HIGH RESOLUTION SUBSURFACE IMAGING OF DEEP TARGETS BASED ON DISTRIBUTED SENSOR NETWORKS

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ABSTRACT

A realistic forward model based on a near-ground distributed sensor grid for a target buried under soil is devised. The soil medium is modeled as a planar stratified medium with a complex dielectric constant profile. The Dyadic Green's function for multilayer dielectric is used to compute the electric field at the target. A high resolution inversion algorithm based on phase-conjugation approach to detect deeply submerged targets is also presented. The sensor network is setup to enhance the lateral resolution by forming a synthetic aperture. The depth resolution is improved by using bandwidth. So as to improve the efficiency of the search algorithm a soil dielectric model to predict the real and imaginary parts of the dielectric constant from the volumetric soil moisture for a given soil textural composition is extended to the frequency of interest (VHF) resulting in less number of variables.

Index Terms—Subsurface imaging, Distributed sensor networks, UXO detection

I. INTRODUCTION

Interest in distributed sensor networks for subsurface sensing has justifiably increased in recent years due to the growing need for high resolution detection and imaging techniques for various applications. Such Sensor networks can be useful in many areas including the military, homeland security and civilian applications. Detections of buried pipelines, wires and cables are examples of civilian applications. Military and Homeland security applications include the detection of Unexploded Ordnance (UXO), tunnels and underground facilities. Imaging based on distributed sensor networks could also be utilized for biomedical applications such as detection of cancer. A significant amount of work has been devoted towards development of hardware and signal processing for mono-static and bi-static radar systems for subsurface detection. Tegan et al have developed a Multi-static ground penetrating radar system using beamforming [1]. Several other researchers have focused on developing various inversion algorithms and carried out experiments for multi-static systems [2-6]. Research related to the development of a 3-D high-resolution technique for deep subsurface imaging using distributed sensor networks is little. In this work, a realistic forward model based on a distributed sensor network for a target buried under a multilayer soil with lossy dielectric profile is devised. Simulation results of an inversion technique with high transverse and depth resolution for 3-D detection of deep targets (in the range of several meters) and retrieval of the dielectric profile of the region under investigation are also presented. To make the inversion algorithm more efficient, a semi-empirical model to predict the real and imaginary parts of the dielectric constant based on volumetric soil moisture content and soil type is developed for the frequency of interest (VHF range). This soil dielectric model which is based on the work of Ulaby et al [7] reduces the number of unknowns in the inversion making the inversion more efficient.

II. FORWARD MODEL

Dielectric or metallic targets such as a UXO are typically found buried under soil surface at various depths, and the goal is to be able to image these targets, with high lateral and depth resolution. In this work, the ground is modeled by a stratified media composed of several thin layers where each layer has constant electromagnetic properties resulting in a staircase approximation of the complex dielectric profile of the soil medium. The region under investigation is first illuminated with the electric field from the transmitter and we want to somehow use the backscattered field to image any possible inhomogeneity (other than the stratified media representing the background). Having a realistic forward model that accurately captures the change in phase and magnitude of the electric field radiated by the transmitting antenna until it is received by each sensor is an essential step in order to test the subsurface imaging algorithm.

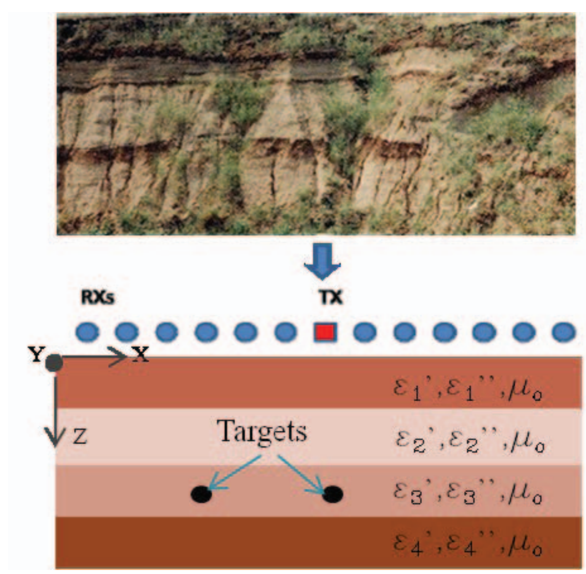


Fig. 1: Forward model (Cross-Sectional View)

