RETRIEVAL OF SURFACE AND DEEP SOIL MOISTURE FROM RADAR OBSERVATIONS USING SIMULATED ANNEALING

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1. INTRODUCTION

Soil moisture is of fundamental importance to many hydrological and biological processes. Soil moisture information is vital to understanding the cycling of water, energy, and carbon in the Earth system. Knowledge of soil moisture is critical to agencies concerned with weather and climate prediction, runoff potential and flood control, soil erosion, agricultural productivity, drought monitoring, and human health. The need to monitor soil moisture on a global scale has motivated missions such as NASA's Soil Moisture Active and Passive (SMAP) [1].

Effects of soil moisture on the backscattered field have been studied since the 1970s [2], but soil moisture estimation from radar data remains a challenging problem and there is still a need for more accurate and more efficient inversion algorithms. Such algorithms are key in the success of missions such as SMAP. This work is directly intended for soil moisture retrieval from SMAP L-band radar observations. We have shown that the simulated annealing method is a powerful tool for inversion of model parameters for rough surface structures, which are representative models for soil [3]. The sensitivity of this method to measurement noise has also been investigated assuming a two-layer structure characterized by the layers dielectric constants, layer thickness, and statistical properties of the rough interfaces [3]. What sets apart simulated annealing from other techniques that use local optimizations is its extremely high accuracy and its capability to find the global minimum that might be hidden among many local minima. Since, unlike the assumed geometry in [3], the moisture profile varies with depth, it is necessary to model the rough surface as a layered structure with a rough interface on top and a stratified moisture gradient below. Each layer is assumed to have a constant volumetric moisture content. Here, we investigate the performance of simulated annealing in retrieving not only surface but also deeper soil moisture and in the presence of noise. We start by examining the retrieval capability of simulated annealing with noise-free data when number of layers used to model a layered soil increases. We then investigate the accuracy of inversion in presence of noise for L-band as well as lower frequencies. We show that lower frequencies not only are necessary for deep soil moisture retrieval but also increase the accuracy of retrieval.

2. FORWARD MODELS

Soil moisture varies with depth and we model this gradient by a stratified dielectric structure as shown in Fig. 1. We use a first-order small perturbation method (SPM) [4] to calculate the scattered field by this structure. Measured scattered fields are synthesized assuming an eight-layer geometry with the layer boundaries located at $z = 5, 15, 30, 50, 70, 100, 200$ cm. These depths, which are used here for modeling the moisture profile, are the actual measurement points in a field campaign by University of Arizona and USDA-ARS Southwest Watershed Research Center in 2003 to measure soil moisture in Arizona's Lucky Hills in support of the Microwave Observatory of Subcanopy and Subsurface (MOSS) project [5]. The reason for using an eight-layer structure for synthesizing the measured scattered field is to achieve better consistency with real measurements. However, as explained in Section 3, number of layers included in the inversion process can be limited by measurement parameters, meaning that we use different models for data synthesis and inversion process. The inverse crime is thus avoided as an added benefit.

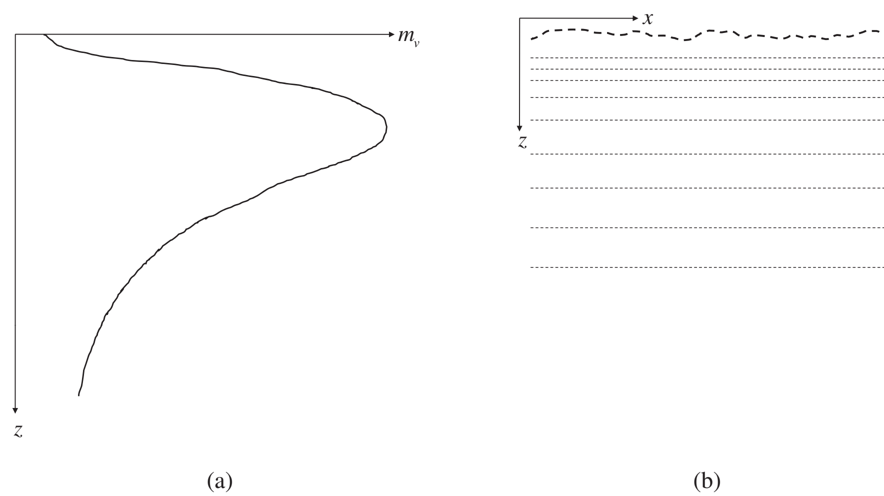
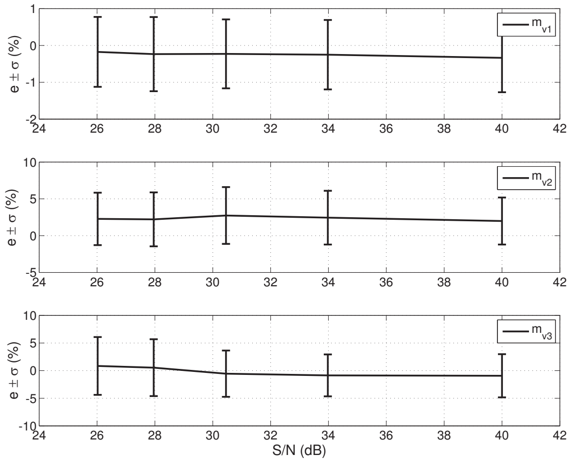


