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GNSS Reflectometry (GNSS-R) for Environmental Monitoring

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ABSTRACT

Global Navigation Satellite System Reflectometry (GNSS-R) is emerging as a promising remote sensing technique for environmental monitoring. It utilizes the reflected signals from GNSS satellites, such as GPS, GLONASS, Galileo, and BeiDou, to infer the properties of Earth's surface and atmosphere. Unlike traditional remote sensing systems that require active transmitters or complex sensors, GNSS-R leverages existing satellite signals, making it cost effective and scalable. In this review paper, we summarize the principles, methods, applications, challenges, and future prospects of GNSS-R in environmental monitoring. We give emphasis on its use in soil moisture estimation, sea level and wave height measurement, snow and ice monitoring, vegetation sensing, and atmospheric profiling. We also discuss limitations and propose recommendations for further research. This overview offers insights to researchers and practitioners interested in deploying GNSS-R approaches for environmental observation.

KEYWORDS: *GNSS Reflectometry, Remote Sensing, Soil Moisture, Sea Level Monitoring, Atmospheric Sensing, Biophysical Parameters, Signal Reflectance.*

INTRODUCTION

Environmental monitoring is becoming more important as climate change accelerates and human activity alters natural systems. Traditional remote sensing methods—such as optical satellites and radar—have served well but often come with cost, complexity, and limitations like dependency on sunlight or weather conditions. **Global Navigation Satellite System**

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Reflectometry (GNSS-R) offers an alternate or complementary approach by using already existing navigation signals from GNSS satellites. Instead of looking directly at the direct signal, GNSS-R collects the *reflected* signals from Earth surface and infers environmental parameters from the changes in signal characteristics.

GNSS-R began gaining research interest in early 2000s, with scientific missions such as UK's *TechDemoSat-1* and NASA's *CYGNSS* constellation. Over time, its potential has widened beyond basic altimetry to soil moisture, biomass, snow and ice thickness, sea surface roughness, and atmospheric water vapor detection. This review attempts to introduce GNSS-R fundamentals, discuss major environmental applications, explore technical challenges, and look at future directions.

GNSS-R FUNDAMENTALS

GNSS Reflectometry (GNSS-R) is a passive remote sensing technique that leverages signals from Global Navigation Satellite Systems (GNSS) such as GPS, GLONASS, Galileo, and BeiDou. Unlike traditional active remote sensing methods, GNSS-R does not emit its own signals but instead uses the existing navigation signals that are already transmitted by satellites. These signals, after reflecting off the Earth's surface, carry valuable information about the properties of the reflecting surfaces.

Basic Concept

At its core, GNSS-R operates on a **bistatic radar configuration**. In bistatic radar, the transmitter and receiver are physically separated, unlike monostatic radar where both are co-located. In GNSS-R:

- **Transmitter:** The GNSS satellites continuously emit L-band microwave signals, which are stable, well-characterized, and cover wide areas of the Earth's surface.
- **Receiver:** A dedicated GNSS-R receiver, positioned either on a satellite, aircraft, drone, or ground station, collects both the **direct signal** (line-of-sight from the satellite) and the **reflected signal** (after bouncing off Earth's surface).

Key principle: By comparing the direct and reflected signals, the receiver can measure differences in:

- **Time Delay:** The reflected signal travels a longer path due to reflection, causing a

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measurable delay. This delay can be converted into distance, helping infer surface height or roughness.

- **Amplitude (Signal Strength):** The strength of the reflected signal depends on the surface's dielectric properties. For example, water has higher reflectivity than dry soil, so amplitude changes can indicate moisture content.
- **Phase Shift:** The phase difference between direct and reflected signals carries information about surface texture, roughness, and even vegetation structure.
- **Polarization:** Depending on the orientation of the electromagnetic wave relative to the reflecting surface, polarization changes can provide additional clues about surface composition and structure.

The combination of these measurements allows GNSS-R to extract geophysical information without the need for active radar systems, making it **low-cost, passive, and scalable**.

