A 3D SUBSURFACE IMAGING TECHNIQUE BASED ON DISTRIBUTED NEAR-GROUND SENSORS: INVESTIGATION USING SCALE MODEL MEASUREMENTS

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ABSTRACT

A high resolution subsurface imaging approach based on near-ground sensor networks operating in the VHF range that utilize ultra-wideband near-field focusing was recently proposed [1]. An accurate scattering model for targets buried in realistic subsurface environment modeled as a vertically stratified medium as well as an efficient inversion technique using an UWB near-field focusing were proposed. Numerical models were used to analyze the signal penetration depth in the VHF range and validate the proposed technique for targets that are buried at various depths [2]. In this paper, in order to investigate the performance of the proposed approach under practical limitations, laboratory-based scale model measurement results are utilized. In addition, various non-uniform sensor arrangements are tested to get an insight into how to best arrange a given number of sensors to cover the largest possible area and obtain the best possible lateral resolution.

Index Terms— Subsurface imaging, distributed sensor networks

1. INTRODUCTION

While we can image planets, stars and galaxies, creating high resolution images even a few meters into the earth has proven to be very difficult. High resolution subsurface detection and imaging techniques are sought for various applications in civilian, military and homeland security areas. Military and Homeland security applications include the detection of landmines, Unexploded Ordnance (UXO), perimeter-breaching tunnels and weapons facilities. The detection of buried pipelines, wires and cables, and rescue missions under collapsed buildings are examples of civilian applications.

Fig. 1 Antennas mounted on robotic rovers or flyers to collect data and transmit it to a central location for subsurface imaging and detection applications

In many scenarios, the depth of the various targets that need to be imaged could vary from a few centimeters for shallow targets to several meters for those that are deeply-submerged. If we take the case of hazardous ordnance, while landmines are usually placed at shallow depths (on ground or a few centimeters below the surface), UXO can be found at depths from near surface up to 7-8 m [3]. Although, there has been encouraging developments especially in imaging shallow targets, there are various issues related to achieving better resolution and penetration depth. One of the limitations of current radar based subsurface imaging techniques is caused by the inhomogeneity of the host medium (e.g. due to varying soil type and moisture content) which cause signals to experience significant attenuation and scattering (especially at high frequencies) making the detection of deeply-submerged targets very challenging.

A significant amount of work has been devoted towards development of various techniques to image targets and underground structures. These include active sensor systems such as GPR and passive sensors such as magnetometers. Other techniques include electro-optical infrared sensors and electromagnetic induction (EMI). Another challenge that has yet to be addressed is efficient subsurface mapping of large areas for the purpose of detection and remediation of landmines and UXO.

2. BACKGROUND WORK

A high resolution imaging approach based on near-ground sensor networks operating in the VHF range that utilizes ultra-wideband near-field focusing was recently proposed [1]. Imaging systems based on distributed sensor networks seem to be an attractive choice for applications such as efficient detection and remediation of UXO. The distributed sensors are envisioned as a network of antennas mounted on autonomous rovers, flyers, or Unattended Ground Sensors (UGS) which will collect data and transmit it to a central location as illustrated in Fig. 1. The data is then combined in post-processing resulting in large synthetic apertures which will greatly improve the lateral resolution when the subsurface image is formed. A realistic forward model based on vertically stratified medium and an efficient frequency-domain inversion algorithm which is similar to the phase-conjugation approach in time-domain are proposed. Simulation results based on row data created using MATLAB and FDTD based full-wave solver were used for validation. Some the challenges that are the current focus of this research include the efficient arrangement of the sensors (relative position and polarization) to achieve the best possible resolution while covering the largest possible area and minimizing the coupling among the Tx and Rx antennas. Here, measurement results based on scale model experiment performed in the laboratory are used to experimentally validate the technique as well as investigate various sensor arrangements.

The main focus of this paper is to utilize experimental results to investigate the possibility of using fewer receiving points while achieving resolution that is comparable to the uniform receiving point grid. For this analysis, various receiver arrangements will be investigated both in terms of relative position and polarization. A uniform grid of receiver antenna distributions as well as non-uniform arrangements will be tested and the resulting depth and lateral resolution compared. Since the Tx and Rx antennas are in close proximity to the ground (< λ above ground), the relative orientation (polarizations) of the antennas have to be wisely chosen. For example, in near-ground scenarios, the direct signal is minimized when both Tx and Rx are horizontally polarized. Experimental analysis of the penetration depth for various soil types and moisture content will also be performed.

