IMPACT OF THE WAVE NUMBER ESTIMATION IN UNDERGROUND FOCUSING SAR IMAGES

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1. ABSTRACT

This work studies the impact estimating soil wave number in Underground Focusing SAR imaging for tunnel detection applications. It is demonstrated that poor underground imaging results when wave refraction at the ground surface is neglected, but that incorporating refraction with sufficiently high estimates of soil dielectric constant produce clear target images. Using a wrong wave number for the soil incorrectly predicts the tunnel's depth, but gives positive identification of its transverse and extent.

1.1. Keywords

Underground Focusing Spotlight Synthetic Aperture Radar (UF-SL-SAR), Synthetic Aperture Radar (SAR), Rough Surfaces, Signal Processing, Tunnel detection.

2. INTRODUCTION

The Underground Focusing Spotlight Synthetic-Aperture-Radar [1] (UF-SL-SAR) configuration has been recently proposed for tunnel detection applications [2,3]. This sensing method is based on a radar mounted on a plane (or multiple radars mounted on multiple planes) that moves over a region of ground with a suspected tunnel. The radar transmits electromagnetic waves at multiple frequencies, which are scattered by the ground and the tunnel. The recorded scattered field is coherently combined for multiple frequencies and positions in order to synthesize an underground spatially localized spot. This underground focusing procedure requires a good approximation of the ground's constitutive parameters. This work studies the impact of uncertainty in the soil's constitutive parameters on UF-SL-SAR images.

3. UNDERGROUND FOCUSING SPOTLIGHT SYNTHETIC APERTURE RADAR CONFIGURATION

Fig. 1 presents an schematic of the UF-SL-SAR configuration [2, 3]. The parameters of the problem are the same as the ones described in Table 1 in [2].

In a Multiple Simultaneous Bistatic (MSB) configuration, the only phase imaging function at the underground point $\mathbf{r}_u^s$ (where $s = 1..N_s$) can be written as:

$$I(\mathbf{r}_u^s) = \sum_{l,n,p} \mathbf{E}(f^l, \mathbf{r}_t^n, \mathbf{r}_r^p) e^{j\Phi(f^l, \mathbf{r}_t^n, \mathbf{r}_r^p, \mathbf{r}_u^s)} \tag{1}$$

This work is supported by CenSSIS, the Gordon Center for Subsurface Sensing and Imaging Systems NSF ERC Program (Award number EEC-9986821)

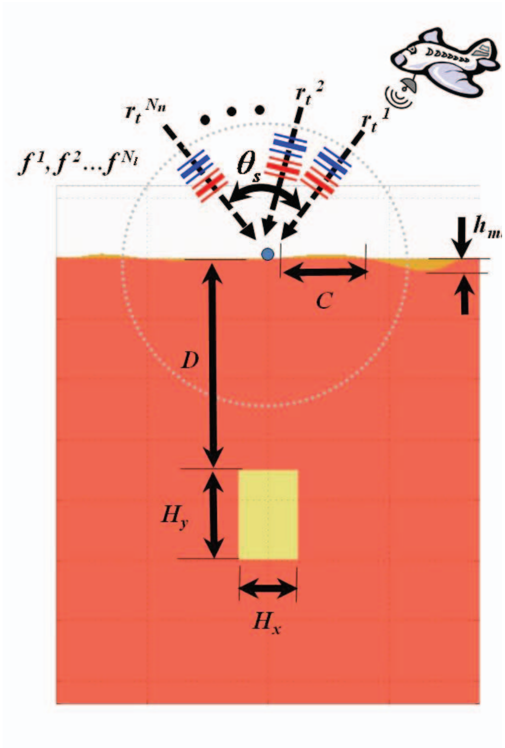

Fig. 1. Spotlight Synthetic Aperture Radar configuration: tunnel configuration, schematic of a multiple aspect angles, and schematic of a multiple frequencies per aspect angle.

