# Ground-Based Microwave Radiometry to Characterize Atmospheric Attenuation Affecting Earth-Space Links

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***Abstract:*** *This contribution provides an overview on ground-based microwave radiometric techniques to characterize atmospheric attenuation affecting Earth-space links up to millimeter wave frequencies. The classical and well-established radiometric approach is described together with its limitations of applicability to rain-free conditions. The most recent Sun-tracking approach and its capability of estimating atmospheric attenuation in all-weather conditions, developed to overcome the shortcoming of classical radiometers, is then described. Latest enhancements of Sun-tracking techniques in the estimation of the Sun brightness temperature are illustrated, along with a preview of future developments.*

## 1 Introduction

Since the beginning of the Space Era, inaugurated by the Moon landing in 1969, Earth-space communication systems have faced an incessant increase in the carrier frequency, dictated by the need of wider bandwidths to support increasingly advanced services and by the congestion of lower bands. While commercial systems nowadays operate at Ka band, the shift to Q/V bands is currently taking place, and the W band is already the subject of some research activities [1]. Unfortunately, the increase in the carrier frequency implies a stronger negative influence of the troposphere on the propagation of electromagnetic waves: among the effects causing the degradation of the link quality, such as wave depolarization and ray bending, signal attenuation, induced by absorption and scattering, certainly plays the most relevant role [2].

Currently, the design of Earth-space communication links at W band represents a challenge, not only because of the lack of propagation data at such frequencies, but also due to the availability of propagation models whose applicability is typically limited to the V band [3]: a clear need for propagation measurements emerges, especially beyond 50 GHz.

This goal has been traditionally achieved by means of experimental campaigns exploiting space-borne beacon signals, such as those transmitted, with European coverage, by the propagation payload onboard the Alphasat satellite (19.7 and 39.4 GHz) [4]. As an obvious drawback, this kind of experiments are complex and extremely expensive, which has pushed to consider additional approaches to estimate the impact of the troposphere on Earth-space links.

This contribution provides an overview on the simpler and less expensive alternatives to measure the attenuation along Earth-space links offered by ground-based microwave radiometers (MWR), which are passive instruments measuring the natural electromagnetic emission from tropospheric constituents: the characterization of the channel can be obtained by taking advantage of inversion algorithms based on the measured sky noise signal [5],[6]. Specifically, this contribution is organized as follows. Section 2 illustrates the advantages and limitations to non-rainy conditions of the most common MWR measurement approach, typically referred to as "Cosmic background" (CB), which consists in pointing the instrument along a fixed direction (typically at zenith or towards a satellite) [5]. Section 3 focuses on a

# Ground-based and space-based GNSS receivers for atmospheric parameter retrievals

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***Abstract:*** *It is well known that the use of the Global Navigation Satellite Systems (GNSS), with both ground-based and Low Earth Orbit (LEO) receivers, allows retrieving atmospheric parameters in all weather conditions. Ground-based GNSS technique provides the integrated precipitable water vapor (IPWV) with temporal continuity at a specific receiver station, while the GNSS LEO technique allows for Radio Occultation (RO) observations of the atmosphere, providing a detailed atmospheric profiling but without temporal continuity at a specific site. Therefore, the GNSS technique can be considered as a supplemental meteorological system useful in studying the atmosphere in clear sky condition and during precipitation events, but with very different spatial and temporal features depending on the receiver positioning. In this report, the theoretical basis for the IPWV remote sensing by ground-based GNSS receivers will be presented, as well as the use of RO from GNSS LEO receivers for atmospheric profiling. The retrieval techniques developed by the research group and currently used are described, reporting also the experimental results carried out to test such techniques.*

## 1. Introduction

It is well known that signals from the Global Navigation Satellite Systems (GNSS), commonly processed for navigation purposes, can also be used to characterize media where they propagate in. Such signals are in the microwave L band, and therefore clouds and rain insensitive. Atmosphere remote sensing by GNSS has become more and more important, exploiting the improvements in the processing of such "free-of-charge" data, everywhere available. For example, the wet part of the troposphere can be estimated by identifying the atmospheric delay from the carrier phase of GNSS observations. Part of these delays, accumulated by the signal along its propagation path, can be associated to the water vapor [1].
Considering the growing employment of ground-based GNSS receivers for the estimation of integrated precipitable water vapor (IPWV), time series of IPWV become available with high temporal and spatial resolution, with the advantage that GNSS can be considered an all-weather system [2], [3].
Experimental measurements for monitoring the atmospheric water vapor are important for reliable climate studies, operational weather forecasting, and to characterise the influence of the atmosphere on microwave propagation. For instance, the knowledge of water vapor field comes usually from radiosonde observations (RAOB's), but the availability of data two or four times per day does not meet the requirement of frequent sampling of such parameter, taking into account the high degree of variability. Ground-based microwave radiometers, able to work continuously for the retrieval the IPWV with a high temporal resolution, provide

