

SOIL DIELECTRIC AND SENSITIVITY ANALYSIS FOR SUBSURFACE IMAGING APPLICATIONS BASED ON DISTRIBUTED SENSOR NETWORKS

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ABSTRACT

The concept of a subsurface imaging technique based on Unattended Ground Sensor Networks operating in the VHF range using ultra-wideband waveforms was recently proposed in [1]. In this approach a forward model for realistic subsurface environment based on the Dyadic Green's function for a stratified medium and an inversion technique using an ultra-wideband near-field focusing were presented. Simulation results showed that very good lateral and depth resolution could be achieved. Before carrying out an experiment to test the proposed technique, three vital aspects of the work which are imposed by practical limitations are investigated and presented in this paper. First, the sensitivity analysis to assess the signal penetration depth in realistic subsurface environments for various frequencies is performed. Analysis of the frequency requirements of the inversion as they relate to depth resolution is also analyzed. A semi-analytic soil dielectric model originally devised for microwave frequencies is extended to VHF and validated using measurement results available in literature.

Index Terms— VHF soil dielectric model, Signal penetration depth, Subsurface imaging

1. INTRODUCTION

Devising an efficient technique to image underground targets with high resolution is a challenging task and there are various issues that still need to be addressed despite the significant investment and technical progress in this area. Due to soil inhomogeneity and soil moisture content, electromagnetic signals experience significant attenuation (especially high frequency signals) and scattering in subsurface environment which make the solution for the forward model and imaging technique very challenging. A high resolution subsurface imaging technique can be very useful in many applications such as the detection and imaging of buried UXO, land mines, perimeter breaching tunnels, underground weapons facilities, wires and cables. Available methods such as ground penetrating radars (GPRs) do not provide adequate imaging resolution and/or

sufficient depth which renders them of limited use in the considered applications.

In [1], we proposed a subsurface imaging technique based Unattended Ground Sensor (UGS) networks operating in the VHF/UHF range and using ultra-wide band near-field focusing. The data that is collected by the UGSs positioned at strategic locations or near-ground antennas that are mounted on rovers is sent to a central location as depicted in Figure 1. Based on simulation results, we showed that our proposed technique can provide very good ground penetration and resolution by accurately estimating and correcting for the complex propagation phenomena in the ground such as soil inhomogeneity and moisture content.

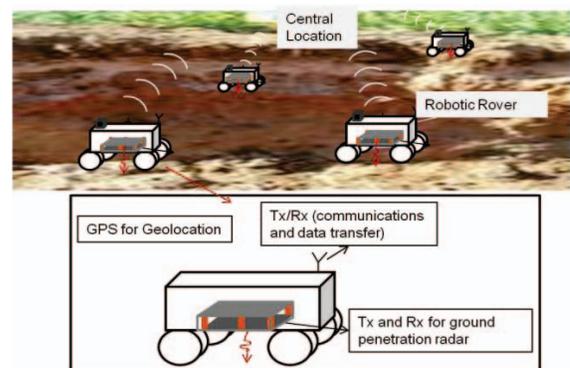


Fig. 1 Unattended ground sensor (UGS) networks collect data and transmit it to a central location for subsurface imaging and detection applications

In this work, we investigate three important aspects of the forward model and the proposed imaging technique. First, the sensitivity analysis in the frequency of interest (Lower UHF and VHF) is performed to assess the signal penetration depth for realistic soil textural compositions and soil moisture content. Since the proposed inversion technique utilizes ultra-wideband waveforms, it is vital to investigate parameters such as frequency range and number of frequency points as they relate to the depth resolution. This is especially important because using intelligent sampling can ease design requirements of bandwidth of the antennas for such low frequency applications. Simulation

results of the frequency requirement of the imaging technique are discussed. In both the scattering model and the inversion algorithm, the dielectric profile of the subsurface medium which depends on frequency, soil textural compositions and soil moisture is required. Complex dielectric constants for various types of soils calculated based on a semi-empirical model that was originally developed for microwave frequencies and extended to lower frequencies are validated with measured results available in the literature.

2. SENSITIVITY ANALYSIS

Before designing and carrying out an experiment to test the proposed imaging technique, it is vital to assess the signal penetration depth for realistic subsurface environments by calculating the signal amplitude a receiver would see for various frequencies. This analysis will be useful in selecting the best frequency range to be used for the subsurface imaging and detection of targets that are buried at different depths. Possible subsurface regions of interest can be divided into two categories; 1) regions where the soil type is homogeneous and the soil dielectric varies mainly due to variation in soil moisture and, 2) those where the soil is highly inhomogeneous consisting of multiple soil textural compositions with varying soil moisture.