where $\mathbf{E}(f^l, \mathbf{r}_t^n, \mathbf{r}_r^p)$ is the scattered field measured at the p-th receiving antenna, which is located at $\mathbf{r}_r^p$ (where $p = 1..N_p$), when the n-th transmitting antenna, which is located at $\mathbf{r}_t^n$ (where $n = 1..N_n$), is radiating with the l-th frequency f^l (where $l = 1..N_l$). The term $\Phi(f^l, \mathbf{r}_t^n, \mathbf{r}_r^p, \mathbf{r}_u^s)$ is the phase shift associated with a wave propagating from the transmitting antenna $\mathbf{r}_t^n$ to the receiving antenna $\mathbf{r}_r^p$, when the focusing is performed at $\mathbf{r}_u^s$. Underground focusing requires the refraction points $\mathbf{r}_{x1}$ and $\mathbf{r}_{x2}$ at the ground surface interface. Once the refraction points are derived, the wave vectors: $\mathbf{k}_{01} = k_0^l(\mathbf{r}_{x1} - \mathbf{r}_t^n)/|\mathbf{r}_{x1} - \mathbf{r}_t^n|$, $\mathbf{k}_{g1} = \Re(k_g^l)(\mathbf{r}_u^s - \mathbf{r}_{x1})/|\mathbf{r}_u^s - \mathbf{r}_{x1}|$, $\mathbf{k}_{g2} = \Re(k_g^l)(\mathbf{r}_{x2} - \mathbf{r}_u^s)/|\mathbf{r}_{x2} - \mathbf{r}_u^s|$ and $\mathbf{k}_{02} = k_0^l(\mathbf{r}_r^p - \mathbf{r}_{x2})/|\mathbf{r}_r^p - \mathbf{r}_{x2}|$, can be computed and the phase term in equation (1) can be written as:

$$\Phi_B^{UF}(f^l, \mathbf{r}_t^n, \mathbf{r}_r^p, \mathbf{r}_u^s) = \phi_1 + \phi_2 + \phi_3 + \phi_4 \tag{2}$$
$$\phi_1 = \mathbf{k}_{01} \cdot (\mathbf{r}_{x1} - \mathbf{r}_t^n),\ \phi_2 = \mathbf{k}_{g1} \cdot (\mathbf{r}_u^s - \mathbf{r}_{x1})$$
$$\phi_3 = \mathbf{k}_{g2} \cdot (\mathbf{r}_{x2} - \mathbf{r}_u^s),\ \phi_4 = \mathbf{k}_{02} \cdot (\mathbf{r}_r^p - \mathbf{r}_{x2})$$

The wave number in air $k_0^l = 2\pi f^l \sqrt{\mu_0 \epsilon_0}$ and in the soil $k_g^l = 2\pi f^l \sqrt{\mu_0 \epsilon \prime \epsilon_0}$ (where μ_0 and ϵ_0 is the permittivity and permeability on the air, and $\epsilon \prime$ is the relative complex permittivity of the ground) are required to perform the imaging. The main problem encountered when performing the latter procedure is that the complex permittivity on the ground is generally unknown, and a guess of such quantity is needed to reconstruct an image of the subsurface.

4. NUMERICAL EXAMPLE: IMPACT OF FOCUSING WITH DIFFERENT WAVE NUMBERS

The Finite Difference Frequency Domain (FDFD) method is used to numerically generate scattered field from a soil half space with a rough ground surface [4,5]. The ground is assumed to be very dry clay soil characterized by complex dielectric permittivity of $\epsilon = \epsilon_0(8 - j0.01)$. Although this is unusually high for most dry soils, it provides a challenging scattering geometry for reconstruction. Similar test and results have been found for easier case of dry sand with $\epsilon = \epsilon_0(2.55 - j0.01)$.

For reconstruction, the estimated soil relative real dielectric constant was tested parametrically, varying from $\hat{\epsilon\prime} = 1$ to $\hat{\epsilon\prime} = 12$. Fig. 2 presents the UF-SL-SAR images obtained for five different representative cases. The top of the tunnel can be easily distinguished for every case except for those with $\hat{\epsilon\prime} < 4$. The primary imaging error using the wrong wave number is that the predicted depth of the tunnel is incorrect. If the complex dielectric permittivity used in the imaging is too small relative to the true permittivity, the tunnel image is poor (Fig. 2.a). However, even for the 50% underestimate of $\hat{\epsilon\prime} = 4$, the tunnel shows up well.

5. CONCLUSIONS

This work has addressed the impact of using different wave number estimates for soil in determining the refraction focusing to produce UF-SL-SAR images. It has been shown that using a sufficiently high but incorrect wave number can accurately predict the transverse tunnel position, but fails to correctly reconstruct the tunnel's depth. This study demonstrates that as long as the soil is not too lossy, tunnels can be successfully detected using refraction focusing without precisely knowing the actual wave number.