1. Signal Interaction with Earth Surfaces

The interaction of GNSS signals with the Earth's surface depends on several factors:

- **Surface Type:** Water, soil, ice, snow, and vegetation reflect signals differently due to their dielectric constants and roughness.
- **Surface Roughness:** Smooth surfaces (calm water) produce specular reflections, whereas rough surfaces scatter signals, spreading energy over multiple directions.
- **Dielectric Properties:** Wet soil or water has a high dielectric constant, reflecting more signal energy than dry soil or sand.
- **Incidence Angle:** The angle at which the GNSS signal strikes the surface affects reflection strength and scattering pattern. Low angles favor stronger reflections from smooth surfaces.

By analyzing these factors, GNSS-R can infer **soil moisture, ocean roughness, snow depth, ice thickness, and vegetation characteristics**.

2. Advantages of the Bistatic Approach

The bistatic configuration offers several advantages for environmental monitoring:

- **Passive Sensing:** No transmitter is needed, reducing power requirements and system complexity.
- **Wide Coverage:** GNSS satellites cover the entire globe, allowing near-global sampling.

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- **All-Weather Operation:** L-band signals penetrate clouds, rain, and light vegetation, making GNSS-R effective in conditions where optical remote sensing fails.
- **Temporal Resolution:** Multiple GNSS satellites in the sky provide frequent revisit times, enabling high temporal resolution for dynamic environmental monitoring.

3. Practical Example

Consider a GNSS-R ground station monitoring **soil moisture**:

- A GPS satellite emits a signal toward the Earth.
- The station receives the **direct signal**, which serves as a reference.
- Simultaneously, it receives the **reflected signal** from the soil surface.
- The reflected signal amplitude is lower for dry soil and higher for wet soil.
- Delay and phase differences are calculated, and inversion algorithms translate these values into soil moisture estimates.

Similarly, on an ocean monitoring satellite:

- The reflected signals from sea surface waves contain information about **wave height** and **sea surface roughness**.
- By analyzing the spread in the reflected signal's Delay-Doppler Map (DDM), wind speed over the ocean can also be inferred.

