Remote Sensing of Environment 209 (2018) 107–117

Contents lists available at ScienceDirect

Remote Sensing of Environment

journal homepage: www.elsevier.com/locate/rse

# Characterization of vegetation and soil scattering mechanisms across different biomes using P-band SAR polarimetry

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ARTICLE INFO

*Keywords:*
AirMOSS
P-band
Polarimetric decomposition
SAR
Soil moisture
Vegetation

ABSTRACT

Understanding the scattering mechanisms from the ground surface in the presence of different vegetation densities is necessary for the interpretation of P-band Synthetic Aperture Radar (SAR) observations and for the design of geophysical retrieval algorithms. In this study, a quantitative analysis of vegetation and soil scattering mechanisms estimated from the observations of an airborne P-band SAR instrument across nine different biomes in North America is presented. The goal is to apply a hybrid (model- and eigen-based) three component decomposition approach to separate the contributions of surface, double-bounce and vegetation volume scattering across a wide range of biome conditions. The decomposition makes no prior assumptions about vegetation structure. We characterize the dynamics of the decomposition across different North American biomes and assess their characteristic range. Impacts of vegetation cover seasonality and soil surface roughness on the contributions of each scattering mechanism are also investigated. Observations used here are part of the NASA Airborne Microwave Observatory of Subcanopy and Subsurface (AirMOSS) mission and data have been collected between 2013 and 2015.

## 1. Introduction

Soil moisture is the key state variable that controls the terrestrial water, carbon, and energy fluxes between land surface and atmospheric boundary layer, mainly by regulating photosynthesis and surface evaporation (Seneviratne et al., 2010). By constraining the partitioning of energy fluxes between latent and sensible heat fluxes in water-limited regions, soil moisture also plays a significant role in the prediction skill of weather and climate models (Entekhabi et al., 1996; Koster et al., 2010). Soil moisture has a memory that captures the anomalies in precipitation and radiation and can be used to identify regions of strong feedback between land surface and atmospheric boundary layer (McColl et al., 2017). Moreover, vegetation stress, and subsequently photosynthetic activity, depends on the amount of water available through the roots (as well as atmospheric conditions). Therefore, knowledge of Root Zone Soil Moisture (RZSM) (and where applicable, interaction of roots, soil moisture, and the water table) are necessary to accurately model evapotranspiration seasonality (Thompson et al., 2011). Characterization of the spatio-temporal patterns of soil moisture with depth, therefore, enables improved predictions of the response of plants to the changing climate. Thus, remotely sensed, large-scale estimates of root-zone soil moisture have a number of operational and scientific use in hydrometeorology and ecology, if they can be obtained.

The penetration depth associated with microwave remote sensing soil moisture increases as the electromagnetic frequency of the measurement decreases (Ulaby et al., 2014). Current global microwave satellite observations of soil moisture are limited to those at L-band frequency and higher due to spectrum availability, readiness of science algorithms and technological restrictions of obtaining reasonable spatio-temporal resolution from low-earth orbit satellites (Entekhabi et al., 2014; Kerr et al., 2010). However, L-band instruments, are sensitive to only a few centimeters of the top soil layer. Detection of RZSM requires P-band instruments, which have a penetration depth of several tens of centimeters, depending on soil texture, the profile of soil moisture content and vegetation cover (Moghaddam et al., 2007; Konings et al., 2014). The future BIOMASS mission will carry a fully polarimetric P-band Synthetic Aperture Radar (SAR) instrument and provide an opportunity to estimate RZSM globally (except over North

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https://doi.org/10.1016/j.rse.2018.02.032
Received 8 August 2017; Received in revised form 30 January 2018; Accepted 20 February 2018

Table 1
List of AirMOSS campaign sites and their biome type.

| Name & location | Biome type |
|---|---|
| BERMS, Saskatchewan, Canada | Boreal forest/evergreen needle-leaf, mixed forest, cropland |
| Howland Forest, ME, USA | Boreal transitional/mixed forest |
| Harvard Forest, MA, USA | Boreal transitional/mixed forest |
| Duke Forest, NC, USA | Temperate forest/mixed forest, cropland |
| Metolius, OR, USA | Temperate forest/evergreen needle-leaf |
| MOISST, Marena, OK, USA | Temperate grasslands/crops |
| Tonzi Ranch, CA, USA | Mediterranean forest/woody savanna |
| Walnut Gulch, AZ, USA | Desert and shrub/open shrubland and grassland |
| Chamela, Mexico | Subtropical dry forest/broadleaf deciduous, crops, woody savanna |
| La Selva, Costa Rica | Tropical moist forest/evergreen broadleaf, crops |

America and Europe) from satellite-based SAR observations (Toan et al., 2011; Carreiras et al., 2017).

The Airborne Microwave Observatory of Subcanopy and Subsurface (AirMOSS) mission (a NASA Earth Venture-1 project) is the first P-band airborne campaign to estimate RZSM and use that to better characterize Net Ecosystem Exchange (NEE) across North America (Allen et al., 2010). AirMOSS employs an airborne fully polarimetric SAR operating at P-band (430 MHz) to monitor the dynamics of RZSM across ten sites in North America, covering nine different biomes representative of the entire North American continent (Table 1). The biomes across AirMOSS sites range from tropical and temperate forest to boreal transitional forest and evergreen needle-leaf as well as cropland, woody savanna, grassland and shrubland. AirMOSS backscatter estimates have a high radiometric calibration accuracy of 0.5 dB (Chapin et al., 2015), and a noise equivalent $\sigma^{\circ}$ of $-40$ dB (Tabatabaeenejad et al., 2015) which makes them suitable for accurate soil and vegetation parameter estimation (although the data require a phase calibration for polarimetric applications, as further discussed below).

