

# An Overview of Microwave Remote Sensing for Earth Observation

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## Abstract

*To understand the Earth from space, one must look beyond the visible eye. While optical satellites rely on the Sun's reflection, much like the human eye, they are frequently blinded by the "curtain" of cloud cover, smoke, or the dark veil of night. To bypass these limitations, we turn to microwave satellite sensing. By utilizing electromagnetic waves with wavelengths ranging from 1 millimeter to 1 meter, we can "see" through the atmosphere, measuring the physical properties of the land, ocean, and ice. Microwave remote sensing has revolutionized our ability to monitor the Earth's surface by providing data that is independent of solar illumination and cloud cover. Unlike optical sensors, which rely on reflected sunlight, microwave systems, specifically synthetic aperture radar (SAR) and passive radiometers, transmit and receive backscattered energy in the microwave spectrum. This paper explores the core principles of microwave satellite sensing, highlighting its unique capability to penetrate atmospheric moisture, smoke, and darkness. The study examines the interaction of microwave signals with surface characteristics such as dielectric constant, roughness, and moisture content. Furthermore, the paper discusses current applications in soil moisture mapping, oceanic wind vector retrieval, and cryospheric monitoring, demonstrating how microwave sensing provides critical insights into global environmental variables.*

**Keywords:** Synthetic aperture radar (SAR), microwave radiometry, backscatter, Earth observation, remote sensing, dielectric constant

## INTRODUCTION

In the choreography of Earth observation, optical sensors are the prima donnas—they capture sunlight and produce recognizable, postcard-perfect images of our planet. However, they are fickle performers, blinded by clouds, stifled by smoke, and rendered useless by the cover of darkness. With the intensification of climate variability and the rising frequency of extreme weather events, the shortcomings of optical sensing are becoming more apparent, leading to a crucial need for monitoring

capabilities that can operate in all weather conditions and at any time of the day. This change emphasizes the value of supplementary sensing technologies capable of overcoming atmospheric and lighting limitations while providing stable and dependable data streams.

## Enter the Microwave Sensor

The silent, all-seeing workhorse of satellite remote sensing. Microwave sensors operate in the "radio window" of the electromagnetic spectrum and are capable of piercing through dense cloud cover and functioning independently of solar illumination. To harness this potential, satellite missions must operate within a rigorous multi-layered framework [1–7].

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In satellite engineering, miniaturization, and onboard processing, it has become possible to deploy more advanced microwave instruments that offer better spatial resolutions and temporal coverages. These advancements have broadened the range of applications, including disaster management, precision agriculture, hydrological modeling, and cryosphere monitoring. Therefore, it has become essential to integrate microwave sensing into global observation systems to achieve comprehensive analyses of the Earth system.

As multi-mission datasets become more widely available, the establishment of standardized data interoperability protocols is essential to guarantee that observations from various platforms can be effectively integrated for large-scale environmental evaluations. This all-encompassing strategy bolsters decision-making processes and aids in global sustainable development initiatives.

The architectural framework for the deployment and use of microwave sensing from space is as follows: A robust framework begins by distinguishing between the two fundamental “modes” of microwave collection:

1. *Passive sensing (radiometry)*: This can be considered as “listening.” The sensor acts as a high-precision thermometer that measures the natural microwave emissions (bright temperature) radiated by the Earth’s surface and atmosphere. This is the bedrock of meteorological forecasting, soil moisture mapping, and sea-ice detection.
2. *Active sensing (radar/SAR)*: This can be considered as “shouting and listening.” The satellite emits its own microwave pulse and measures the backscattered signal. Synthetic aperture radar (SAR) is the star here, utilizing the motion of the satellite to create high-resolution imagery regardless of the weather.

Microwave data is inherently noisy and sensitive to atmospheric water vapor. A framework for usage demands a Triple-Lock Calibration Strategy:

- *Internal calibration*: Utilization of stable onboard reference targets to ensure that the sensitivity of the antenna remains constant over time.
- *External/vicarious calibration*: Aligning satellite measurements with ground-based “super-sites” (e.g., highly stable desert regions or deep-space calibration targets) to ensure data coherence across different satellites.
- *The harmonization layer*: Because microwave sensors vary in frequency (X, C, L, and P-bands), the framework must include *cross-calibration algorithms* that allow data from a European mission (such as Sentinel-1) to be seamlessly stitched with an American or Japanese mission.