	Sandy Loam	Loam	Silt Loam	Silty Clay
Sand (%)	51.51	41.96	17.16	5.02
Silt (%)	35.06	49.51	63.84	47.60
Clay (%)	13.43	8.53	19.00	47.38

Table 1. The textural compositions of various types of soils as given in [2]

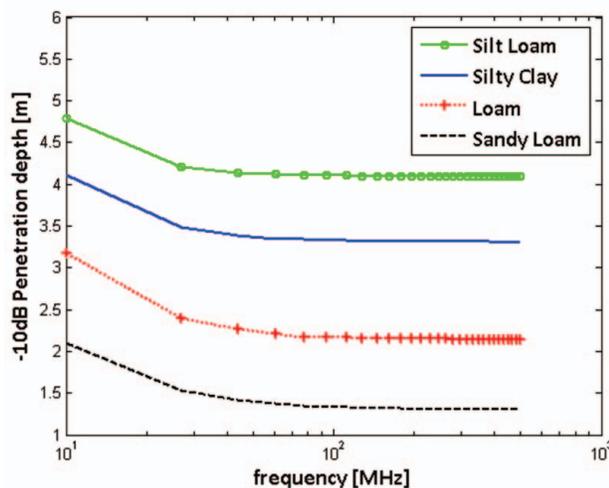


Fig.2. Cutoff point for various types of soil textural compositions as a function of frequency

We performed two sets of simulations to analyze these cases. In the first set, the subsurface region is modeled as a homogeneous half space. The soil textural composition (%)

of clay, silt and sand) was constant and soil moisture content is varied. The penetration depth computed from the depth at which the signal level reaches 10% of its value at the top interface (decay of -10dB) is calculated for the frequency of interest. As can be seen in Figure 2, the penetration depth for silt loam is much higher than that of loam indicating that the dependence on soil textural compositions of the signal loss can be significant.

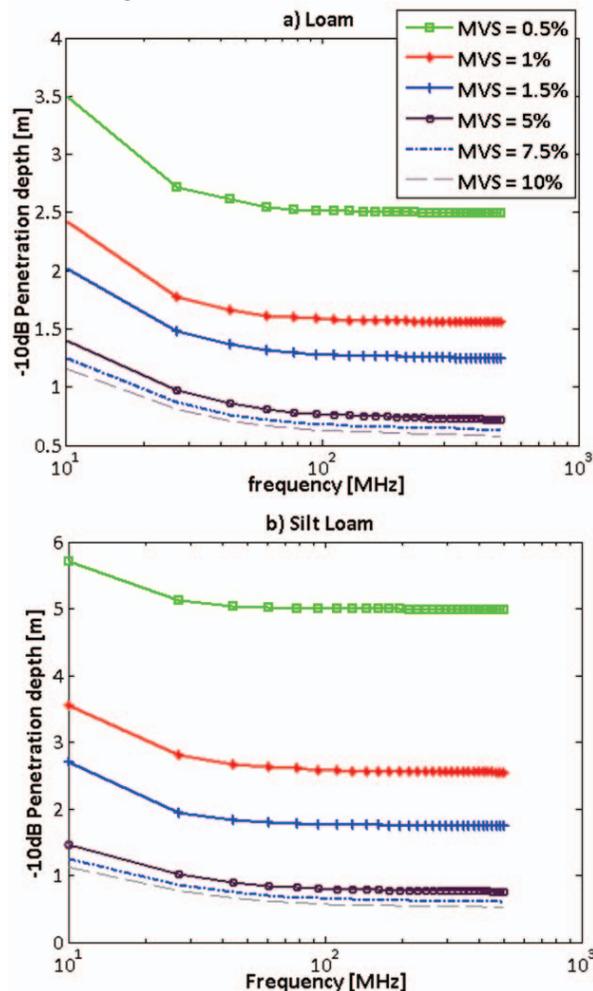


Fig.3. Cutoff point for loam (a) loam (b) silt loam with various soil moisture content as a function of frequency. The soil textural composition for the different soil types is given in table 1.

However, a more important factor in determining the penetration depth is the soil moisture. For lower soil moisture contents (less than 2%), the variation in the penetration depth with frequency is not as strong as the case with much higher moisture contents (higher than 5%). It's important to note that in relatively drier areas, the -10dB penetration depth would be much higher.

