

## 1.6 GPR Imaging for Deeply Buried Objects: A Comparative Study Based on FDTD Models and Field Experiments

### GPR Imaging for Deeply Buried Objects: A Comparative Study Based on FDTD Models and Field Experiments

Roger Tilley

University of California, Santa Cruz, CA

[rtvax@soe.ucsc.edu](mailto:rtvax@soe.ucsc.edu)

Farid Dowla

Lawrence Livermore National Laboratory

[dowla1@llnl.gov](mailto:dowla1@llnl.gov)

Faranak Nekoogar

Lawrence Livermore National Laboratory

[nekoogar1@llnl.gov](mailto:nekoogar1@llnl.gov)

Hamid Sadjadpour

University of California, Santa Cruz, CA

[hamid@soe.ucsc.edu](mailto:hamid@soe.ucsc.edu)

**ABSTRACT** – Conventional use of Ground Penetrating Radar (GPR) is hampered by variations in background environmental conditions, such as water content in soil, resulting in poor repeatability of results over long periods of time when the radar pulse characteristics are kept the same. Target objects types might include voids, tunnels, unexploded ordinance, etc. The long-term objective of this work is to develop methods that would extend the use of GPR under various environmental and soil conditions provided an optimal set of radar parameters (such as frequency, bandwidth, and sensor configuration) are adaptively employed based on the ground conditions. Towards that objective, developing Finite Difference Time Domain (FDTD) GPR models, verified by experimental results, would allow us to develop analytical and experimental techniques to control radar parameters to obtain consistent GPR images with changing ground conditions. Reported here is an attempt at developing 2D and 3D FDTD models of buried targets verified by two different radar systems capable of operating over different soil conditions. Experimental radar data employed were from a custom designed high-frequency (200 MHz) multi-static sensor platform capable of producing 3-D images, and longer wavelength (25 MHz) COTS radar (Pulse EKKO 100) capable of producing 2-D images. Our results indicate different types of radar can produce consistent images.

## 1.0 INTRODUCTION

Ground Penetrating Radar (GPR) systems have been used to identify voids, pipes, unexploded ordinance and other objects in different soil types. Interpretation of experimental GPR data is often difficult when hampered by varying environmental conditions such as increased or decreased water content in soil. Modeling and simulation techniques can be used to determine the effects of weather and other ground characteristics on the GPR data. Controlled experiments with known ground truth information provides a basis for developing accurate models and a means to develop test beds to study changes in experimental results by varying the model

soil parameters, transmitting frequency, bandwidth, etc. . The Finite Difference Time domain (FDTD) method [4][5][6] has emerged as the leading method of modeling GPR modeling and simulation. Software platforms of interest are FDTD methods that are user-friendly and can run on PC based platforms. Such software platforms can be used to vary dielectric permittivity ( $\epsilon$ ), electric conductivity ( $\sigma$ ), and magnetic permeability ( $\mu$ ), the main variables representing the properties of different soil types. The transmitting pulse can also be a variable. There are many such modeling programs that are made available from leading GPR companies and University research centers. We have used the GprMax program, developed by A. Giannopoulos [1], in this paper. In this

study we also used an experimental test site with known objects at known depths to validate the simulation and modeling results. The site was scanned with two types of radar. The first was a monostatic single transmitter (TX) and a single receiver (RX) design; the second system used was a multi-static design with multiple transmitters and multiple receivers. Each “ground truth scan” was processed to remove surface reflections, the global background trace (“system noise”), compensate for the mean or median attenuation, and enhance data by re-sampling the output data at a higher rate. This result was used to compare it with the simulated data from the GprMax FDTD simulation code. Using the site dimensions, the object dimensions, buried depths of each object and soil type a model was created and the simulation results were then compared to the “ground truth” scan results.

This paper is organized as follows. In section 2.0 we describe the field experiments and the test site. In section 3.0 we describe the construction of the FDTD 2-D and 3-D models and discuss the results of each FDTD analysis. In section 4.0 we compare the model results with scanned ground truth data. In section 5.0 we discuss our conclusions.

## 2.0 Description of the Experimental Tests and Field Data

Target objects were buried in a remote experimental test site, ‘The Forest Lodge,’ located near Greenville, California of the Northern Sierra about 60 miles (96.56 km) north of Lake Tahoe. The objects chosen were metal (tin) roofing sheets approximately 1.83 m (6 ft) long by 66 cm (26 in) wide by 1.27 mm (0.05 in) thick. There were 8 sheets in total, buried at depths of 0.5 (1.64), 1.0 (3.28), 1.5 (4.92), 2.0 (6.56), 2.75 (9.02), 3.0 (9.84), 3.5 (11.48), 4.0 m (13.12 ft) and roughly 1.83 m (6 ft) between sheets. The surrounding soil was a mixture of clay and sand. Figure 1 depicts the tin sheets before burial.