# 40 years of research in microwave radiometry for monitoring natural surfaces

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***Abstract:*** *The Microwave Remote Sensing Group of CNR-IFAC is active in the field of microwave research on natural surfaces (soil covered by agricultural-forestry vegetation and snow) using microwave radiometric sensors since the first 80s. Experimental campaigns, electromagnetic modeling and inversion algorithm implementation have been and still are the main activities of the group. Microwave observations make it possible to collect information on soil and vegetation characteristics, to estimate soil moisture content, even under a dense vegetation layer, agricultural and forest biomass, as well as monitoring the water status of crops. The combined use of optical/microwave sensors leads to an accurate knowledge of the water status of the soil/vegetation system, with possible applications to water management also in view to the mitigation of the effects of climate change, thanks to a better optimization of natural resources. The multi-frequency satellite data collected and subsequently processed allow the generation of multi-temporal maps in near-real time concerning several parameters of soil and vegetation. This information is suitable for generating multi-temporal maps on regional scale. However, recent developed algorithms integrating SAR data allowed the achievement of a spatial resolution can reach up to 10 meters.*

*In this paper a short history of microwave radiometry in Italy and a review of the most important results obtained during the years by the group will be highlighted.*

## 1. Introduction

Microwave radiometry revealed to be very appealing in investigating important surface phenomena over the oceans and land at global scale since the first satellite observation. First experiments demonstrated that parameters such as ice concentration, wind speed and precipitations over the ocean, as well as some physical characteristics of soil, snow and vegetation might be retrieved at different levels of accuracy and reliability using electromagnetic models and sophisticated inversion algorithms developed since the '80s. (e.g., [1]).

First studies conducted in several parts of the word (mainly USSR, USA and Italy) focused on estimating the sensitivity of the microwave brightness temperature (Tb) to soil moisture and vegetation biomass were carried out since the late '70s on the basis of ground-based and aircraft experiments and model simulations (e.g., [2-4]). The research showed that data collected at different frequencies and polarizations in microwave bands made it possible to significantly improve the accuracy of the measured quantities, with respect to the one achievable with single frequency/polarization observations. In particular, some Microwave Indices (i.e. specific combinations of polarizations and frequencies) have been successfully related to the main geophysical parameters associated to land hydrological cycle, such as soil

# Microwave Radiometry of Land Surfaces

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**Abstract:** *This chapter provides an introductory overview of passive microwave (PMW) remote sensing of land and its applications for retrieving surface variables. We begin by reporting the first experiments and application of microwave radiometry. Subsequently we continue by delving into the fundamental principles of natural surface emission at microwave. Finally, we discuss the diverse range of surface variables that can be retrieved using PMW data, highlighting the state-of-art outcomes of scientific research and the open points*

## 1 Introduction

Radiometers detect and quantify the natural microwave emissions emanating from the Earth's surface. This emission is expressed as brightness temperature ($T_B$), which represents the temperature of a blackbody emitting the same brightness intensity as the observed surface. The relationship between brightness temperature and a surface's actual physical temperature ($T$) is determined by its emissivity ($e$). Emissivity is a material property with values ranging from 0 (no emission) for a perfect non-emitter, to 1 (complete emission) for a perfect emitter (which behaves as a blackbody). The microwave electric field, characterized by a preferred orientation known as polarization, is often influenced by the geometric structure of the emitting or reflecting object [1, 2]. Due to longer wavelengths and practical limitations on spacecraft antenna size [3], passive microwave radiometers generally have coarser spatial resolutions compared to instruments operating in the visible and infrared regions, or SAR. Typically, spaceborne passive microwave radiometers offer resolutions in the range of 10-100 kilometers. While this coarse spatial resolution might seem like a limitation, it doesn't hinder the application of these instruments in regional or global terrestrial biosphere models. These models commonly operate at spatial resolutions of several kilometers, making them compatible with the data provided by microwave radiometers. Notably, capturing small-scale landscape variations (meter to kilometer scale) is often less crucial for these models compared to obtaining frequent observations. This is because computational limitations typically restrict the model's spatial resolution [4, 5]. Therefore, for terrestrial biosphere models, the fine temporal resolution (typically less than 2-3 days, with the possibility of multiple daily overpasses in polar regions) offered by microwave instruments might be more advantageous than high spatial resolution. The longer wavelengths of microwaves enable subsurface measurements because they can penetrate vegetation, ground, and snowpack, unlike visible and infrared remote sensing, which is restricted to information from the surface of

