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COMPLEX PERMITTIVITY AND PENETRATION DEPTH ESTIMATION FROM AIRBORNE P-BAND SAR DATA APPLYING A HYBRID DECOMPOSITION METHOD

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ABSTRACT

A method for estimating complex soil permittivity (or moisture) and penetration depth based on SAR decomposition is presented. By combining model- and eigen-based decomposition techniques, SAR observations are separated into single scattering components (from soil & vegetation). The proposed method incorporates a multi-layer rough surface scattering model to simulate the soil scattering contribution. From the decomposed soil scattering component, permittivity and thus penetration depth can be estimated from SAR observations. Results are presented for the AirMOSS campaign within the MOISST site, OK, USA. As first results, a median value of 16.44 + 2.02 for the complex permittivity was estimated from the 19 P-band data takes at the SoilSCAPE *in situ* station in Canton, OK, USA. Overall, the retrieval results for the real part of the complex permittivity are similar to *in situ* values at 30 cm soil depth, with differences in respective median values of 3.44. The median of penetration depths at the Canton site is 23.91 cm.

Index Terms— AirMOSS, Multi-layer SPM, Polarimetry, SoilSCAPE, Surface Scattering

1. INTRODUCTION

The determination of soil moisture has gained more and more significance in the field of microwave remote sensing in recent decades [1-5]. The reason for this is, for instance, the influence of soil moisture on many hydrological processes, controlling the terrestrial water, carbon and energy fluxes, and therefore playing a significant role in weather predictions and climate modeling [1]. Another aspect is that penetration capabilities of electromagnetic waves into soils mainly depend on the soil moisture content. Theoretically, electromagnetic waves in the low-frequency domain (e.g., UHF) can penetrate into the soil up to several meters [2]. When estimating soil moisture from microwave remote sensing data, polarimetric radar backscatter coefficients provide knowledge on geometry, structure, and scattering mechanisms. There exist several eigen-based and model-based decomposition methods to estimate single scattering mechanisms from SAR data [2], [3]. Ground scattering components can then be used to invert for soil moisture information. Based on determined complex permittivity, the soil penetration depth can be estimated. Knowledge of the penetration capabilities of SAR data into soil is important, for instance, when relating observations with forward modeled output, e.g. in data assimilations studies [6].

In this study, we are proposing a hybrid decomposition method with an incorporated multi-layer soil scattering model, appropriate for P-band scattering scenario. This hybrid decomposition method has the advantage of combining information from remote sensing data and modeling, as well as the limited initial assumptions, which have to be made for instance about the present vegetation canopy. Results of this decomposition method can then be used to estimate complex permittivity, and subsequently determine penetration depths.

2. METHODS

In order to estimate geophysical parameters such as soil permittivity, the decomposition method proposed in this study separates P-band SAR observations into the individual scattering components from ground, dihedral (double-bounce), and vegetation. In order to analyze the contribution of these individual scattering mechanisms, the decomposition method estimates the two eigen-based scattering angles α_s and α_d [°], as well as the intensities of surface scattering f_s, double-bounce scattering f_d, and vegetation scattering f_v [-]. Since we solve for five variables (α_s, α_d, f_s, f_d, and f_v) out of four SAR observations within this method, the ambiguity for α_s and α_d is solved by assuming an orthogonality condition with $\alpha_s = \frac{\pi}{2} - \alpha_d$ [2]. Hence, the angle between 0° to 45° is assigned to represent surface scattering, denoted by α_s, and the angle between 45° to 90° is assigned to present dihedral surface scattering, denoted by α_d [3].

The proposed hybrid decomposition method is supported by a soil scattering model, i.e., the multi-layer small perturbation method (SPM) [4], which computes backscatter coefficients based on soil characteristics for multiple layers. The modeled backscatter coefficients are then used to estimate the modeled α_s, which is required within the decomposition of the SAR observations. The individual steps of the method are shown in Fig. 1 and will be described in detail in the following sections.