**Figure 1. Target GPR imaging objects, tin roofing sheets, were buried at various depths. The experiments provided ground truth GPR data for this study.**

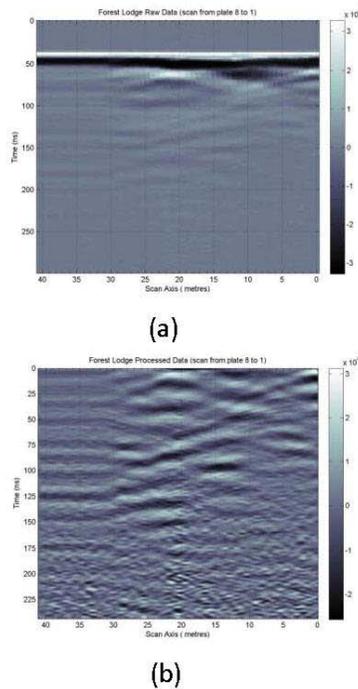
The pulseEKKO 100 radar, built by Sensors and Software Inc., was used to obtain the first set of field data. This radar consists of one TX and one RX operating at 25 MHz, making the antennas approximately 3.68 m (12 ft) long by 11.4 cm (4.5 in) wide by 1.6 cm (0.63 in) thick. The antennas were mounted on a low profile platform made of PVC tubing with wheels. The TX and RX antennas were spread apart as necessary to avoid signal saturation by the receiver, shown in Fig. 2.



**Figure 2. pulseEKKO 100 radar on a wheeled platform in front of test lane containing buried tin sheets at Forest Lodge.**

This radar was used in a mode to generate a 2-D scanned image. Each scan started with the deepest buried object first proceeding to the shallowest object. The transmitting antenna encountered each object first followed by the receiving antenna. The TX and RX antennas were approximately 9.14 m (30 ft) apart.

Examples of the scanned images are shown in Fig.3. Figure 3a and 3b depict the raw data and the processed data respectively.



**Figure 3.** “Ground truth” GPR scan results from the COTS pulseEKKO 100 radar over the Forest Lodge test site at 25 MHz. Raw data is depicted in (a) while processed data is depicted in (b).

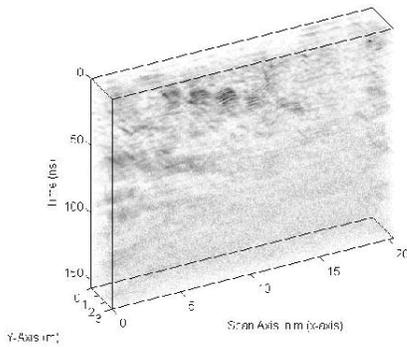
The processing used in Fig. 3(b) includes moving the time-zero to remove ground bounce; removing global background to enhance coherent signals and reduce randomly varying signals (noise). Applying an empirical gain function that compensates for the mean or median attenuation observed is part of the image processing. Removing the low frequency component of the data, and lastly, re-sampling the time and scan axes to enhance observed artifacts completes our processing. The axes markings on the pulseEKKO data need some clarification. The axes represent time to target verses distance, scanned over a 30 meter distance. The scan proceeded from 0 meters to 30 m (98.4 ft) beginning with sheet number 8 (the

deepest sheet) to sheet number 1 (the shallowest sheet). The radar was stationary and not part of the testing for scans from 30 (98.4) to 41 m (134.5 ft). For a depth calculation, we multiply time by the assumed velocity in the medium of 0.1 m/ns for the soil type [2], Sand in this case. The existences of voids or objects are clearly shown, some correlate with the tin sheets buried noted in the 2-D model (Fig. 5). The shallowest sheet is approximately at the 22 m (72.2 ft) mark. Other sheets are difficult to distinguish from other artifacts. In the scanned processed results, all known buried objects occur within the first 40 ns using the depth calculation mentioned above. Buried object detail is lacking do to the use of the 25 MHz operating frequency of the radar, but signal response is expected at depths as much as 55 m (180.4 ft) [7].