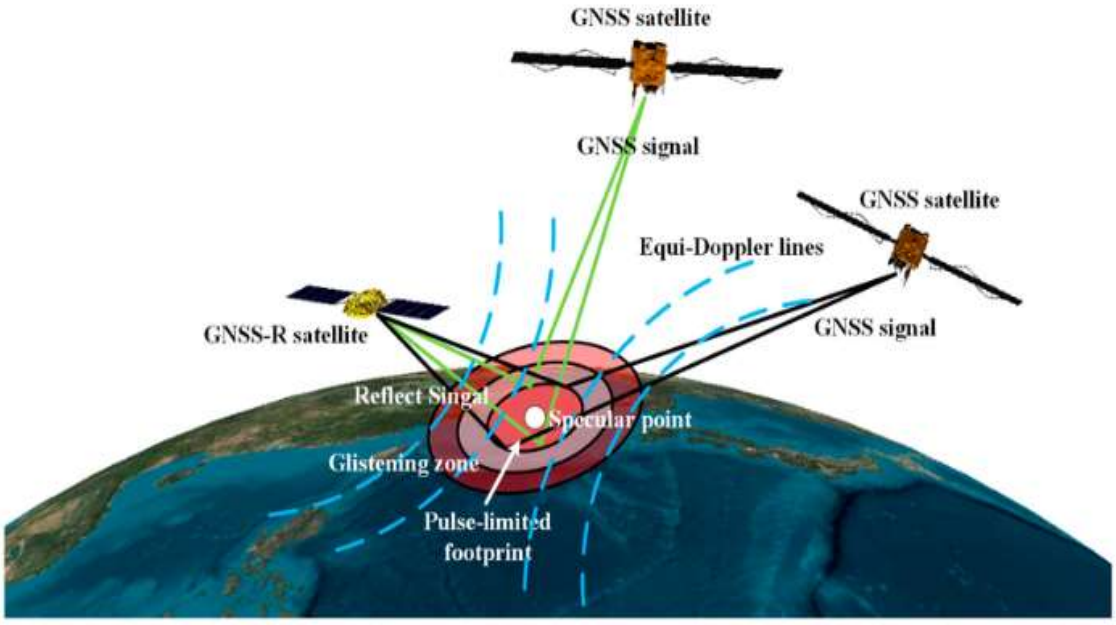


Figure 1: GNSS-R Operational Schematic

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Signal Characteristics

GNSS Reflectometry (GNSS-R) relies on careful analysis of the **reflected GNSS signal**, which behaves differently depending on the surface it interacts with. Understanding these characteristics is crucial for interpreting environmental parameters accurately. The main properties of GNSS-R signals include **amplitude, phase, delay, and polarization**. Each provides unique insights into surface conditions and environmental variables.

1. Amplitude (Signal Strength)

Amplitude refers to the power of the reflected signal received by the GNSS-R receiver. It is strongly influenced by the **dielectric properties** and **roughness** of the reflecting surface.

- **Smooth Water Surfaces:** Calm water acts like a mirror, producing strong specular reflections. The received amplitude is high if the incidence angle is low.
- **Rough Water Surfaces:** Wind-driven waves scatter the signal, reducing peak amplitude and spreading the energy across multiple paths.
- **Soil Surfaces:** Wet soil has a higher dielectric constant (~15–30 for wet soil vs ~3–5 for dry soil), reflecting more signal energy. Conversely, dry soil absorbs more signal, reducing amplitude.
- **Vegetation or Snow:** Dense vegetation or deep snow scatters signals and attenuates amplitude, sometimes causing multiple weak reflections.

Practical Example:

- A GNSS-R receiver monitoring farmland can detect higher signal amplitude after rainfall due to increased soil moisture, while amplitude decreases during dry periods.

2. Phase Shift

Phase indicates the position of the electromagnetic wave within its cycle. Reflected GNSS signals undergo a **phase shift** depending on the **surface dielectric constant** and **roughness**:

- Smooth surfaces cause predictable phase shifts that can be modeled analytically.
- Rough surfaces introduce multiple reflection paths, leading to **phase scattering**, which complicates signal interpretation.
- Phase information is particularly useful in **altimetry** and **soil moisture estimation**, as small phase changes correlate with surface height or moisture variations.

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Quantitative Example:

- A reflection from wet soil may cause a phase lag of a few degrees relative to the direct signal, whereas dry soil introduces a slightly smaller phase lag. High-precision GNSS-R receivers can detect phase differences in the order of millimeters in path length.

3. Delay Differences

Time delay occurs because the reflected signal travels a longer path than the direct signal. This delay is proportional to the **distance between the reflecting surface and the receiver**:

$\tau = 2h \cdot \cos(\theta_i) c \tau = \frac{2h \cdot \cos(\theta_i)}{c} \tau = c2h \cdot \cos(\theta i)$

Where:

- $\tau \tau$ = delay of reflected signal
- h = surface height relative to receiver
- $\theta_i \theta i$ = incidence angle of signal
- c = speed of light

Applications:

- **Sea Surface Height Measurement:** Small delay variations (on the order of centimeters) allow estimation of ocean surface height.
- **Snow and Ice Monitoring:** Delay changes indicate snow depth or ice thickness.

Illustrative Example:

- A GNSS-R satellite receiver observing ocean waves can detect fluctuations in delay due to wave crests and troughs. These variations can be converted into **wave height and roughness estimates**.

4. Polarization Effects

GNSS signals are **right-hand circularly polarized (RHCP)** when transmitted, but reflection can modify the polarization depending on surface properties:

- **Smooth Water:** The reflected wave may become **left-hand circularly polarized (LHCP)** for specular reflection at low incidence angles.
- **Rough Surfaces or Vegetation:** Signal depolarization occurs, producing mixed polarization components.

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- **Soil Moisture & Snow:** Polarization characteristics can provide additional constraints for distinguishing between wet/dry soil and snow-covered areas.

Importance:

- Polarization helps improve discrimination between different surface types, reducing ambiguity in inversion models.

MAJOR ENVIRONMENTAL APPLICATIONS

Soil Moisture Estimation

Soil moisture is a critical parameter for agriculture, hydrology, and climate studies. Traditional methods include in-situ sensors or microwave radiometry, which can be expensive or low resolution.

