RADAR RETRIEVAL OF SUBSURFACE PARAMETERS FOR LAYERED MEDIA WITH NONSMOOTH INTERFACES

Yuriy Goykhman* and Mahta Moghaddam
Radiation Laboratory, Department of EECS, The University of Michigan, Ann Arbor, MI
yuriy@umich.edu, mmoghadd@umich.edu

1. Problem Definition

Many environmental, industrial, military, geological, and civil engineering applications require fast and accurate non-contact estimation of parameters of subsurface structures that have multiple non-smooth layers. These applications include estimating the depth of bodies of fresh water, through-the-wall imaging, detecting buried objects, and estimating root-zone soil moisture and composition. The penetrating abilities of low frequency radiation make it a good candidate for this group of applications, provided sufficient resolution can be achieved. Since the radar measures the scattered fields which are proportional to the radar cross section of the targets, an efficient inversion methodology is needed to obtain the sought-after parameters from the scattering measurements. Most inversion algorithms require multiple iterative evaluations of a forward scattering model. Therefore, an efficient forward model with a large region of validity is crucial for the success of the inversion. In this work, we use a recently developed forward model, which is based on the extended boundary condition method (EBCM) and scattering matrix method and is optimized for application to media where the top interface is approximated as a periodic surface, while the lower interface is treated as a random rough surface. This model would apply, for example, to bodies of fresh water, desert sand, and adobe walls. The inversion algorithm is implemented as a modified conjugate-gradient-based nonlinear optimization, using a multidimensional closed-form equivalent of the forward solver. It is assumed that multifrequency radar measurements are available from tower-mounted or airborne platforms, for example at typical radar frequencies of L-band and P-band (UHF) [1].

2. Methodology

We have recently reported the solution for scattering from the target 3-layer 2-interface medium using EBCM and cascaded scattering matrix techniques [2]. First, discrete Floquet modes are generated for the top periodic surface. Then, a period is assigned to the bottom random rough surface, which equals an integer multiple of the period of the top surface, and used to generate the Floquet modes for this lower interface. Finally, the modes are matched to obtain the overall transition matrix for the system and to calculate the scattering cross sections. Even though the computational complexity of this forward model is significantly less than a fully numerical routine such as the Method of Moments (MOM), it is still too costly for use in an iterative inversion algorithm. To make the model more suitable for inversion, the full model is simulated for a range of parameters such as dielectric constant, surface statistics, and layer separation. Then, the dependence on each of these parameters is sequentially modeled using much simpler, analytically differentiable functions, such as polynomials. Once the closed-form model is developed, the subsequent evaluations of the forward model are extremely fast and the forward model is suited for both local and global inversion techniques.

The inversion process requires at least as many independent data points (measurements) as there are unknown model parameters. In practice, the initial overhead cost of simulating the function for a range of values of all of the unknowns may be too large to be practical, especially considering that the lower interface is a random rough surface, requiring the scattering simulation of many realizations of the surface. Therefore, a sequential layer characterization algorithm is applied by using a multifrequency radar scenario. Assuming the medium between the first and second interfaces is lossy, the scattering problem is first simulated at a sufficiently high frequency such that the effect of the 2^{nd} interface is negligible (typically L-band). Since only the top layer affects the cross section coefficients at this frequency, the number of unknowns is greatly reduced, and the retrieval of the top layer unknowns can be efficiently accomplished. With the top layer characterized, the scattering contribution of the subsurface layer can be simulated at a lower frequency (e.g., UHF). The coupling between the two interfaces is still represented in the solutions of the forward and inverse models through the lower frequency radar measurement, but the retrieval of their properties has been effectively decoupled through this approach.

Once the simulation over the range of parameters is complete, special care is needed to select the proper polynomial representation for the data. While it may be tempting to fit a high order polynomial such that the residual error is exactly zero, the new polynomial function oscillates rapidly between the sample points which represents nonphysical behavior and significantly degrades the robustness of the inversion algorithm. A lower degree fit produces less accurate function representation with errors accumulating rapidly with each subsequent dimension. To address both of these problems, the method developed in the work greatly increases the quality of the closed form models and the robustness of the inversion algorithm, as follows. The initial simulated data matrix is broken up into sections (e.g., cubes for the 3D case) with a subset of total points along each dimension (typically 4 points). Then, 3rd order polynomials are fitted along each dimension to produce an analytical model for the data segment. The 3rd order polynomials are fitted with high accuracy and generally produce non-zero 2nd order partial derivatives, which are used in the conjugate gradient based inversion algorithm. If a unique solution for the problem exists, it must be contained in one of the data segments. The problem is solved for each individual data segment and the best solution is then picked out based on the magnitude of an appropriately defined cost function. The inversion algorithm used in this work is a local optimizer so the convergence to the global minimum is not guaranteed [3]. Breaking up the problem as explained above increases the chances of finding a global minimum since the algorithm can only get trapped in the local minimum and not converge to a global minimum if both are present within one data chunk; the probability of this event is very small compared to the case where the search is over the entire data domain.

3. Results and Conclusions:

The algorithm described in this work is an efficient and robust method for retrieving parameters of interest from radar cross section measurements. Once the initial simulation over multiple parameters is complete and closed formed expressions are obtained, all subsequent operations such as 2nd order partial derivatives are analytical and therefore are very efficient and do not accumulate errors. The algorithm has been extensively validated using simulated data for a wide variety of layered medium parameters. The effect of noise has also been analyzed through simulations. With the expected availability of radar instruments – tower- or aircraft-based - operating simultaneously (or in tandem) at multiple frequencies, this technique provides an effective tool for high-accuracy and robust retrievals for a variety of applications.

References:

[1] Moghaddam, M., Y. Rahmat-Samii, E. Rodriguez, D. Entekhabi, D. Moller, J. Hoffman, L. Pierce, “Microwave Observatory of Subcanopy and Subsurface (MOSS): A mission concept for global deep and subcanopy soil moisture observations,” IEEE Trans. Geosci. Remote Sensing, vol. 45, no. 8, pp. 2630-2644, August 2007.

[2] Goykhman, Y., and Moghaddam, M., “An efficient forward scattering model for a three layer medium representing bodies of fresh water”, Proc. IEEE-URSI, July 2008, San Diego, US.

[3] Goykhman, Y., and Moghaddam, M., “Retreival of subsurface parameters for three-layer media”, Proc. IEEE-IGARSS09, July 2009.

[4] C. h. Kuo and M. Moghaddam, "Electromagnetic Scattering From Multilayer Rough Surfaces With Arbitrary Dielectric Profiles for Remote Sensing of Subsurface Soil Moisture," IEEE Transactions on Geoscience and Remote Sensing, vol. 45, pp. 349-366, 2007