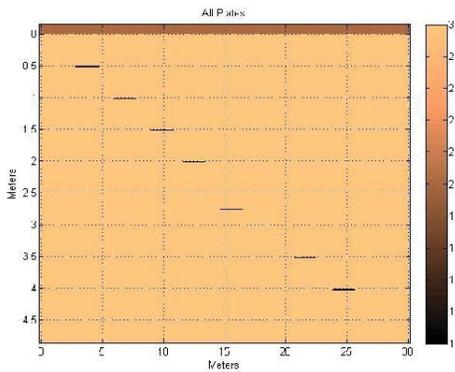
The 200 MHz multistatic sensor platform was used to scan the Forest Lodge site. This radar consisted of 9 Transmitters and 8 Receivers, fashioned such that each receiver received a signal from 2 adjacent transmitters but, not at the same time forming 2 channels received by one receiver. In this test, the radar provides 16 channels of data that cuts a 2 meter swath over targets of interest to create a 3-D image. The result of the test is shown in Fig. 4, where 5 roofing sheets are clearly present, depicted as stair steps. The depth calculation is the same as in the COTS 2-D pulseEKKO radar case.

### 3.0 FDTD Models

Modeling of the Forest Lodge site was conducted using GprMax software program developed by A. Giannopoulos described in [1]. GprMax code runs on mainframe computers and Personal Computers (PCs), capable of running compiled C programs like Windows or Linux operating systems. Using techniques described in the GprMax User's manual a 2-D model was constructed as shown in Fig. 5.



**Figure 4. Processed 3-D data scanned by the multistatic radar over the Forest Lodge test site of buried tin sheets of known depth. 5 roofing sheets are visible in a stair step fashion.**



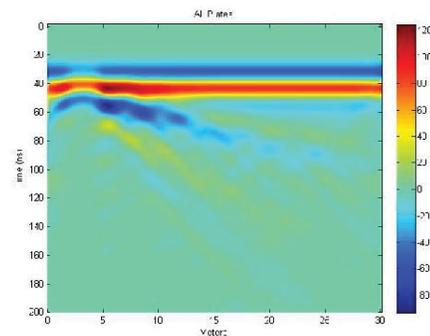
**Figure 5. 2-D GprMax model of buried tin roofing sheets, simulating the Forest Lodge test site.**

A sample GprMax input consists of defining the media type (sand, clay, water, etc.) and its parameters (dielectric permittivity ( $\epsilon$ ), electric conductivity ( $\sigma$ ), and magnetic permeability ( $\mu$ )). Defining the model boundaries, the spatial step in x and y directions and the time window (the length of time to simulate a GPR trace) are included. Of importance are the dimensions of the buried targets, the excitation waveform, transmitting source(s) and receiver(s) location(s). The final items necessary are the number of analyses to run and the step interval of the source(s)

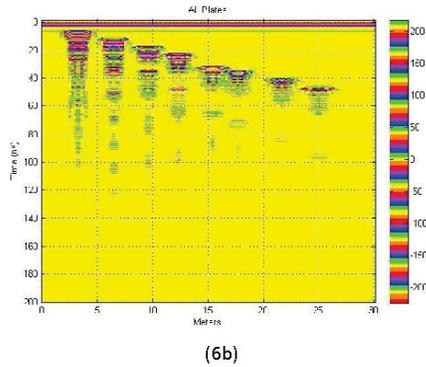
and/or receiver(s). Units of measure in the model are meters for distance, nanoseconds for time and hertz for frequency.

The 2-D model contains an air space of 0.15 m (0.5 ft) in depth followed by the tin sheets buried at 0.5 (1.64), 1.0 (3.28), 1.5 (4.92), 2.0 (6.56), 2.75 (9.02), 3.0 (9.84), 3.5 (11.48), and 4.0 m (13.12 ft) deep over an area of 30 m (98.4 ft) with spacing between tin sheets of 1.22 (4), 1.04 (3.4), 0.89 (2.92), 1.1 (3.6), 0.33 (1.08), 2.1 (6.89), and 1.3 m (4.27 ft) respectively. Sand was chosen as the medium in which the tin sheets were buried with a relative permittivity ( $\epsilon_r$ ) of 3.0 and an electrical conductivity ( $\sigma$ ) of 0.01 mS/m. Two experiments were conducted. The first experiment was conducted at 25 MHz for 1 to 8 tin sheets individually then all tin sheets. The second experiment was run at 900 MHz on all plates to note the response by the model of Fig. 5. Figure 6 depicts the results of the 2-D analysis.

At 25 MHz the object detail is lacking, as expected, though a general trend of the existence of plates is noted. However, the FDTD analysis of individual sheets shown in Fig. 6, demonstrates the effectiveness of this technique in recognizing each sheet but not in detail. Inferred is that the combination of the individual sheet responses results in the trend shown when scanning all sheets at once. At 900 MHz, each plate position is well defined, also as expected [2][4].