GNSS-R can estimate soil moisture by analyzing reflected signal amplitude and delay. Higher moisture increases dielectric constant, altering reflectivity. GNSS-R observations can be processed to give soil moisture estimates at spatial scales ranging from a few meters (with ground stations) to hundreds of kilometers (with space missions).

Table 1: Comparison of Soil Moisture Methods

Method	Spatial Coverage	Cost	Weather Sensitivity	Accuracy
In-situ Sensors	Local	Moderate	N/A	High
Microwave Radiometry	Regional	High	Low	Moderate
GNSS-R	Local to Global	Low to Moderate	Very Low	Good

From Table 1, GNSS-R stands out for lower cost and better all-weather capability, making it suitable for continuous monitoring.

Sea Surface Height and Ocean Monitoring

Sea surface height (SSH) variation is important for sea level rise tracking and ocean dynamics.

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Traditional altimeters use active radar or laser instruments. GNSS-R provides an alternative by measuring the timing difference between direct and reflected signals to estimate surface height. Missions like *CYGNSS* have been demonstrating capability of estimating sea surface roughness and wind speed as well, since ocean surface state affects signal scatter patterns.

GNSS-R altimetry is especially appealing due to its lower cost and scalability for constellation missions.

Snow and Ice Monitoring

Snow depth and ice thickness are challenging to monitor from optical sensors due to cloud cover and low contrast. GNSS-R can penetrate snow layers to an extent, depending on frequency and snow properties. Reflected signals help estimate snow depth through changes in signal delay and attenuation.

For polar ice monitoring, GNSS-R is useful to detect melt onset, ice roughness, and seasonal changes. It is also used in high latitude for studying ice sheets and sea ice dynamics.

Vegetation and Land Cover Sensing

Vegetation cover affects the reflectivity and absorption of GNSS signals. GNSS-R is used to estimate vegetation water content, biomass, and canopy structure. Reflected signal characteristics are influenced by vegetation roughness, leaf water content, and canopy density. This application still has challenges because vegetation structures are complex and signal interpretation requires careful modeling.

Atmospheric Profiling

Though indirect, GNSS-R can contribute to atmospheric monitoring by tracking signal delay caused by atmospheric water vapor and ionosphere. Techniques like GNSS occultation have been used widely, and GNSS-R complements this by providing reflected path delay.
This application may help improve weather prediction and atmospheric research.

PLATFORMS AND MISSIONS FOR GNSS-R

GNSS Reflectometry (GNSS-R) can be implemented on **various platforms**, ranging from **ground-based receivers** to **airborne systems** and **spaceborne satellites**. Each platform offers

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unique advantages in terms of spatial resolution, coverage, and application scope. Over the past two decades, several experimental and operational missions have demonstrated the versatility and effectiveness of GNSS-R in environmental monitoring.

Spaceborne Platforms

Spaceborne GNSS-R missions provide **global coverage** and are ideal for studying large-scale environmental phenomena such as oceans, soil moisture, and atmospheric water vapor. These satellites are typically equipped with **dual antennas**—one facing the Earth to capture reflected signals and one pointing toward the GNSS satellites to capture direct signals.

1. CYGNSS (Cyclone Global Navigation Satellite System)

- **Launch Year:** 2016
- **Operator:** NASA
- **Platform:** Constellation of 8 micro-satellites in low Earth orbit (LEO)
- **Primary Applications:** Ocean surface wind speed, hurricane monitoring, sea state, soil moisture

Key Features:

- Delay-Doppler Maps (DDMs) are generated for reflected GPS signals.
- High temporal resolution (~12 hours revisit) due to constellation coverage.
- Passive sensing reduces operational costs compared to traditional active radar satellites.

2. TechDemoSat-1 (TDS-1)

- **Launch Year:** 2014
- **Operator:** Surrey Satellite Technology Ltd. (SSTL), UK
- **Primary Applications:** Ocean monitoring, soil moisture, snow and ice reflectivity

Key Features:

- Demonstrated feasibility of spaceborne GNSS-R in multiple environmental applications.
- Used L-band GNSS signals to measure sea surface roughness and altimetry.