# High-Resolution Soil Moisture Monitoring: Using Resources and Overcoming Challenges with SAR Systems

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***Abstract:*** *The dynamics of soil moisture at different spatial and temporal scales are important for the exchange of energy, water, and biochemical fluxes between the atmosphere and the land surface. Synthetic Aperture Radars (SARs) have the potential to retrieve soil moisture at high resolutions (~0.1–1.0 km), which promises to advance meteorological predictions, irrigation management, drought-seasonal forecasts, and other related fields. While the high variability of land use and soil properties poses important challenges, the limitations of past spaceborne SARs, such as revisit time and spatial coverage, have hindered the take-up of high-resolution soil moisture products. The paper reviews the key methodological trends that have emerged over the past 50 years for retrieving soil moisture from SAR data at C- and L-bands. A chronological viewpoint underlines the interplay between the technological development of SAR systems and the improvements made to retrieval techniques. The validation process, which requires standardized procedures and dedicated experimental facilities, is key to the quality assurance of the developed products.*

## 1. Introduction

Soil moisture dynamics influence the hydrological cycle, ecosystem function, and climate processes. In dry and semi-arid regions, like in the majority of the Mediterranean basin, soil moisture directly restricts surface evapotranspiration. In a warmer climate, this may have important effects on the terrestrial energy, water, and biochemical cycles [1]. Monitoring soil moisture can therefore support a better understanding of the energy feedback between the Earth's surface and the atmosphere, mitigate the impact of extreme events, and improve the meteorological forecast and management of water resources in agriculture.

Currently, satellite soil moisture products at coarse resolution (e.g., 10–40 km) are in operation, while those at higher resolution (e.g., 0.1–1.0 km) are in transition from a research phase to systematic use in applications. For high resolution, active technology—specifically, Synthetic Aperture Radar (SAR)—is the most appropriate [2]. The electromagnetic frequencies most suited to retrieve soil moisture are in the microwave region, primarily in the L- and C-bands.

Microwave systems retrieve the volumetric water content [$m^3/m^3$] in the top soil layer (e.g., 0-5 cm), therefore, the quantity measured is referred to as surface soil moisture (SSM). Whereas root zone soil moisture (RZSM), in the upper 100 cm of soil, is the water accessible to crops. A wealth of methods have been developed to derive RZSM from SSM, though the issue is still under study (for a recent topical review, see [3]).

Lower electromagnetic frequencies, such as the P-band, may be used to directly sense the soil's deeper layer using microwave measurements [4]. The Earth Explorer P-band SAR BioMASS mission of the European Space Agency (ESA) [5] is planned to be launched by 2024. Although soil moisture is not its primary objective, there will be the opportunity to investigate, on a large scale, the retrieval of a soil moisture profile up to 30–50 cm.

The very variable crop cover and soil characteristics on land surfaces make it more challenging to retrieve the SSM at high resolution than at coarse resolution, where the

# Coastal waterline detection from satellite Synthetic Aperture Radar imagery: an overview

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**Abstract:** *In this chapter, an overview on the capabilities of satellite imagery collected by multi-polarization Synthetic Aperture Radar (SAR) to observe coastal areas is provided. The almost all-weather and day and night imaging capability of SAR allows obtaining fine spatial resolution imagery routinely. Such measurements are at the basis of the information processing chain fostering a continuous information source of paramount importance to detect the waterline, i.e., the boundary between land and sea, in different coastal scenarios depending on their backscattering properties. In addition, it is shown that the multi-polarization imaging capabilities offer remarkable potential in effectively extract the waterline.*

*In this chapter, a baseline unsupervised paradigm that consists of a backscattering-based land-to-water contrast enhancement and edge extraction is applied on a C-band dual-polarimetric synthetic aperture radar data set collected over different coastal environments, including man-made structures, steep rocky coasts, sandy beaches and wetlands, to show the potential and the effectiveness of using spaceborne SAR multi-polarization imagery for coastal waterline detection purposes.*