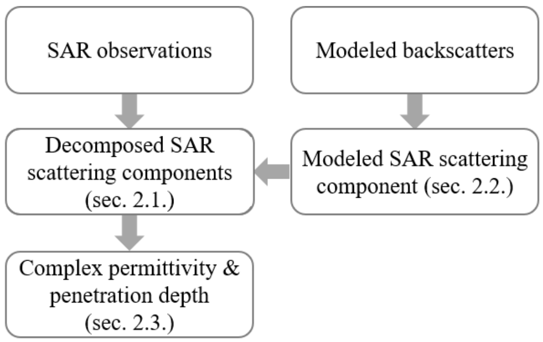

Fig 1. Flow chart of the presented decomposition method for complex permittivity and penetration depth estimation.

2.1. Polarimetric hybrid decomposition

The hybrid decomposition method employed in this study was originally proposed in [3]. The method is adapted here to be applied in a non-iterative way and for P-band frequency.

The polarimetric coherency matrix, characterized by five parameters by assuming reflection symmetry of observed media leading to correlation terms between co- and cross-polarized signals being zero (T_{13}, T_{23}, T_{31}, and T_{32}), is decomposed into three canonical scattering components: surface $[T_s]$, dihedral $[T_d]$, and vegetation volume $[T_v]$ [3]:

$$\begin{bmatrix} T_{11} & T_{12} & 0 \\ T_{12}^{*} & T_{22} & 0 \\ 0 & 0 & T_{33} \end{bmatrix} = [T_s] + [T_d] + [T_v], \qquad (1)$$

with T_{12}^{*} as the complex conjugate of T_{12}.

In order to determine soil parameters from relevant soil scattering components only, (1) can be rearranged to solve for $[T_s]$ + $[T_d]$ as proposed in [3]. Thereby, the component representing scattering from any vegetation volume, $[T_v]$, can be estimated based on the particle anisotropy A_p [-], the width of the orientation angle distribution (degree of orientation) $\Delta\psi$ [-], and f_v [3]. Since the approach proposed in [3] is computationally expensive and requires certain assumptions to initialize the iterative procedure, we propose to estimate f_v in a non-iterative way for a realistic parameter space, that is, real and imaginary part of complex permittivity ($\varepsilon_s' \in [2{,}50]$, $\varepsilon_s'' \in [0{,}10]$) and vegetation volume parameters ($Ap \in [0{,}0.8]$ and $\Delta\psi \in [10{,}90]$). For that, complex radar backscatter channels are computed as functions of $\varepsilon_s' + \varepsilon_s''$ $[-]$ in order to then estimate model-based α_s (cf. Eq. (2)). Finally, from polarimetric SAR data and the model-based α_s, the decomposition results for α_s, α_d, f_s, f_d, and f_v can be calculated for varying $\varepsilon_s' + \varepsilon_s''$ and individual $Ap - \Delta\psi$ combinations. In order to guarantee valid scattering intensities and to prevent unrealistic negative powers after volume scattering removal, only vegetation volume types (A_p, $\Delta\psi$) leading to positive ground scattering powers were allowed within the decomposition. From decomposition results, the normalized power indices ($P_s/P_t, P_d/P_t$ and P_v/P_t), giving total contribution of individual scattering mechanisms, can be calculated after [1], with P_t being the sum of P_s, P_v, and P_d.

2.2. Multi-layer SPM for Soil Scattering at P-band

In this study, the multi-layer SPM [4] is employed for simulations of complex radar backscatter channels σ. This model is able to consider backscattering from multiple sub-surface layers from top to deeper soil depths. It computes the first-order scattering from layered surfaces by considering "multiple scattering processes between the boundaries" [4]. Because of its ability to simulate backscattering from layered sub-surfaces, it is well suited for P-band-soil interactions, as shown in [4].

Required model input parameters of the multi-layer SPM with respective values used in this study are listed in Tab. 1. Note that the chosen value set is one possible approximation for the assumed scenario (monostatic, smooth soil roughness) in this study.

Tab 1. Input parameters for multi-layer SPM modeling.