Raw microwave data are unintelligible to the human eye. The framework dictates standardized progression as follows:

- *Level 0 (raw)*: The raw telemetry stream.
- *Level 1 (sensor-corrected)*: Transformation of raw data into engineering units (e.g., radar backscatter coefficient).
- *Level 2 (geophysical products)*: Extraction of scientific meaning, such as wind speed at the ocean surface, sea surface temperature, or vegetation water content.
- *Level 3 (gridded/mosaicked)*: Spatiotemporal averaging, bringing different orbital paths into a clean, uniform grid, ready for analysis.

Not all microwaves are created equally. The framework for usage must dictate the frequency of selection based on the target.

- *L-Band (1–2 GHz)*: Deep penetration. It is ideal for mapping biomass and soil moisture under dense forest canopies.
- *C-Band (4–8 GHz)*: The “Goldilocks” zone. It is perfect for ocean wave monitoring and general-purpose land imaging.
- *X-Band (8–12 GHz)*: High resolution. It is essential for infrastructure monitoring, urban planning, and small-target detection.

As we crowd the low earth orbit (LEO) with sensors, the framework must incorporate Spectrum Management. Microwaves are shared with 5G networks, terrestrial radio, and scientific telecommunications.

### **The Mitigation Protocol**

Satellites must adhere to strict “blanking” zones to ensure that their active pulses do not interfere with civilian communication infrastructure, and conversely, that terrestrial interference does not “blind” the sensitive radiometers scanning the planet for climate data.

The final layer of the framework is the utility layer. We are moving away from simply “taking pictures” toward “dynamic modeling.” By integrating microwave data with machine learning (ML) pipelines, satellite radar can be used to detect millimeter-scale shifts in a dam wall, track the hidden movement of ice shelves in the Antarctic night, or monitor the growth of crops beneath clouds during the monsoon season [8–10].

The framework for microwave satellite sensing is more than a list of technical specifications—it is a bridge between the unseen physics of our planet and the urgent needs of humanity. By standardizing calibration, frequency selection, and data processing, we transformed the chaotic noise of the microwave spectrum into a crystalline map of our changing world. In the dark of the night and the thick of the storm, the microwave beam remains our most reliable witness [11–14].

## **FRAMEWORK FOR MICROWAVE SATELLITE SENSING**

To understand the Earth from space, one must look beyond the visible. While optical satellites rely on the Sun’s reflection—much like a human eye—they are frequently blinded by the “curtain” of cloud cover, smoke, or the dark veil of night.

To bypass these limitations, we turn to microwave satellite sensing. By utilizing electromagnetic waves with wavelengths ranging from 1 mm to 1 m, we can “see” through the atmosphere and measure the physical properties of the land, ocean, and ice.

To effectively leverage this technology, we must follow a robust operational framework. This framework acts as the bridge between raw, invisible data and actionable scientific insight.

### **Phase 1: The Signal Acquisition (The “Hardware” Layer)**

Before the analysis can begin, the microwave signal must be captured. This phase is divided into two distinct methodologies.

1. *Passive microwave sensing*: Similar to a thermometer, the sensor measures the natural microwave energy emitted by the Earth’s surface and atmosphere. This is vital for monitoring soil moisture, snow cover, and sea-ice concentrations.
2. *Active microwave sensing (radar/SAR)*: The satellite acts as an active agent, sending a pulse of energy to the ground and measuring the “backscatter” (the echo). This is the hallmark of SAR, which provides high-resolution imagery capable of detecting structural changes, such as urban growth or tectonic deformation, regardless of darkness or weather.

### **Phase 2: Signal Processing and Normalization**

Microwave data are inherently “noisy.” To make it useful, raw data must pass through a rigorous processing pipeline.

