Inversion of Soil Moisture Profiles Under Tall Vegetation with Low-Frequency Radar: Theory and Experiment

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Simultaneous estimation of deep and shallow soil moisture will provide a major breakthrough for estimation of key unobserved hydrologic fluxes, evapotranspiration and acquifer recharge, linking surface hydrologic processes with those in the subsurface. Given that more than 35% of the global land surface is covered with substantial vegetation cover, exceeding 50 tons/ha, it is also imperative that the capability to estimate soil moisture under such amounts of vegetation is developed. We have previously presented the theoretical basis for estimating soil moisture under forest canopies using a combination of coherent and incoherent scattering models for radars in the UHF and VHF bands [1]. The present work focuses on sensitivity analyses and the application of the proposed method to experimental data. The results of this study directly impact retrieval of information from data obtained by low frequency radar systems on tower, airborne, and prospective spaceborne platforms. Representative of many natural subsurface structures, we assume the ground layers to be separated by rough interfaces of arbitrary depth and dielectric constant. Due to the large depth of penetration at VHF and to some extent at UHF, the waves can travel well into the ground surface and scatter from subsurface layers, even in the presence of dense forests. The wave scattering mechanisms, therefore, will include the interactions between the vegetation and subsurface layers in addition to the standard vegetation and top ground surface. Subsurface multiple scattering processes also need to be included. We have shown that the coherent scattering processes between the vegetation layers (crown and stems) and ground interfaces generally dominate the backscattered signal for VHF and UHF radars for tall forests. For shorter forests and other vegetation, the incoherent ground scattering effects may still dominate. In both cases, there is significant sensitivity to subsurface properties, such as the layer depths and dielectric constants (therefore soil moisture), in the coherent wave signature for these low frequencies. Depending on the number of distinct frequency and polarization channels available, information from multiple soil moisture depth columns could therefore be retrieved.

The inversion algorithm for subsurface soil moisture in the presence of significant amount of vegetation proceeds as follows: Using ancillary information such as land cover maps, the vegetation is classified roughly into short forest or tall forest categories. For both vegetation types, canopy allometric relations are used to correlate crown and stem parameters and therefore significantly reduce the number of vegetation unknowns. For the short forest category, higher frequencies such as C-band are used to estimate canopy moisture and density [2] such that their effects can be simulated at the lower UHF and VHF bands and removed from the total. The remainder is essentially the contribution of ground layers in the case of short vegetation cover, and the coherent trunk and multilayer ground interactions in the case of tall forest cover. Inversion of subsurface soil moisture using UHF and VHF radar when surface scattering dominates is explained in [3]. For the case of taller vegetation where the coherent multiple scattering effects dominate, the backscattered signal is simulated for a representative set of tree and ground parameters. The simulated data are used to generate a closed form multidimensional model in terms of a small number of unknowns. This model, which is nonlinear, is inverted using local optimizations techniques with judicious choices of cost functions. Local optimization is chosen to take advantage of the high computational speed afforded by such techniques.

A sensitivity analysis is carried out that guides the selection of the most relevant unknown parameters to achieve optimum estimation accuracy. Both the forward and the inverse models are simulated for a wide range of vegetation and subsurface soil conditions. It is shown that for noise-free data, the algorithm results in very good retrievals. Subsurface layer depths are generally retrieved more accurately for drier top layers. Both top and bottom layer moisture are estimated with high accuracy in the majority of the cases considered. But generally, as the depth of the subsurface layer increases, the estimate of the top layer permittivity becomes less accurate. The estimates of the vegetation (stem) height are also found to be accurate to within 10%.

We demonstrate the utility of the proposed inversion technique for data collected by a tower-based UHF/VHF radar system in a forested region, representing the tall vegetation category. The radar is equipped with L-band, UHF, and VHF bands, all with 4 polarizations channels. The incidence angle can be controlled both during data acquisition and in post-processing. The radar is moved vertically to produce a synthetic aperture for finer beam width and beam-steering. The focusing process is performed iteratively with subsurface wave speed estimation. The challenges of data processing, beam focusing, and radar calibration are presented, followed by inversion results. The results are compared against ground truth data to validate the inversion algorithm.

References

1. Moghaddam, M., Y. Goykhman, and A. Tabatabaeenejad, “Estimating forest parameters and underlying layers of soil moisture with low-frequency radar,” IGARSS’07, Barcelona, Spain, July 2007.
2. M. Moghaddam and S. Saatchi, “Monitoring tree moisture using an estimation algorithm applied to SAR data from BOREAS,” IEEE Trans. Geosci. Remote Sensing, vol. 37, no. 2, pp. 901-916, 1999.
3. Tabatabaeenejad, A., and M. Moghaddam, “Inversion of dielectric properties of layered rough surface using the simulated annealing method,” IEEE Trans. Geosci. Remote Sensing, submitted.