PARAMETER	VALUES
Frequency	430 MHz
Number of layers N	2
Incidence angle in range θ_i and azimuth φ_i	θ_i from AirMOSS $\varphi_i = 0°$
Scattering angle in range θ_s and azimuth φ_s	$\theta_s = \theta_i$ $\varphi_s = 180°$
z-coordinates of the respective boundary layers	$d_1 = \lambda/2$
Surface roughness of each layer (vertical RMS height s, horizontal correlation length l)	$s_1 = 0.5\ cm$; $l_1 = 30\ cm$ $s_2 = 0.25\ cm$; $l_2 = 60\ cm$
Autocorrelation function ACF	Exponential
Complex permittivity for each layer	$\varepsilon_{r_1} = \varepsilon_1' + \varepsilon_1''$ $\varepsilon_1' \in [5{:}40], \varepsilon_1'' \in [0{:}10]$ $\varepsilon_{r_2} = \varepsilon_{r_1} + (10 + j0.5)$

Based on simulated σ for both horizontal and vertical polarization, the complex model-based α_s is determined after Cloude, 2010 [2], valid for $0 \le \alpha_s \le \frac{\pi}{2}$:

$$\alpha_s^{Model} = tan^{-1}\left(\frac{\sigma_{HH}-\sigma_{VV}}{\sigma_{HH}+\sigma_{VV}}\right). \qquad (2)$$

2.3. Complex permittivity and penetration depth retrieval

In order to estimate complex permittivity from polarimetric SAR measurements, the decomposed data-based α_s^{Data} is compared with the model-based α_s^{Model}. By minimizing the difference between α_s^{Data} and α_s^{Model} for individual $Ap - \Delta\psi$-combinations (cf. sec. 2.1.), the corresponding complex permittivity values can be estimated. First, the absolute value of the modulus r and phase angle ϕ of the real (α_s') and imaginary (α_s'') parts of α_s^{Data} and α_s^{Model}, respectively, are calculated:

$$r_{\alpha_s}(Ap, \Delta\psi) = \left|\sqrt{\alpha_s'^2 + \alpha_s''^2}\right|, \qquad (3)$$

$$\phi_{\alpha_s}(Ap, \Delta\psi) = \left|tan^{-1}\left(\frac{\alpha_s''}{\alpha_s'}\right)\right|. \quad (4)$$

Second, the minimum sum of the absolute differences between data- and model-based r_{α_s} or ϕ_{α_s} are used to determine the complex permittivity:

$$\varepsilon_r' + \varepsilon_r''(Ap, \Delta\psi) = min\left(\left|r_{\alpha_s^{Data}} - r_{\alpha_s^{Model}}\right| + \left|\phi_{\alpha_s^{Data}} - \phi_{\alpha_s^{Model}}\right|\right). \quad (5)$$

Since $\varepsilon_r' + \varepsilon_r''$ values are estimated for multiple $Ap - \Delta\psi$ combinations (cf. sec. 2.1.), the final complex permittivity is estimated as the average value of all estimated $\varepsilon_r' + \varepsilon_r''$.

Based on the estimated $\varepsilon_r' + \varepsilon_r''$ from decomposed polarimetric SAR observations, one possible application is the estimation of the penetration depth δ_p [cm]. In literature, the penetration depth (also known as sampling depth) describes the depth at which the power density of the propagating electromagnetic radiation is reduced by a factor of 1/e (≈ 37%) [5]. There are many formulations to calculate δ_p, e.g. [5, 7]. In this study, we are exemplarily employing the well-known formulation of [7], with estimation of the refraction index from [8]:

$$\delta_p = \lambda / \left(4\pi \sqrt{\frac{\sqrt{{\varepsilon_r'}^2 + {\varepsilon_r''}^2} - \varepsilon_r'}{2}}\right). \quad (6)$$

Although this formulation does not account for different soil conditions (e.g. texture, type or density), it is taken as indication for the permittivity-related penetration ability of the P-band waves.