In the second case, a subsurface region with inhomogeneous soil type and moisture content is considered. To analyze such a medium, the forward model

we devised utilizes a planar stratified medium where each layer is assigned a soil textural composition and soil moisture content resulting in a stair-case approximation of the complex dielectric profile. Then, the complex dielectric constant is predicted based on a semi-empirical soil dielectric model [2-4]. Simulation results for this case indicate that signal penetration depth is significantly affected by soil texture. Of course, soil moisture profile is the other main factor in determining the signal penetration depth. It was found that Silt loam results in the highest penetration depth while Sandy loam resulted in the lowest because it turned out to be the lossiest compared to the other soil textural compositions.

3. FREQUENCY REQUIREMENTS FOR INVERSION

The bandwidth of the system is the main factor that determines the depth resolution. However, in order to be able to realize the proposed imaging system, a compact and low-profile ultra-wideband antenna in the VHF range is required. Designing such an antenna proves to be challenging due to antenna size requirements. Basically dimension of an ultra-wideband antenna is determined in terms of the lowest wavelength. However, it is possible to design narrowband miniaturized antennas and combine them with a small ultra-wideband antenna covering higher portion of the band. Intelligent sampling allows such schemes to work. To fill the bandwidth in the lower frequency range we propose to utilize a few antenna elements and operating them at their principal frequency and a number of harmonics. However, factors such as the number of frequency points and range as they relate to the resolution need to be investigated.

	Frequency points(MHz)	Higher freq.
Case 1	30,35,40,60,70,80,90	and [100-600 MHz, 30 pts],
Case 2	30,35,40,60,70,80,90	-
Case 3	[30-90 MHz, fstep = 5MHz]	-

Table 2. The frequency points used in the simulations

Simulations were performed to compare various sets of frequency points for a given bandwidth. The bandwidth used in the low-band is from 30 to 90MHz. In one case, only six frequency points were selected in such a way that they match the antenna center frequencies (30MHz, 35MHz and 40MHz) and harmonics resulting in the following frequency samples: 30, 35, 40, 60, 70, 80, 90MHz. Next, in addition to the six frequencies, the higher contiguous band in the 100-600MHz range is also included. The final case includes the whole 30- 90 MHz range densely sampled. When higher frequencies are included, the depth resolution plot displays lower side lobe levels. Although, higher frequencies do not have high penetration depth, including higher frequencies as in case 1(Table 2), could improve the depth resolution because some energy may still propagate (even for deeper

targets) at those frequencies. Figure 4 shows the depth and transverse resolution for the three different frequency sampling cases for a targets located at 6.9m. The plots show that it's indeed possible to use a few number of frequency points (Case 23 in table 2) and still achieve almost the same resolution as in the densely sampled case (Case 3 in table 2).

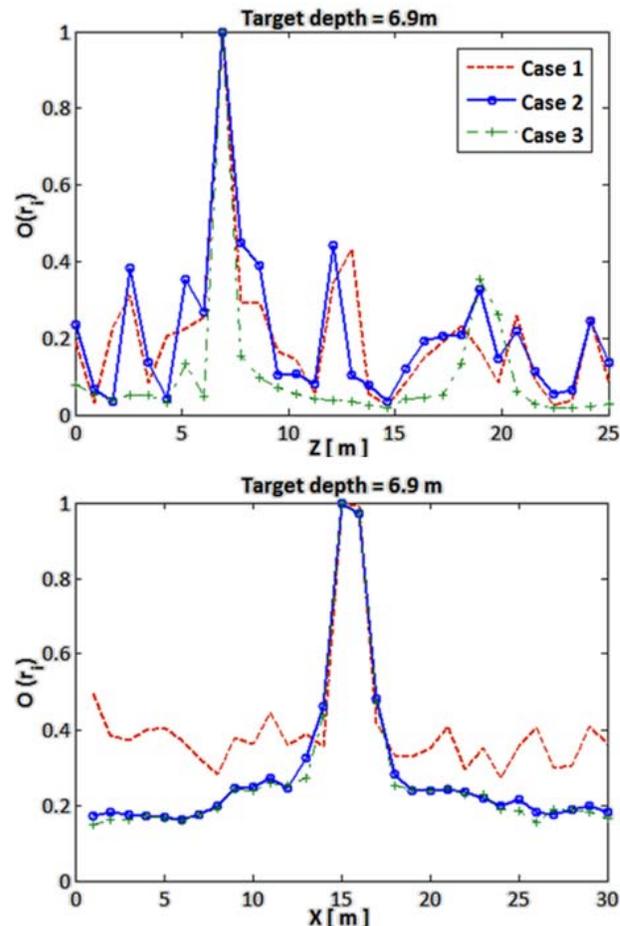


Fig.4. Comparison of (a) depth and (b) transverse resolutions for various set of frequency points (given in table 2), the target location was $x, y = 15\text{m}$ and $z = 6.9\text{m}$.