# Spaceborne Earth Observation and food production: not just Precision Agriculture.

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**Abstract:** *Agriculture is a major pillar of human life, providing livelihoods to billions of individuals worldwide. The ever-growing global population drives an increasing demand for food, implying that sustainable agricultural practices are paramount to ensuring food security and environmental stability. Remote sensing has emerged as a powerful tool for supporting agricultural practices; a range of sensors, including from spaceborne platforms, enable collection of a wealth of data, whose analysis and interpretation provides farmers with actionable insights into the status of their crops. Precision agriculture, or a data-driven approach to crop management, permits tailoring of agricultural practices to the specific needs of each area, thus optimizing resource allocation. However, precision agriculture is not the only possible paradigm when Earth observation is applied to the agricultural context. Another important role that the technology can play is collection of information relevant to crop traceability and - in general - to food traceability, farm-to-fork. Satellite data can indeed offer an alternative, independent source of quantitative and thematic information about monitored crops. Such information enriches and complements "regular" traceability information offered with agricultural products, with the added benefit of being automated and thus more secure - a valuable feature when organic certification is considered as a possible application. This book chapter discusses the issue and provides two working examples of how satellite data can reveal cultural details. In the first example, the potential of Earth observation technology is explored for large-scale assessment of inter-row management practices in vineyards; in the second example, spaceborne radar acquisitions are used to discriminate two different approaches to tillage (ploughing and minimum tillage), which have significantly different impact on the farmland biome. In the first case, sequences of NDVI (Normalized Differential Vegetation Index) values from Sentinel-2 acquisitions over a test site in northern Italy, are analysed to assess discriminability between inter-row spaces with vegetation development and tilled, exposed soil. While accuracy levels vary, a joint analysis of features and accuracy offers valuable insights, laying the foundation for future improvements in identifying and classifying inter-row management in vineyards. In the second case, sequences of Sentinel-1 acquisitions are investigated to identify the temporal location of ploughing and discriminating the two basic approaches to tillage, i.e. deep ploughing vs. minimum tillage. A link is hypothesised and assessed between the type of tillage and superficial roughness resulting from the operation on the one side, and consequent intensity of backscatter on the other side. Similarly to the cases laid out above, many other relevant information items can be derived from satellite data, building a space-based description of crop features that enrich food traceability information.*

# Semantic segmentation and heterogeneous change detection with SAR imagery

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**Abstract:** *The use of Synthetic Aperture Radar (SAR) imagery has become a central tool in Earth Observation, primarily due to its high spatial resolution and operational independence from atmospheric and Sun-illumination conditions. This versatility positions SAR as the sensor of choice across various applications as diverse as flooded area detection, urban settlement mapping, forest biomass retrieval, coastline detection, and many others. Moreover, SAR capabilities can be expanded by simultaneously analysing data from other sensors. These can be either other SAR sensors, leading to multitemporal, multifrequency, or multiresolution techniques, or even sensors that measure an entirely different physical quantity, such as optical, multispectral, or hyperspectral sensors.*
*This chapter reviews recent advances in relation to two different scenarios of SAR image analysis rooted in deep learning and structured output learning. Firstly, we look at the fusion of SAR data in multifrequency and multiresolution environments, specifically addressing the complexities of land cover mapping. We present an in-depth investigation of a recently developed method, accompanied by experimental results.*
*Subsequently, we will explore the synergistic use of SAR data with different sensors, including optical, multispectral, and hyperspectral technologies. This integration proves useful in the application of heterogeneous change detection techniques. The chapter concludes with a comprehensive overview of a recently developed method for this purpose, providing insightful experimental outcomes.*

## 1 Introduction

Thanks to the unique capabilities and the flexibility of synthetic aperture radar (SAR) imaging systems, there has been an enormous surge of interest in their use for remote sensing image analysis. Satellites with SAR payload make use of the motion of the platform along its path to simulate a long antenna, which, in turn, makes it possible to achieve high spatial resolution along the flight direction (i.e. azimuth) from both airborne and spaceborne platforms [1]. It is worth noting that a radar system for earth observation (EO) operates regardless of Sun illumination, because it makes use of its own source of transmitted energy. In addition, due to the long wavelength of the electromagnetic waves used in radar, these do not get occluded by clouds, yielding the resulting data almost insensitive to cloud cover and atmospheric conditions [2]. Therefore, unlike optical sensors, radar sensors for EO provide day-and-night and all-weather acquisition capability, thus