3. AIRMOSS DATA AND TEST SITE

Polarimetric P-band SAR observations were acquired during the Airborne Microwave Observatory of Subcanopy and Subsurface (AirMOSS) campaign (a NASA Earth Venture-1 project), which was conducted between 2012 to 2015 over nine different biomes across ten sites in North America [1]. It was the first P-band airborne mission for root-zone soil moisture estimation operating at a center frequency of 430 MHz. Every observed site covers an area of ~25 km x 100 km at ~100 m resolution and was revisited ~2 to 3 times every year throughout the campaign duration. The different test sites cover varying land surface types from grasslands to tropical rain forests [1].

In this study, the AirMOSS site *Marena Oklahoma In Situ Sensor Testbed* (MOISST), OK, USA, was chosen since the land surface is mainly covered by grasslands (~45%) and crops (~39%), offering sufficient soil penetration capabilities at P-band. Results are presented over the entire campaign duration (in total 19 dates) for one representative AirMOSS pixel at the *Soil moisture Sensing Controller and oPtimal Estimator* (SoilSCAPE) monitoring station at Canton [9], in order to compare retrievals with *in situ* data. The pixel and station are located at Latitude 36.002 North and Longitude 98.628 West.

4. RESULTS

In Fig. 2 the decomposition results for individual scattering mechanisms are displayed. It can be seen that the results for α_s^{Data} and α_d^{Data} are strictly located in the 0°–45° and 45°–90° ranges, respectively. In detail, α_s^{Data} ranges from 21.3° to 42.72° and α_d^{Data} ranges from 47.3° to 68.7°. Further, the calculated power indices display the normalized contribution of surface (P_s/P_t), dihedral (P_d/P_t), or vegetation (P_v/P_t). While the dihedral scattering shows lowest median value of 0.1 of all three indices, the surface and vegetation scattering have median values of 0.42 and 0.48, respectively, with the vegetation contribution spanning the largest range. Hence, the contribution of dihedral scattering is less than that of the surface or vegetation scattering, with the vegetation scattering showing the highest contribution.

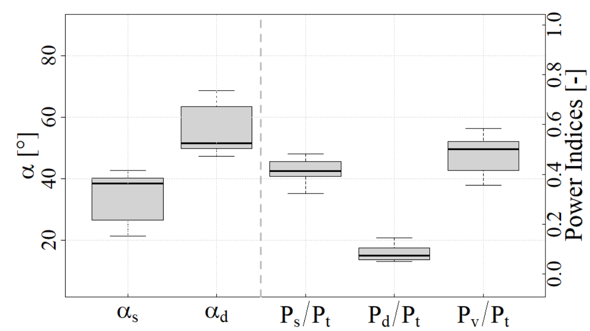

Fig 2. Polarimetric hybrid decomposition results for scattering angles (α_s, α_d) and power indices (calculated after [4]) at Canton, OK, USA from 2013 to 2015 (cf. sec. 2.1.).

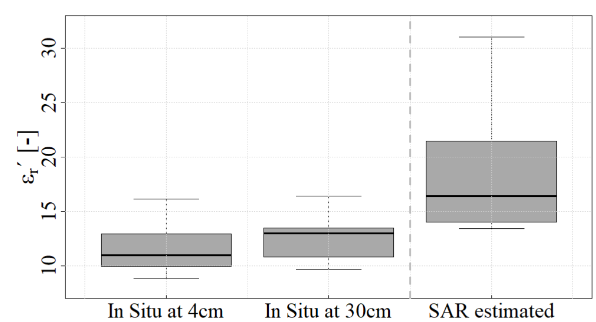

Fig 3. *In situ* soil permittivity at Canton, OK, USA, for soil depths at 4 cm and 30 cm (left), in comparison with ε_r' retrievals from AirMOSS P-band SAR observations between 2013 and 2015 (right).

In Fig. 3, *in situ* soil permittivity at the SoilSCAPE station Canton, for soil depths of 4 cm or 30 cm, are compared to ε_r' retrievals. Conversion from soil moisture to permittivity are conducted after [10].

For one, it can be seen that *in situ* permittivity increases with increasing soil depth, with median values of 11 at 4 cm and of 13 at 30 cm soil depth. Second, the estimated permittivity has a higher median value of 16.44, with its value range showing the most distinct variations. Overall, retrieval results are closer to *in situ* permittivity at 30 cm soil depth than at 4 cm.