- *Radiometric calibration*: Correcting for instrument drift and atmospheric noise to ensure that the intensity of the return signal represents the true physical property.
- *Geometric orthorectification*: Correcting for terrain-induced distortions that occur because radar sensors look at the Earth from an angle (side-looking), ensuring that the pixel aligns perfectly with the geographical coordinates.

- *Speckle filtering*: Microwave imagery often carries a “salt-and-pepper” visual noise known as speckles. Advanced algorithms (such as Frost or Lee filters) are applied to smooth the imagery without losing the crisp edges of the buildings or coastlines.

### Phase 3: The Geophysical Retrieval (The “Conversion” Layer)

This is where the magic happens: converting decibels and temperature values into useful environmental data.

- *Dielectric constants*: Microwave interactions are heavily influenced by the dielectric constant of the target. Water is highly reflective, and dry sand is transparent. By applying specialized models, we can infer the moisture content in the soil or the salinity of the ocean from these physical properties.
- *Backscatter coefficients*: By analyzing the roughness of the surface (the “texture”), we can differentiate between a calm ocean (specular reflection) and a choppy sea, or between a smooth agricultural field and a dense, complex forest canopy.

### Phase 4: Integration and Application

The final layer of the framework connects the processed satellite data to the real-world impact.

- *Disaster resilience*: Using SAR to map flood extents in real time. Because microwaves penetrate clouds, satellites can “see” the water beneath a typhoon’s cloud cover, providing emergency responders with vital maps when optical satellites fail.
- *Strategic resource management*: Calculating biomass density in forests or monitoring crop health by measuring the interaction of microwave signals with the vertical and horizontal structures of plant leaves and stems.
- *Climate monitoring*: Tracking the Cryosphere. Passive microwave sensors provide long-term daily records of polar ice extent necessary to model the impacts of global warming.

The true power of this framework lies in Sensor Fusion. Modern frameworks no longer treat microwave data in a vacuum. Instead, they integrated microwave signals with optical deep-learning models.

## DISCUSSION

The integration of microwave sensing into satellite constellations has revolutionized several key sectors:

1. *Sub-surface and biomass penetration*: Because of their long wavelengths, microwaves can penetrate the canopy of dense rainforests. This allows for the precise measurement of aboveground biomass and carbon stocks, which are essential for monitoring climate change mitigation efforts. Additionally, microwave signals can penetrate several centimeters into dry soil, enabling the mapping of *root-zone soil moisture*, which is a critical metric for agricultural yield forecasting and flood risk assessment.
2. *Deformation monitoring (InSAR)*: Perhaps the most stunning application is interferometric synthetic aperture radar (InSAR). By comparing two radar images taken from the exact same position at different times, scientists can detect surface displacement with *millimeter-level precision*. It is the gold standard for monitoring volcanic inflation, tectonic plate shifts, and the structural integrity of urban infrastructure.
3. *Cryospheric analysis*: Microwaves are highly sensitive to the physical state of water. They allow researchers to differentiate between “dry snow” (cold and powdery) and “wet snow” (liquid water content), providing unprecedented data on glacial retreat and permafrost degradation.

As we look toward the future, the integration of microwave data with artificial intelligence (AI) is expected to yield “cloud-free” dynamic maps of the entire planet in near real-time. By removing the dependency on daytime and clear skies, microwave sensing ensures that Earth observation is no longer a “snapshot” taken when conditions permit but a continuous, high-definition video of a changing planet.

## CONCLUSION

Microwave remote sensing is a cornerstone of modern satellite-based Earth observation, offering distinct advantages in temporal consistency and atmospheric penetration that optical systems cannot emulate. By enabling all weather, day-and-night surveillance, microwave technology has shifted from a niche scientific tool to the primary source of data for disaster management, climate modeling, and resource monitoring. While the interpretation of microwave data requires complex signal processing and a deep understanding of radar-target interactions, ongoing advancements in multi-frequency and polarimetric sensing are significantly enhancing the accuracy of geophysical parameter retrieval methods. As we move toward constellations of small satellites equipped with sophisticated microwave sensors, the ability to monitor dynamic Earth processes in near real time will play an increasingly vital role in global environmental stewardship and intelligence.

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