# SIASGE temporal sequence harmonization

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***Abstract:*** *This work details some of the results of the project MultiBigSARData which have been coordinated by the University of Pavia. The project that involved three Italian universities and has been supported by the Italian Space Agency, was focused on the definition of processing chains able to work on SAR data coming from the X-band sensors on board of the Italian COSMO-SkyMed constellation as well as the L-Band SAR sensors on board of the Argentinian SAOCOM constellation. Both constellations together form the so-called SIASGE system (Italian-Argentinian satellite system for Disaster Management and economic development). This paper is devoted to providing some details about the activity by the group in Pavia, which is also part of the CNIT Pavia Research Unit. Specifically, methodologies for Cosmo-SkyMed and SAOCOM temporal sequence harmonization are presented and discussed.*

## 1. Introduction

Multi-temporal SAR images typically refer to a sequence of images relating to the same scene at different time intervals, acquired by the same sensor, and organized into a three-dimensional stack (range, azimuth, and time). In our case, the creation of an *ad hoc* pre-processing chain arises from the need to make multi-mission SAR sequences homogeneous, whose images have different characteristics in terms of bandwidth and frequency, acquisition mode (with different spatial resolutions), polarization, and observation angle.

As regards multi-temporal speckle noise filtering techniques, the most current analysis is reported in [2]. In this publication the following classes are identified according to a historical trend:

- Multilook processing is an approach that aims to reduce speckle by averaging bands at the pixel level, to produce a single filtered image. The use of multi-look algorithms for the purpose of speckle reduction leads to a reduction in the standard deviation of the noise present in the SAR image by forcing its distribution to fit a Gaussian, leading to a degradation of the spatial resolution.
- Estimation of parameters through temporal filtering applied to individual pixels, therefore local as in the case of the approach in [3], which proposes an algorithm for estimating reflectivity using multi-temporal data referring to the same scene but for different instants of time. This methodology improves the estimation of local statistics in non-homogeneous areas, such as edges, for example, using minimum-variance unbiased linear estimators.
- Multi-temporal and non-local filtering, which is based on the exploitation of the redundant information present within a SAR image stack by identifying similar regions, also known as patches, in order to guarantee effective speckle reduction in heterogeneous images.
- Filtering using deep learning, paradigms that are enjoying considerable success in the field of SAR despeckling, given the significant availability of zero-cost data, which allows identification of a set of reference images to be used to train neural networks, with the aim of providing sophisticated despeckling models.

# Natural and anthropogenic hazards affecting infrastructures: the role of satellite SAR Interferometry

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***Abstract:*** *The wide availability of SAR satellite missions and constellations allows the extended use of Multi-Temporal SAR Interferometry (MT-InSAR), also named Advanced SAR Interferometry (A-InSAR) techniques. The aim of this work is to highlight how such tools can be exploited for measuring the surface effects of natural phenomena (earthquakes, landslides, etc.) and anthropogenic activities (exploitation of water table, gas storage, etc.) on urban areas and related infrastructures (railways, airports, bridges, etc.). Thanks to the high accuracy of measurements ensured by MT-InSAR such approach has a key role in the detection of centimetric or millimetric movements affecting the infrastructures and their environment. In addition, the exploitation of SAR Interferometry for Critical Infrastructure Protection is a key issue of EISAC.it (the Italian node of the European Infrastructure Simulation and Analysis Centre), an initiative resulting from a joint ENEA and INGV collaboration agreement established in 2018 in the frame of art.15 of the Italian Law 241/1990. EISAC.it gathers a number of technologies useful for an operational risk analysis of infrastructure. A purposely devised DSS (Decision Support Systems) platform, called CIPCast, provides a technological platform which, gathering results coming from the scenario application of different observation measurements and their correlated application, realizes an effective tool for multi-source integrated monitoring.*

## 1. Introduction

Critical Infrastructure Protection (CIP hereafter) is a relevant issue for modern nations. Critical Infrastructure (CI) is an enabling system for producing services to citizens; as such, they must be protected and their resilience against all types of risks must be enhanced in a way to protect citizens against the loss of primary services.

Although this topic is already part of the agenda of all nations, nevertheless the EU has issued several directives on CIP, in the last decades, to attempt to homogenize the CIP policies in the EU-wide perimeter. Since EU Directive 114/2008 [1] which introduced the identification of a few CI (mainly related to the energy sector) within the Member States (MS), a more recent EU Directive (2557/2022) [2], which waits, to date, for being introduced into the national legislations, operated a drastic change of paradigm, by

- Extending the concept of infrastructure to that of entity which embraces not only the technological component of the infrastructure but also the agent that operates it, its management