AirMOSS successfully conducted four years (2012–2015) of airborne campaigns, with 186 science flights each covering an area of approximately 100 km × 25 km. Each site was visited for 2 or 3 campaigns per year. For each campaign, 2 to 3 overflights were performed a few days apart. Data from these campaigns provide an opportunity to develop and validate new algorithms for RZSM, vegetation and surface properties retrieval and to analyze and quantify the contributions of volume and surface scattering, and their interactions to P-band signals across a wide range of vegetation types. In this study, we provide a quantitative analysis of the variability of surface and vegetation parameters across the campaign sites. The AirMOSS radar calibration model was updated in April 2013, so we restrict our study to observations from the period April 2013 through September 2015 to ensure a consistent calibration accuracy/quality.

Unlike at L-band, the variability of the soil moisture with depth is significant over P-band penetration ranges and must be accounted for, which means calculating only a single equivalent soil moisture value may result in values that do not represent the average profile due to the effects of subsurface reflections (Konings et al., 2014). Hence, two different approaches have previously been used for retrieval of soil moisture profiles from AirMOSS observations using modeled vegetation and ancillary vegetation parameters. For campaign sites with mono-species woody or non-woody vegetation (including mono-species forested sites), the approach is to model the vegetation using a detailed scattering model that consists of a stem layer and a canopy layer (Burgin et al., 2011), and assume a second order polynomial shape for the soil moisture profile. Parameters of the vegetation volume scattering model are derived based on field measurements, and the coefficients of the polynomial profile are retrieved using snapshot measurements (Tabatabaeenejad et al., 2015). This approach also assumes a temporally and spatially constant value for the surface roughness parameter, determined by site-specific calibration, for each land cover type to reduce the number of unknowns in the retrieval.

A second retrieval algorithm using AirMOSS observations is focused on campaign sites with multi-species woody vegetation cover (Truong-Loi et al., 2015). This approach uses a semiempirical inversion model to estimate soil moisture profile, surface roughness and the aboveground biomass. The parameters of the scattering model are estimated by regressing the semiempirical model to forward estimates of the full scattering model using field measurements from the Forest Inventory Analysis (O'Connell et al., 2013). In order to increase the number of observations and make the system of equations well-defined, a time series scheme is designed that assumes constant surface roughness and above ground biomass across the three flight days of each AirMOSS campaign (2 to 3 observations over 7–10 days). RZSM retrievals from both of these algorithms meet the AirMOSS mission requirements of an unbiased Root Mean Squared Error (ubRMSE) of $0.05\,m^3/m^3$ for soil moisture over the AirMOSS sites when validated against ground measurements (Tabatabaeenejad et al., 2015; Truong-Loi et al., 2015).

Using vegetation (and roughness) parameters that are dependent on site-specific field measurements limits the applicability of these methods outside of the United States (where FIA data are not available) and in areas where *in situ* measurements may be logistically difficult and expensive. Furthermore, these approaches limit the applicability of the retrieval algorithm across diverse and large-scale land covers and may create errors due to variability in vegetation structure even across a single site. Hence, the transferability of the approach to other test sites or remote regions is hardly given. However, the design of retrieval algorithms that require fewer parameters is complicated by the limited amount of information contained in the backscattering coefficients. Use of the coherent fully polarimetric observations, which was not implemented in the existing AirMOSS retrieval algorithms, provides a means to overcome this potential problem.

A quantitative understanding of scattering mechanisms from land surfaces with vegetation cover is required for interpreting P-band SAR observations. Understanding the relative role of attenuated ground backscatter, vegetation volume backscatter and interactions term based on the SAR observations serves as a guide to the design of parsimonious RZSM retrieval algorithms. The goal of this study is to quantify the contributions of ground (surface and double-bounce) and volume scattering across the wide range of vegetation covers in fully polarimetric P-band SAR observations. Such an extensive analysis was not conducted before due to the lack of fully polarimetric P-band data with reasonable SNR over different land covers/biomes and across different seasons.

We use AirMOSS coherent fully polarimetric observations (phase and amplitude information). To begin, it is necessary to overcome the lack of a dedicated phase calibration in the AirMOSS observations. First, we preprocess the observations by merging the four flight lines in each campaign, removing pixels with high topographic slope and calibrating the polarimetric phase of the observations. Then, we apply a fully polarimetric decomposition model to estimate the contribution of each scattering mechanism to the total backscattering power. Vegetation scattering is modeled using a cloud of randomly-oriented dipoles, without the need for prior assumptions on vegetation parameters. Applying the estimation approach to observations across all AirMOSS campaign sites, we characterize the temporal and spatial differences in the relative contributions of the different scattering mechanisms. These results can provide guidance for the design of future low-frequency RZSM retrieval algorithm.

The rest of the study is organized as following: Section 2 reviews the data pre-processing and presents estimates of phase bias from AirMOSS observations. Section 3 describes the fully polarimetric model used to decompose the scattering mechanisms, and Section 4 outlines the estimation steps. Section 5 presents the results, and conclusions are provided in Section 6.