3. VHF SOIL DIELECTRIC MODEL

The proposed inversion approach is an iterative approach where the dielectric profile of the subsurface medium needs to be retrieved. Since our model utilizes several thin layers where each layer has a constant dielectric property, the number of variables to be retrieved quickly becomes large making the computational cost high. To battle this issue, we employed a semi-empirical soil dielectric model that accurately predicts the real and imaginary parts of the dielectric constant. In the literature, there are various empirical, semi-empirical and analytical models for the dielectric constant of soil especially at microwave frequencies [3-6]. However, for frequencies in VHF/UHF

range, there is not a robust model that can be used to predict the complex dielectric constant of various types of soils.

For a given soil mixture that has different soil textural class and moisture, the dielectric constant of the mixture is related to the properties of the individual components of the mixture including the dielectric constant, volume fractions and spatial distributions among other things. In the absence of water, the real part of the relative dielectric constant of soil varies between 2 and 4. A wet soil which is a mixture of soil particles, air pockets and water (bound and free water) has dielectric constant that is significantly different from dry soil.

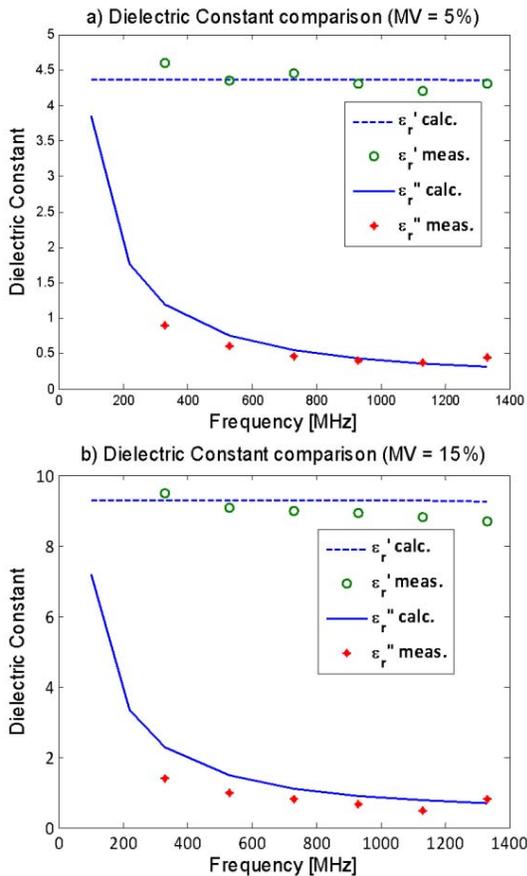


Fig.5. Comparison of the real and imaginary parts of the dielectric constants plotted against frequency,

A semi-empirical soil dielectric model was developed for microwave frequencies by Ulaby et al. The authors later extended the model to UHF frequencies. For our purposes, this semi-empirical model is implemented and the frequency range was further extended down to 10MHz, assuming the empirical formulas do not change by much as the frequency is lowered. We then compared the real and imaginary parts of the dielectric constant predicted by this model to measured results available in the literature [3-5]. The comparison between the measured and calculated dielectric constant of soil at lower UHF and VHF range are given in

Figure 5 showing very good agreement between the predicted and measured values.

4. CONCLUSION

In this work, we discussed the results of our analysis on the forward model and proposed imaging technique that we previously presented. The subsurface imaging technique which is based on UGS networks is analyzed with respect to the frequency requirement of the inversion. This is important because using intelligent sampling can ease design requirements of bandwidth of the antennas for such low frequency applications. Simulation results show that a few carefully selected frequency points used for the inversion can achieve almost the same resolution as in the case where densely sampled frequencies are used. The sensitivity analysis in the frequency of interest (Lower UHF and VHF) is also performed to assess the signal penetration depth for realistic soil textural compositions and soil moisture content. The simulation results indicate strong dependence of the signal penetration depth not just on moisture content but soil type as well. This will help choose the best frequency of operation and also help determine the maximum depth of target that could be detected when the practical limitations of the receiver are included. We are currently working on the design of low-profile wideband antennas and setting up an experiment to test the technique.

11. REFERENCES

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