Several receivers are setup at strategic locations (more about this later) above ground and the signals received at each sensor is used to image the region. By putting these sensors at various points around the transmitter, a synthetic aperture related to the overall length of the sensor setup is formed resulting in an improved lateral resolution. Given the dielectric profile of the layered medium, locations of targets and thicknesses of each layer, the electric field received by the various antennae needs to be calculated accurately. A first order approximation to estimate the received field at each sensor is based on Geometrical optics by making use of the Fresnel transmission coefficients, phase delays and losses for each layer. The electric field at a receiver is given in equation (1).

$$E_{rn} = E_t T_{01}^2 T_{12}^2 T_{23}^2 L e^{-j\{k_o(r_{on}^t + r_{on}^r) + k_1(r_{1n}^t + r_{1n}^r) + \cdots + k_3(r_{3n}^t + r_{3n}^r)\}} \quad [1]$$

$$L = e^{-\{\alpha_1(r_{1n}^t + r_{1n}^r) + \alpha_2(r_{2n}^t + r_{2n}^r) + \alpha_3(r_{3n}^t + r_{3n}^r)\}} \quad [2]$$

Where, T_{qp} and k_m are the Fresnel transmission coefficient from layer q to p and the wave number of layer m respectively. α_m is the loss factor; r_{mn}^t and r_{mn}^r are the distances the wave travels in each layer from the transmitter to the target and back to the receiver.

A more accurate method to calculate the electric field at the location of the target is to use the Dyadic Green's function in the presence of multiple dielectric layers. The Dyadic Green's function is integrated with the transmitting antenna current distribution (J_e) to get the electric field as shown in equation 3. This method is more realistic as it takes into account all the multiple reflections among the layers. Both models are used to verify the inversion technique.

$$E_{target} = jk\eta \iiint J_e(r')\bar{\bar{G}}_{0n}(r, r')dr' \quad [3]$$

III. INVERSION TECHNIQUE

In the inversion, the goal is to detect objects deeply submerged under soil (several meters) with the best possible resolution which also requires estimation of soil dielectric profile. An iterative approach was used to achieve this. First, we make a best guess for the dielectric constant of soil assuming constant soil moisture content for each layer, then the geometric optics approach in conjunction with back propagation algorithm is used to create a 3-D image of the subsurface domain. If there are buried targets, these targets are imaged with poor resolution. Then the image is sharpened by searching for the correct soil dielectric profile. This is done in two ways,: 1) by maximizing the power from a pixel within a target region, and 2) by considering moving resolution boxes around the detected targets and trying to fit the response to the ideal point spread function of the system. The objective function is given below.

$$O(xi, yi, zi) = \sum_{fl}^{fu} \sum_{r1}^{rn} E_{rn}(f) * e^{j*k(f,mv)*r(xi,yi,zi)} \quad [4]$$

E_{rn} is the electric field received by the nth receiver as a function of frequency and the wave number (k) is given as a function of soil moisture content and frequency. Pulse spread function (PSF) comparison methods are given below. I and I_o are the calculated and ideal PSFs respectively.

a) $\mathrm{Max}|O(xi, yi, zi)|$
b) $Min|\sum_n I(xi, yi, zi) - \sum_n I_o(xi, yi, zi)|$

To minimize the search time, the real and imaginary parts of the dielectric constant are related by a single variable, namely, the soil moisture content though a semi-empirical model. The model discussed is extended to the VHF range and compared with actual measurements taken as given in [7,8]. The equation describing the complex dielectric constant is given in equation 4.

$$\varepsilon_{soil}^{\alpha} = 1 + (1 - V_\phi)(\epsilon_{ss}^{\alpha} - 1) + m_v^{\beta}(\epsilon_{fw}^{\alpha} - 1) \quad [5]$$

Where, V_ϕ is the soil porosity and the quantities α and β are empirically found as discussed in [7]. m_v and ε_{fw} are the volumetric moisture content of soil and dielectric constant of water as a function of frequency respectively. Comparison of the dielectric constant model with measured data for the desired frequency is given in Figure 3.