3. UK-DMC2 GNSS-R Experiment

- **Launch Year:** 2009

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- **Operator:** Surrey Satellite Technology Ltd., UK
- **Primary Applications:** Soil moisture, ocean reflectivity, ice monitoring

Key Features:

- Served as a technology demonstrator for passive reflectometry.
- Showed that reflected GNSS signals could be reliably used for global-scale environmental sensing.

Airborne Platforms

Airborne GNSS-R systems are used for **regional and localized environmental studies**, offering **high spatial resolution**. They are often deployed on **aircraft, drones, or UAVs**.

Advantages:

- High spatial and temporal resolution in target areas.
- Flexibility to perform targeted campaigns over rivers, agricultural fields, or coastal regions.

Example:

- **Airborne GNSS-R campaigns in Antarctica:** Used to measure snow depth and ice sheet roughness.
- **Aircraft-mounted GNSS-R for soil moisture:** Provided high-resolution maps of farmland, complementing coarse satellite observations.

Ground-Based Platforms

Ground-based GNSS-R stations are **low-cost, continuous monitoring systems** that capture reflected GNSS signals over small areas. They are particularly useful for soil moisture, snow depth, and vegetation monitoring.

Key Features:

- Uses a **dual-antenna setup**, one pointing at the sky (direct signals) and one at the surface (reflected signals).
- Provides **hourly to sub-hourly measurements**, useful for hydrology and agricultural applications.
- Easily deployed in networks for spatially distributed observations.

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Example:

- **Soil Moisture Networks:** Multiple GNSS-R ground stations in agricultural regions provide real-time soil moisture estimates.
- **Snow and Ice Monitoring:** Ground-based stations in alpine regions detect snow depth and seasonal melt.

Emerging Platforms

Recent research is exploring **novel platforms** for GNSS-R:

- **CubeSats and Microsatellites:** Small, low-cost satellites carrying GNSS-R payloads can provide dense spatial coverage.
- **Unmanned Aerial Vehicles (UAVs):** Drones equipped with GNSS-R receivers enable **flexible, high-resolution measurements** over remote or inaccessible areas.
- **Maritime Platforms:** Buoys equipped with GNSS-R antennas can continuously monitor **ocean surface height, wave heights, and sea state**.

Table 2: Several platforms and missions have demonstrated the use of GNSS-R:

Platform	Type	Primary Use	Year
UK DMC-2	Microsatellite	Ocean and land reflectometry	2009
TechDemoSat-1	Satellite	Multi-purpose GNSS-R	2014
CYGNSS	Constellation (8 satellites)	Ocean winds, sea state	2016
GRL (Ground receivers)	Ground station	Soil moisture, snow	Ongoing

SIGNAL PROCESSING TECHNIQUES

Correlation and Delay Mapping

GNSS-R receivers correlate direct and reflected signals to find differences in time delay. The **Delay-Doppler Map (DDM)** is a common output used to represent signal power as function of delay and Doppler frequency. These maps help extracting environmental parameters.