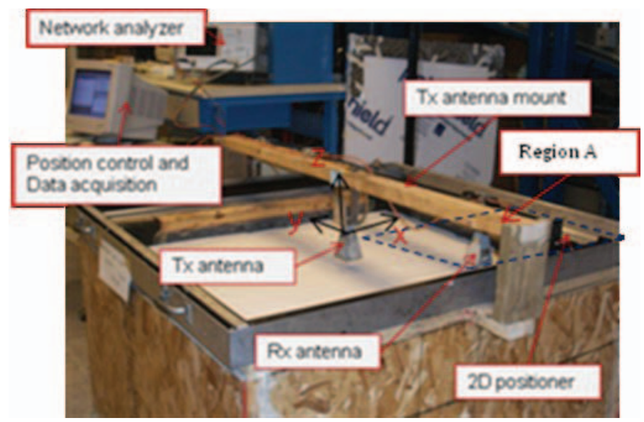

Fig. 2 The laboratory scale model setup. Here, the Rx antenna is moved in the X-Y plane while the Tx antenna is kept stationary. Targets are buried at various depth in the sand.

3. SCALE MODEL MEASUREMENT SETUP

As it was alluded to in the previous section, the proposed imaging approach was validated by utilizing raw data created using MATLAB and a FDTD based full-wave solver. Here, we utilize laboratory measurements to investigate the performance of the proposed technique in the presence of practical limitations. Although, the proposed imaging method is intended to operate in the VHF range, we perform a scale model measurement using a network analyzer based radar operating in the X- band. The setup as can be seen in Fig. 2 consists of a sand box, two dual-polarized quadruple-ridged horn antennas, 2D Positioner to move the Rx antenna, metallic targets buried in the sand, a network analyzer and a PC. The size of the box is made large in terms of wavelength (40λ by 40λ by 20λ) to minimize the effects of unwanted scatterers outside of the region of interest. Analysis of the lateral and depth resolution for various sensor setups and frequency selection will be discussed.

4. INVESTIGATION OF LATERAL RESOLUTION FOR VARIOUS ANTENNA ARRANGEMENTS

Given N number of near-ground sensors (within one wavelength above ground) and the choice of polarization for each sensor, what is the "best" arrangement in terms of relative spacing and polarization? The criteria for this analysis is to meet the following:

1) Get the best possible lateral resolution,
2) Minimize the direct coupling among the Tx and Rx antennas,
3) Maximize the region to be imaged using the given number of receiving points

It's worth looking at the propagation characteristics of near-ground antennas as it will prove helpful to meet the second criteria discussed above. When the Tx and Rx antennas are in close proximity to the ground (near-grazing incidence angle), the received field, in addition to the geometrical optics components, will consist of higher order terms such as Norton waves. In the case of VV polarization, these higher order components become dominant. An extensive study of near-ground antennas and the pros and cons of using the various polarization combinations has been investigated [4].

Tx	Rx	Comment
H	H	Direct signal not as dominant as VV case because of near-ground effects
H,V	V,H	Minimizes the direct signal, imaging is target dependent
V	V	Direct signal dominates because of Norton surface waves

Table 1: The near-ground characteristic of various polarization combinations based on the analysis in [4].

As can be seen in the table above, for near-ground antennas, VV polarization results in the highest coupling between the Tx and Rx antennas. The HH polarization is less susceptible to directly coupled signal. In addition, in the cases where the Tx and Rx antennas are parallel to the ground, the relative orientation becomes important. As can be seen in Fig. 3, for near-ground antennas, it's found that the coupling between Tx and Rx1 is stronger than that of Rx2 (for the same Tx-Rx separation) for the setup shown below.

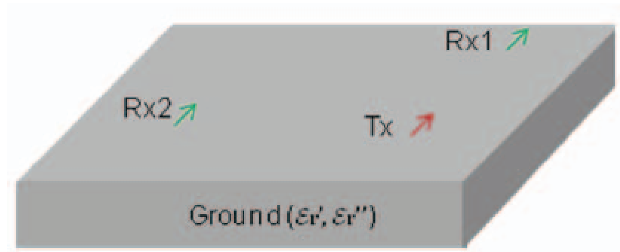

Fig. 3 Possible setup of horizontally oriented Tx and Rx antennas

Based on the above discussion, the HH polarization was chosen for our scale model experiment. We now focus on the distribution of the antennas in terms of relative spacing and overall extent.