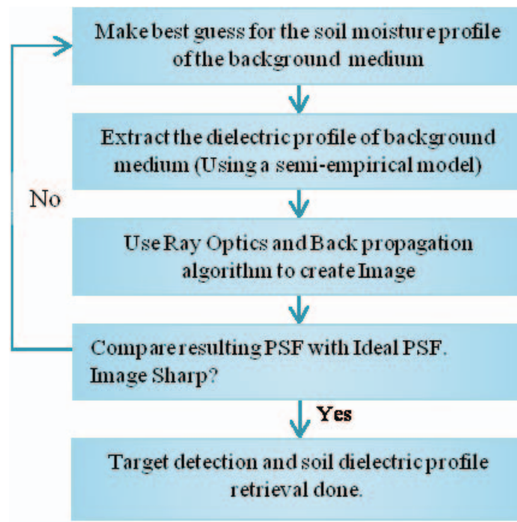


Fig. 2: Inversion algorithm flowchart

As it was alluded to in the previous section, the lateral resolution depends on the synthetic aperture which is implemented by the inner sum in the objective function (equation 4) where the contribution from each antenna element is added to form each pixel. To improve the depth resolution, bandwidth is used. The transverse and depth resolutions are discussed in the next section.

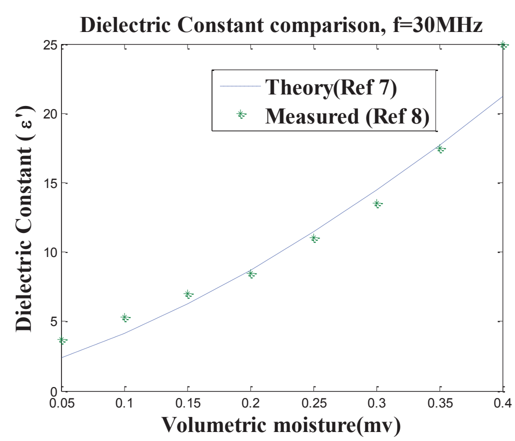
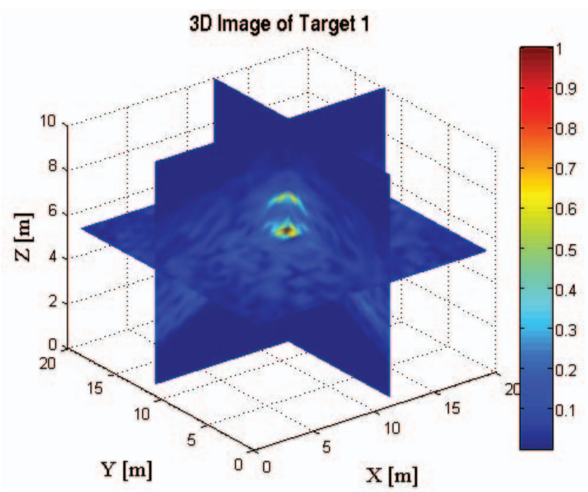


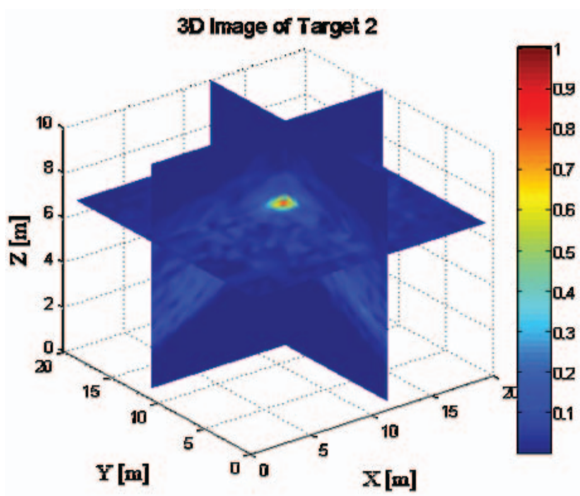
Fig. 3: Comparison of the real part of dielectric Constant and volumetric soil moisture content

IV. SIMULATION RESULTS

The proposed imaging technique was implemented and tested using the raw data generated based on the forward model presented in Section I. As can be seen in Figure 4, the images of two targets buried at two different depths are reconstructed with high resolution. Comparison of the transverse resolution for various sensor setups (rectangular grid of N sensors) is given in Figure 5a. Since the synthetic aperture increases with the length of the sensor setup, the transverse resolution greatly improves with the number of receiving antennae. The depth resolution, which is strongly dependent on Bandwidth, is given in Figure 4b. Simulation results are also given for targets located on the same transverse plane close to each other in Figure 6.