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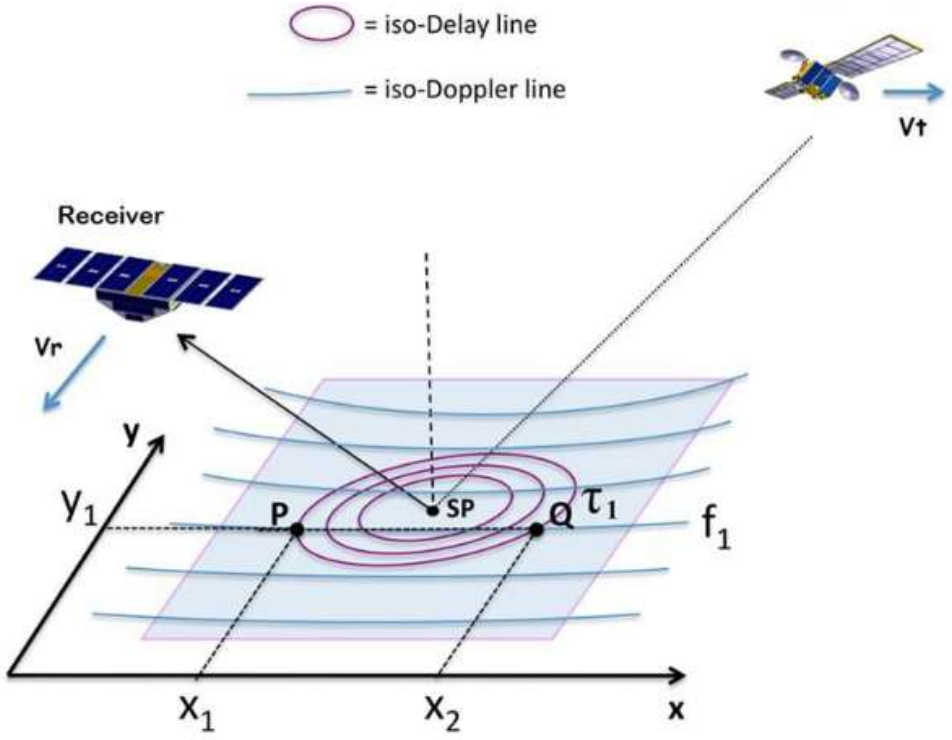


Figure 2: Illustrative Delay-Doppler Map

In the above notional DDM, central peak (* symbol) represents main reflected energy; delay and spread help infer surface roughness.

Inversion Models

After correlation, *inversion algorithms* are used to convert signal metric to geophysical quantity (e.g., soil moisture). Often models use physical or empirical relationships. Errors in models come from noise, surface heterogeneity, vegetation cover, and atmospheric effects.

Machine Learning Approaches

Recent studies are using machine learning to correlate GNSS-R features with surface states. These approaches may handle complex surface types better but require robust training data.

ADVANTAGES OF GNSS-R

- **Cost Effective:** Uses existing GNSS signals, no need for active transmitter.
- **All-weather Capability:** GNSS signals operate in L-band, penetrating clouds, rain, and foliage better than optical.
- **Scalability:** Can use small satellites or ground arrays.

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- **Multi-application:** Suitable for land, ocean, snow, and atmosphere.

Table 3: Strengths and Limitations of GNSS-R

Advantage	Limitation
Low cost	Weak reflected signals require advanced processing
All-weather sensing	Surface complexity complicates interpretation
Scalable platforms	Lower spatial resolution than some active radars
Passive sensing	Sensitivity varies with surface type

CHALLENGES AND LIMITATIONS

- **Weak Signal Strength**

  Reflected signals are much weaker than direct signals and are susceptible to noise. Building sensitive receivers remains expensive.

- **Surface Complexity**

  Heterogeneous surfaces (mixed vegetation, rough terrain) complicate interpretation. Simple reflectivity models may fail.

- **Atmospheric Effects**

  Ionosphere and troposphere can distort signals, adding uncertainty to surface inferences.

- **Calibration and Validation**

  Ground truth data is essential for calibration. Extensive validation campaigns are costly and limited in many regions.

FUTURE DIRECTIONS

- **Constellation Missions**

  New satellites with dedicated GNSS-R payloads can improve spatial and temporal coverage.

- **Advanced Algorithms**

  Better retrieval algorithms using physics-based or AI approaches may enhance accuracy.

- **Multi-sensor Integration**

  Combining GNSS-R with radar, lidar, and optical sensors offers a more complete picture of environment.

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- **Commercial Systems**

  Low cost GNSS-R receivers could support agriculture, flood prediction, and water resource management at local scales.

CONCLUSION

GNSS Reflectometry is a versatile and emerging technology with significant potential for environmental monitoring. Its passive nature, low cost, and all-weather capability make it attractive for measuring soil moisture, sea surface state, snow/ice cover, vegetation, and atmospheric properties. Despite challenges—like weak signal strength and modeling complexity—ongoing research and missions show GNSS-R can complement existing remote sensing. Future developments in sensors, algorithms and integrated systems could elevate GNSS-R from a research tool to operational environmental monitoring platform.

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