6. REFERENCES

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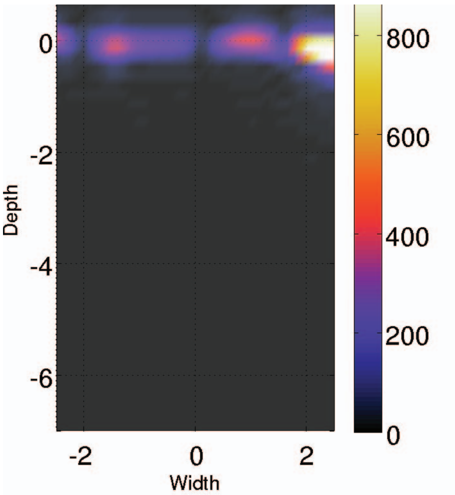
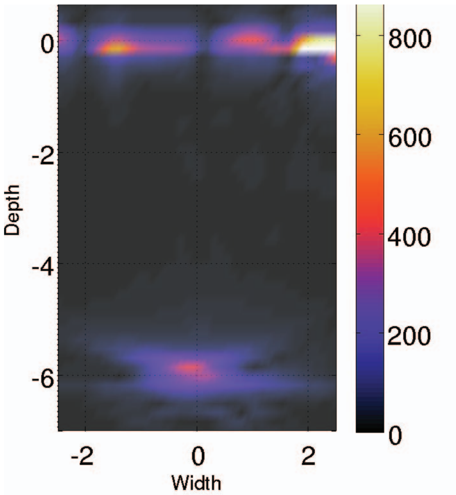
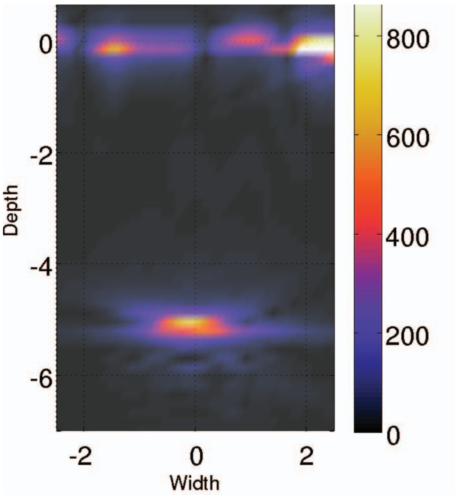


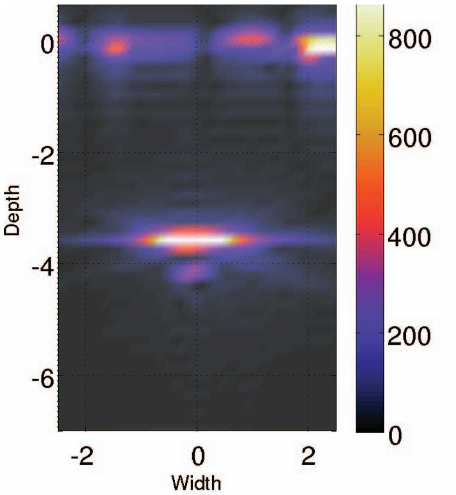
(a) $\hat{\epsilon\prime} = 1$



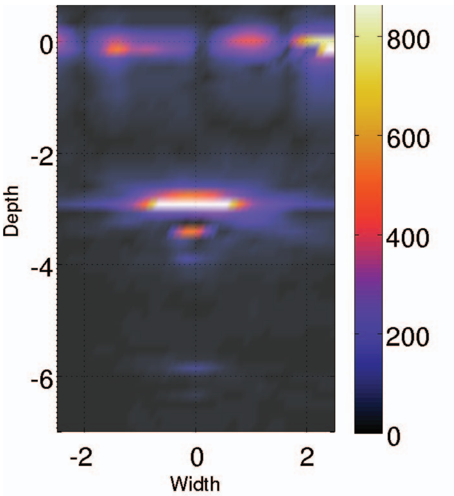
(b) $\hat{\epsilon\prime} = 3$



(c) $\hat{\epsilon\prime} = 4$



(d) $\hat{\epsilon\prime} = 8$



(e) $\hat{\epsilon\prime} = 12$

Fig. 2. UF-SL-SAR images for a soil half space with real relative permittivity $\epsilon\prime = 8$, with a 1.0 m wide by 1.5 m high tunnel with top at -3.5 m, and a rough ground surface with 0.1 m average height variation, when the imaging is performed with an estimated complex permittivity of: (a) $\hat{\epsilon\prime} = 1$, (b) $\hat{\epsilon\prime} = 3$, (c) $\hat{\epsilon\prime} = 4$, (d) $\hat{\epsilon\prime} = 8$, (e) $\hat{\epsilon\prime} = 12$.