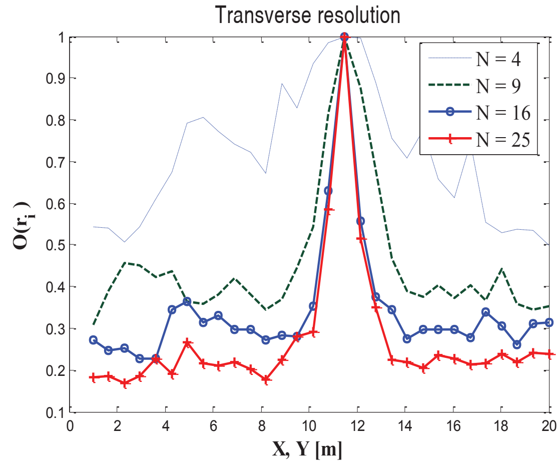
(a)



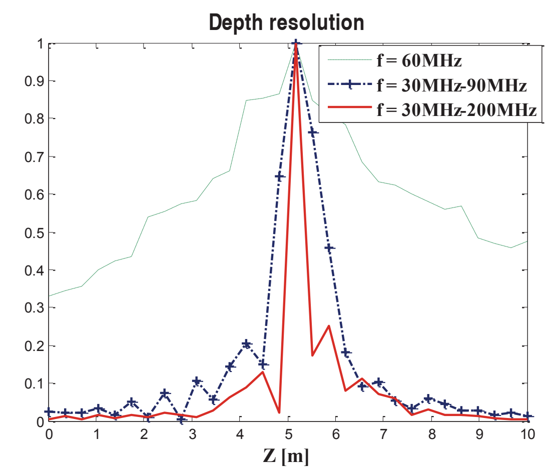
(b)

Fig. 4: 3D view of a reconstructed image of two targets buried under a 5 layer soil medium with dielectric profile given in Fig 5a . The positions of the two targets are (11.48m, 11.48m, 5.18m) and (11.48m, 11.48m, 6.56m) shown in (a) and (b) respectively.

There are two important aspects of this project that call for further investigation. First, the distribution and polarization of the receivers need to be optimized with two objectives, 1) minimizing the signal directly coupled from transmitter to receivers and 2) achieving the best possible resolution. Also, for Unattended Ground Sensors (UGS) type applications, the proximity of the sensor network to ground will dramatically change the characteristics of the antennae [9]. To include such effects, experiments will be carried out and results will be used for sensor network optimization.



(a)

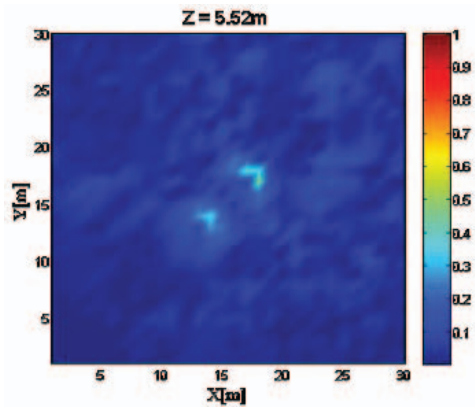


(b)

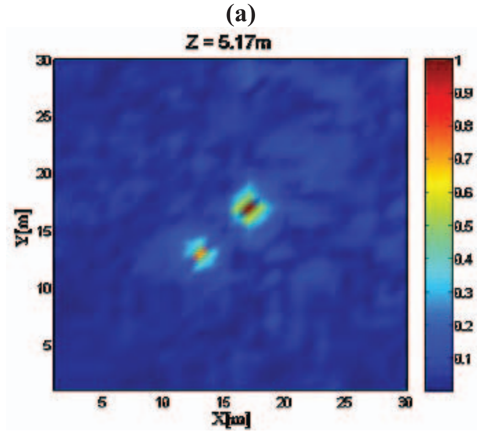
Fig. 5: Transverse and depth resolution, Bandwidth used for the transverse resolution is 30-200MHz with a 1MHz frequency step.

