a novel Earth observation method attracting widespread attention. Due to ocean surface homogeneity and weak polarization characteristics, GNSS-R first matured for ocean applications, with NASA’ s CYGNSS mission marking operational sea surface wind monitoring. Land applications have lagged due to complex surface parameters and heterogeneous polarization characteristics. Soil moisture studies have primarily employed observational methods or developed regional retrieval algorithms. Early airborne experiments like SMEX02 established correlations between soil moisture and GPS reflected signals. The BAO tower experiment used four antennas (RHCP, LHCP, H, and V polarizations) to analyze relationships with soil moisture and attempted to remove surface roughness effects. The IPT method, utilizing coherent interference between direct and reflected signals, employs V-polarization Brewster angle information for soil moisture retrieval, achieving good accuracy in limited experiments. Unlike specialized reflectometers, researchers discovered that existing geodetic or geophysical GPS receivers could directly utilize multipath information (phase, amplitude, and effective height) for parameter monitoring, yielding good results applied to SMAP validation. Spaceborne GNSS-R soil moisture research remains limited, but studies have established correlations between TDS-1, SMOS satellites, and GNSS reflections, validating feasibility and promising applications. This review also covers comparative studies between radiometers and GNSS-R and summarizes receiver development.

Key priorities for GNSS-R/IR soil moisture retrieval involve exploiting angular and polarization information: (1) The bistatic radar geometry formed by GNSS constellations and receivers exhibits spatial heterogeneity in scattering characteristics across different zenith and azimuth angles—effectively utilizing these angular scattering differences represents a major challenge and priority; (2) Polarization is a fundamental electromagnetic property, with reflected signal polarization carrying critical surface information. The BAO tower experiment' s use of linear and circular polarizations demonstrated polarization ratio as an effective means to remove roughness effects. Future research must focus on effectively utilizing both circular and linear polarization information to improve retrieval accuracy.

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