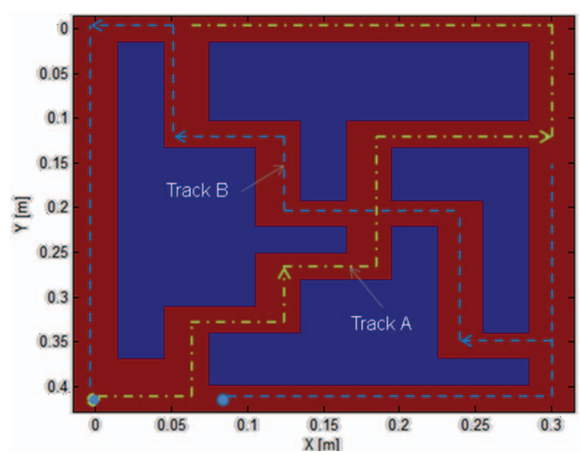

Fig. 4 A non-uniform receiving point setup (top view of the sand box), this could represent the route two rovers follow and take measurements (Tracks A and B for the path of the two rovers).

As it was discussed in Section I, in order to efficiently image large areas for applications such as detection of UXO, finding ways of reducing the number of receiving points required to achieve a certain resolution is vital. We tested different sensor receiving point arrangements for this analysis. Shown in Fig. 4 are two possible routes that rovers could follow while acquiring data. We used the measured data from our scale model measurement to compare a uniform receiving point grid to the one shown in Fig. 4.

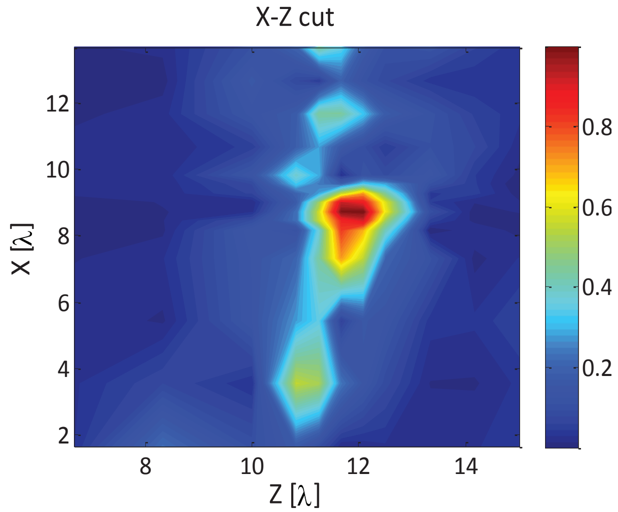

Fig. 5 A slice of the reconstructed image created based on scale model measurement results.

The results shown Fig.5 and Fig. 6 are based on the set of data acquired where a metallic sphere with 3cm diameter was buried 35cm below the top surface of the sand. In this case dry sand having a dielectric constant of $\varepsilon_r' = 2.72$ and $\varepsilon_r'' = 0.0065$. The dielectric constant was measured in the laboratory based on the Cavity resonator method. It should be noted that in the proposed inversion algorithm, the dielectric constants are not assumed to be known.

As can be seen in the X-Z slice of the reconstructed image shows the buried metallic sphere at the correct position. Both the depth and lateral resolution, as can be seen in Fig. 6, are good. For this particular set of results, measured received field data from only a quarter of the sand region was utilized (Region A in Fig. 2). This is why the resolution in the X-direction can easily be improved if measurement results from the other regions are used because of the increased aperture.

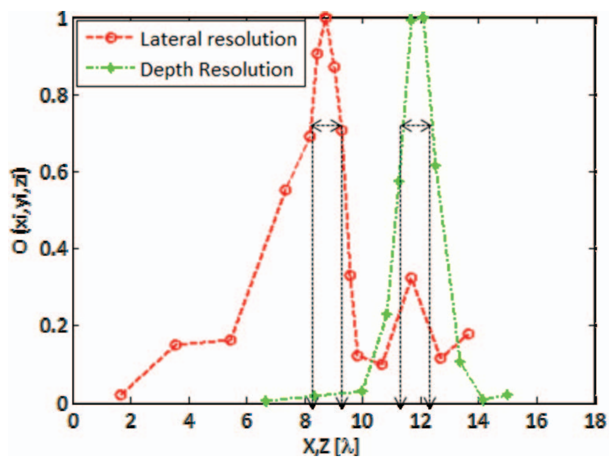

Fig. 6 The lateral and depth resolution based on the scale model measurement data. The sensor setup used for this is the combination of Track A and B as shown in Fig. 3

5. CONCLUSION

In this paper, the performance of a subsurface imaging approach based on distributed near-ground sensors proposed in [1] is investigated under practical limitations. A laboratory-based scale model experiment using a network-analyzer based radar system is utilized. In addition, various non-uniform sensor arrangements are tested to get an insight into how to best arrange a given number of sensors to cover the largest possible area and obtain the best possible lateral resolution.

11. REFERENCES

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