In Fig. 4, the real and imaginary parts of the retrieved complex permittivity ($\varepsilon_r', \varepsilon_r''$) are displayed together with estimated penetration depths. The median value of all estimated ε_r'' is 2.02, with variations between quartiles of 25% and 75% at 1.61 and 2.65, respectively. Lastly, the median δ_p for the P-band SAR observations is 23.91 cm, varying between absolute minimum value of 11.68 cm and absolute maximum value of 27.55 cm. These results concur with the fact that retrievals for ε_r' are closer to *in situ* permittivity at 30 cm soil depth than at 4 cm.

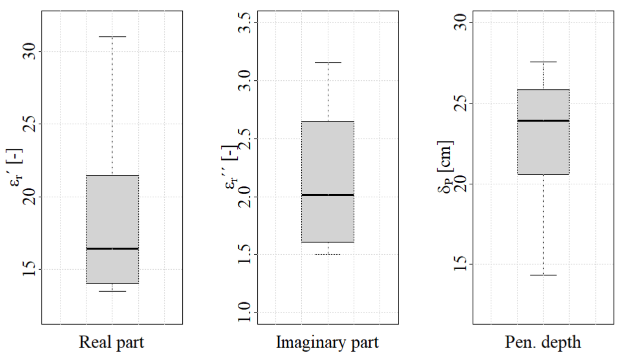

Fig 4. Retrieval results for complex permittivity (ε_r', ε_r'') and penetration depth δ_p at Canton, OK, USA from 2013 to 2015.

5. DISCUSSION AND FIRST CONCLUSIONS

In this study, an enlarged and improved polarimetric hybrid decomposition method is proposed to decompose P-band SAR observations into their individual scattering components of soil and vegetation. Further, complex permittivity is estimated from the comparison of modeled and decomposed soil scattering components. As one application, it is exemplarily used to determine penetration depth of the P-band SAR data into the soil.

As with any other soil scattering model, several assumptions have to be made to estimate complex backscatter channels σ based on the multi-layered SPM. Influences of different input parameters such as soil roughness and incidence angle can be found in [4]. Analyses showed that while the influence of soil surface roughness has minor impact on modeling results, the influence of the incidence angle θ_i on modeling results is significant. However, in this study the modeled α_s^{Model} has minor influence on decomposition retrievals since the θ_i from AirMOSS is almost always ~25.6° over the entire study period.

Decomposition results display varying contributions of surface, dihedral and vegetation scattering, with dihedral scattering showing lowest and vegetation scattering showing highest contributions to the SAR signal. Although the total contribution of surface scattering is smaller compared to vegetation scattering, it was shown that at P-band the method is still able to provide reasonable soil moisture estimates for low-vegetation conditions.

In general, results presented here show similar permittivity retrievals compared to *in situ* values but with larger variations. Moreover, a median penetration depth of 23.91 cm could be estimated. Because of this SAR-retrieved penetration depth, estimation results for ε_r' are more coincident with *in situ* permittivity at 30 cm soil depth than at 4 cm. Furthermore, since estimated δ_p of the P-band SAR data is lower (median: 23.91 cm) due to overall higher permittivity than at a measuring depth at 30 cm, results confirm the sensitivity of penetration depth to soil permittivity since it decreases with increasing moisture. One reason for differences between retrieved and measured ε_r', with a median value of 3.44, may result from scale mismatches of airborne SAR data and *in situ* measurements. Since decomposition results proved the presence of vegetation and because median complex permittivity is 16.44 + 2.02, δ_p results between 11.68 cm and 27.55 cm seem reasonable but should be investigated in more detail.

In summary, these first results for one AirMOSS resolution cell at the Canton *in situ* station over 19 dates between 2013 and 2015 provide a first insight into the feasibility of estimating complex permittivity and penetration depth from AirMOSS P-band data. However, further spatio-temporal analyses based on more AirMOSS data will be conducted to further analyze, optimize, and validate the method to quantify estimation quality of complex permittivity and the penetration depth capabilities of P-band waves.

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