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Review Paper

Advances in soil moisture retrieval from synthetic aperture radar and hydrological applications

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SUMMARY

The sensitivity of Synthetic Aperture Radar (SAR) to soil moisture is well established, however, the retrieval of soil moisture from SAR is confounded by the effects of surface roughness and vegetation. This difficulty has resulted in limited applications of SAR as an operational source of soil moisture in hydrology despite the demonstrated benefits of high-resolution distributed soil moisture. Technical and methodological advances such as multi-configuration radar and forthcoming SAR constellations are increasingly mitigating the shortcomings of SAR with respect to soil moisture estimation at the field and catchment scale. At the same time, progress in data assimilation and a better understanding of the impact of phenomena, such as climate change, are revealing the hydrological importance of soil moisture spatial distribution. Thus, despite the currently modest retrieval accuracy, SAR is an important source of soil moisture state information for the hydrological community. Towards the end of increasing the hydrological utilization of SAR soil moisture, a comprehensive literature review was conducted to provide the state-of-the-art of SAR soil moisture retrieval methodology, its limitations and potential. Following the methodology review, a discussion of the benefits and limitations of soil moisture data retrieved from SAR is used to outline the scope of SAR derived soil moisture for hydrological applications.

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1. Introduction

The spatial and temporal distribution of soil moisture is a key state variable in various hydrological and meteorological applications. From the perspective of climate science, soil moisture and the associated flux between the soil and the atmosphere play an important part in the Earth's climate regimes. The coupling that takes place between soil moisture and the atmosphere can have profound impacts on the planet's climate systems, especially when the role of vegetation is considered (see Seneviratne et al. (2010) for a review). In hydrologic studies, soil moisture is a critical component as it controls the partitioning between infiltration and runoff, where infiltration determines the amount of water available for vegetation growth and runoff has a strong impact on the rate of surface erosion and river processes. Combined, the hydrological and climatological processes influenced by soil moisture can impact many environmental phenomena from extreme events like droughts and flooding to state patterns such as the ecological distribution of homogenous vegetation zones. In each of these cases knowledge of the distribution and amount of water in the soil can aid developing better modeling and decision support tools.

Despite the many advantages that can be derived from the knowledge of soil moisture distribution, measurement of soil moisture at the field or watershed scale remains difficult. This is largely due to the difficulty and cost associated with obtaining spatially representative *in situ* soil moisture measurements by point scale sampling. Such methods are labor intensive and impractical to be carried out in more than a few watersheds worldwide.

Remote sensing offers a potential alternative for characterizing the distribution and quantity of soil moisture at a variety of scales, without expensive *in situ* monitoring networks. Specifically, microwave remote sensing, both active and passive, is influenced by the dielectric properties of the soil, and therefore soil moisture. The relationship between the radar signal and soil moisture must be separated from that of other influences that affect radar signals.

The recent launch of the Soil Moisture and Ocean Salinity (SMOS) satellite has made possible operational monitoring of soil moisture using passive remote sensing (Kerr et al., 2010). The emission behavior of the surface is such that the typical resolution of a passive satellite sensor is on the order of tens of kilometers and even modern sensors such as SMOS have a spatial resolution of 40 km (Kerr et al., 2010). This coarse spatial resolution limits applicability of passive radar sensors at the watershed scale and does not account for the spatial dynamics of soil moisture.

In contrast Synthetic Aperture Radar (SAR) uses a self-contained source of microwave radiation to illuminate the surface and measures the amount of radiation returned to the sensor (Fung, 1994; Ulaby et al., 1982). This allows SAR to monitor surface characteristics, including soil moisture, at a spatial resolution of meters to tens of meters under almost all weather conditions (Ulaby et al., 1982). Despite providing remote sensing capability at high spatial resolutions, retrieval of soil moisture from SAR sensors is a challenging problem due to the inherent complexity of radar backscattered signal and the inverse problem of backscattering models (Loew and Mauser, 2006; Mattia et al., 2006; Shi et al., 1997), and therefore has been the topic of much research over the past 20 years. This difficulty, combined with the prevalence of passive soil moisture products, has restricted research activities to identify the potential benefits of high resolution surface soil moisture using actual SAR data.

This review analyzes the potential for retrieval of soil moisture from SAR satellites to enhance research and operational hydrology. It is broken down into two parts. The first highlights the influence of soil and radar properties on radar backscattering and discusses the most commonly used backscatter models, their advancements and limitations, followed by an overview of techniques used to invert those models for separating soil moisture from other influences. This will provide important background for the hydrologist to identify appropriate methodologies for incorporation of SAR as a data source. The second section focuses on the impact of soil moisture for hydrological applications. It discusses the variability of soil moisture and its distribution at the spatial resolution of SAR sensors, the potential benefits of high resolution distributed soil moisture in hydrological modeling and makes practical recommendations to overcome some of the shortcomings associated with SAR soil moisture retrieval.