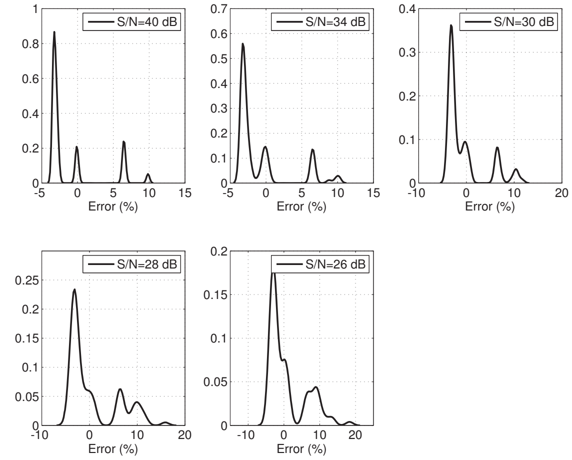
Fig. 1. (a) Sample moisture profile of soil from measurements at Arizona's Lucky Hills. (b) We model moisture variation by a stratified dielectric structure.

3. INVERSION

We use simulated annealing for inversion. Inclusion of more layers, hence more unknowns in inversion, makes the forward model more consistent with reality, but at the same time, makes it more difficult to retrieve all model parameters, especially because the number of scattering measurements is limited. The frequency used in SMAP mission is 1.26 GHz and the measurement angle is $40°$, limiting the performance of the inversion algorithm when soil is modeled by more than one layer. We examine the performance of the inversion not only when limited by these measurement parameters but also when more frequency points are available. This analysis benefits SMAP retrievals as well as retrievals for lower frequency systems.

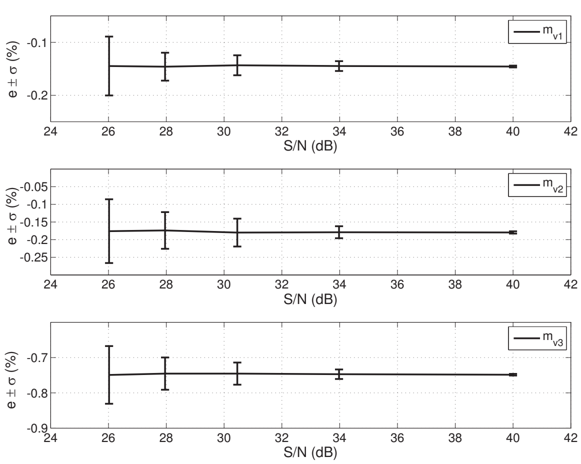


(a) $f = 1.22, 1.26, 1.30$ GHz.

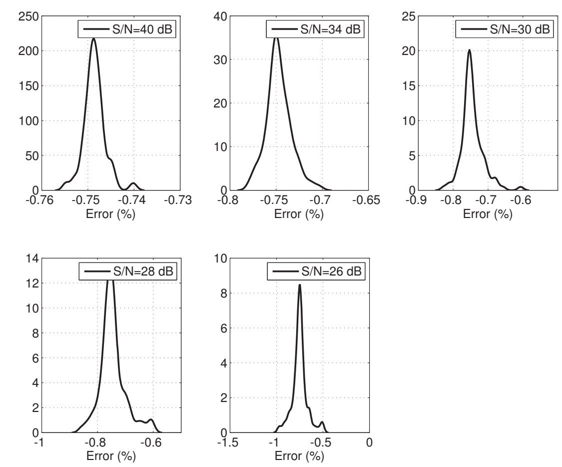


(b) $f = 1.22, 1.26, 1.30$ GHz.

Fig. 2. Three-layer problem: (a) Average and standard deviation of the output error in the moisture content of all three layers when L-band frequencies are used. (b) Distribution of the output error in the moisture content of the third layer.



(a) $f = 137, 435$ MHz, 1.26 GHz.



(b) $f = 137, 435$ MHz, 1.26 GHz.

Fig. 3. Three-layer problem: (a) Average and standard deviation of the output error in the moisture content of all three layers when VHF, UHF, and L-band frequencies are used. (b) Distribution of the output error in the moisture content of the third layer.

4. NOISE ANALYSIS

We consider the background and system noises as well as speckle, invert the moisture content of all layers for 100 realizations, and examine the distribution of output error in the retrieved soil moisture profile. We consider the geometries studied in Section 3 and use one measurement angle, i.e., 40° and frequency values in P- and L-bands. Figs. 2 and 3 show examples of the effect of frequency values on the output error. Five signal-to-noise ratios are considered when only background and system noises are present. These plots suggest that simulated annealing can retrieve deep (more than 5 cm) soil moisture with good noise responses if frequencies in P-band or lower are used. Our extensive study of noise response of simulated annealing for several cases has shown that for a fixed number of subsurface layers, lower frequencies such as in P-band are required to achieve soil moisture estimation accuracy of better than 4%. Using only L-band frequencies, our results show that in the presence of noise, simulated annealing is very likely to produce soil moisture retrievals with better than 5% accuracy, as required by SMAP.

5. REFERENCES

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