V. CONCLUSION

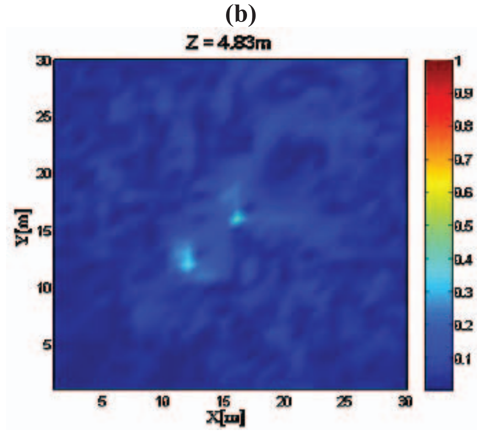
A subsurface imaging technique based on a near-ground distributed sensor network to detect targets such as UXO that are submerged underground is discussed. In the forward model, a multi-layer soil background medium consisting of several thin layers with varying electromagnetic properties and possible targets buried in any of the layers is assumed to generate raw data. In order to calculate the received field at each sensor, a method based on Geometrical optics and another more realistic approach using the Dyadic Green's function are implemented. For the inversion, an iterative approach is pursued. The distributed sensor network is setup to enhance the lateral resolution; and bandwidth is used to improve the depth resolution. Simulation results, discussed in the previous section, showed high lateral and depth resolution as expected. Currently, we are investigating the optimization of the sensor network to reduce the directly coupled signal while achieving the best possible lateral resolution.



(a)



(b)



(c)

Fig. 6: The reconstructed image of two targets buried in a 5 layer soil medium with a complex dielectric profile (Fig. 7). The location of the targets are (11.48m,11.48m,5.17m) and (8.86m,8.86m,5.17m) in the raw data(Geometry shown in figure 1).

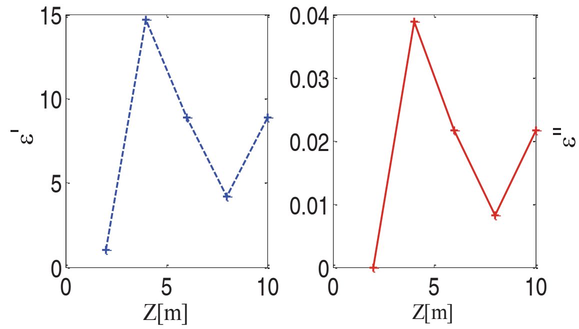


Fig. 7: Dielectric profile of the soil background medium used for the raw data (soil mixture: sand and silt, soil moisture: up to 30%)

VI. REFERENCES

[1] Tegan Counts,Ali Cafer Gurbuz, Waymond R. Scott, Jr, James H McClellan and Kandwook Kim, "Multistatic Ground Penetrating Radar Experiments," *IEEE Trans. Geosci. Remote Sensing,* vol.45, no. 8, August 2007

[2] Reza Firoozabadi, Eric L. Miller, Carey M. Rappaport, and Ann W. Morgenthaler , "Subsurface Sensing of Buried Objects Under a Randomly Rough Surface Using Scattered Electromagnetic Field Data," *IEEE Transactions On Geosci. Remote Sensing, Vol. 45, No. 1, January 2007*

[3] Joaquim Fortuny-Guasch, "A Novel 3-D Subsurface Radar Imaging Technique," IEEE Trans. on Geoscience and Remote Sensing, vol. 40, No. 2, February 2002

[4] Russell D. Brown, David D. Mokry, James M. VanDamme, Michael C. Wicks, "Experimental HF radar for subsurface sensing," *7th International Conference on Ground-Penetrating Radar*, May, 1998

[5] Serguei Y. Semenov, Alexander E. Bulyshev, Aria Abubakar,Vitaliy G. Posukh, Yuri E. Sizov, Alexander E. Souvorov, Peter M. van den Berg, and Thomas C. Williams, "Microwave-Tomographic Imaging of the High Dielectric-Contrast Objects Using Different Image-Reconstruction Approaches," *IEEE Trans. on Microwave theory And techniques*, Vol. 53, No. 7, July 2005

[6] Lawrence Carin, Jeffrey Sichina, and James F. Harvey, "Microwave Underground Propagation and Detection," *IEEE Trans. Microwave theory and techniques,* Vol. 50, No. 3, March 2002

[7] Fawwaz T. Ulaby, Richard K. Moore, and Adrian K. Fung, "Microwave remote sensing-Active and passive," Feb,1982

[8] Darold Wobschall, "A Theory of the Complex Dielectric Permittivity of Soil Containing Water: The Semidisperse Model," *IEEE Transactions On Geoscience Electronics,* January 1977

[9] DaHan Liao, Kamal Sarabandi, "*Terminal-to-*Terminal hybrid hull-wave simulation of low-profile, electrically-small , near-ground antennas,*"* IEEE Trans. on antennas and propagation, March 2008