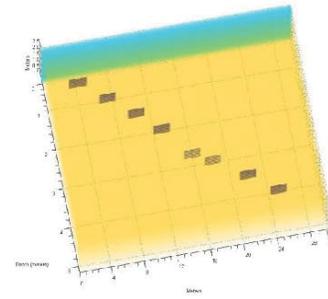
(6a)



**Figure 6. FDTD analysis results of the 2-D model using GprMax at 25 MHz (a), showing minimal detail and 900 MHz (b) showing distinct detail. Unexpected results in (b) are the reflections underneath each tin sheet reflection which has been found to occur in actual scans.**

A 3-D model was constructed using the techniques described in the GprMax User's manual. Like the 2-D case, the input file is the same but with added variables to define the third dimension. Included in the 3-D model, as in the 2-D model case, is an air space of 0.15 m (0.5 ft) in depth followed by the tin sheets buried at 0.5 (1.64), 1.0 (3.28), 1.5 (4.92), 2.0 (6.56), 2.75 (9.02), 3.0 (9.84), 3.5 (11.48), and 4.0 m (13.12 ft) deep over an area of 30 m (98.4 ft) with spacing between the tin sheets of 1.22 (4), 1.04 (3.4), 0.89 (2.92), 1.1 (3.6), 0.33 (1.08), 2.1 (6.89), and 1.3 m (4.27 ft) respectively. Each tin sheet is 66 cm (26 in) wide. A value of 2.5 m (8.2 ft) in width was added to the model, completing the third dimensional variable. In the model a matrix of 9 TXs with 8 RXs was constructed without defining which TX and RX communicates at any one time. The completed 3-D model is shown in Fig. 7.

The resulting FDTD analysis of the 3-D model is shown in Fig. 9 depicted at each of the 8 RX antennas. All 8 metal sheets are shown at each of 8 RXs, but some show the reflection from each sheet a little more clearly. An analysis was run at 900MHz for comparison with a more pronounced illumination of the targets as a result.



**Figure 7. GprMax 3-D model of the Forest Lodge site of buried objects. This model was used to study FDTD response experiments conducted for this study.**

#### 4.0 DISCUSSION

Comparing the response of the model at 25 MHz (Fig. 6a) to the actual data (Fig. 3b) taken has proven to be challenging. In general the model and the actual data response is not a good fit. However, the model and actual data have items in common such as the downward sloping trend in the model also noted in the actual data. The downward sloping trend begins at the 22 m (72.18 ft) mark of the actual data, proceeding towards the 15 m (49.21 ft) mark. Another common item is the secondary reflections appearing beneath each tin sheet in the model results as well as in the actual data. Many other artifacts appear in the actual data which were unexpected. We are reminded by the literature that at 25 MHz one can image up to 55 m (180.4 ft) in depth with reduced fidelity [7], which explains the voids at depths well below where our site preparation efforts disturbed the soil. At this time we are without information as to what exists at levels below 4 meters at Forest Lodge. In reviewing the data from the actual 3-D scan at 200 MHz (Fig. 4) we are encouraged that our 2-D response is plausible, because of the clear delineation of targets in the actual 3-D data.

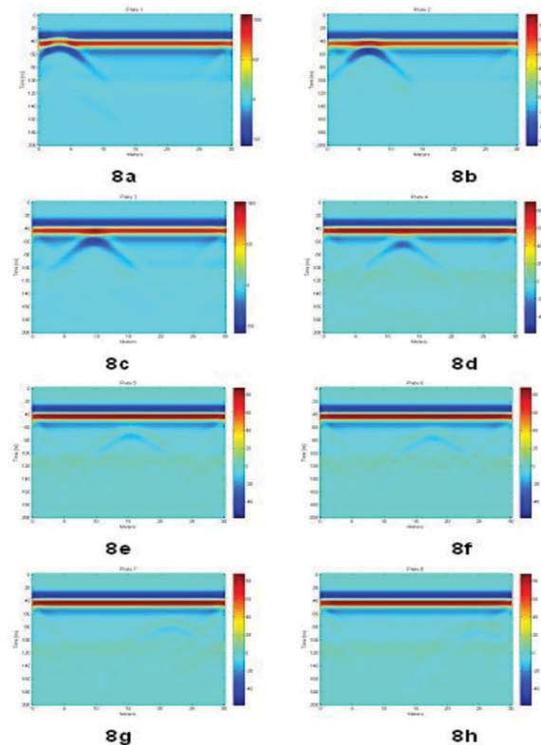
A comparison of the 3-D model (Fig. 7) with the actual data (Fig. 4) at 200 MHz denotes

a better fit. The model locates more tin sheets at lower depths but the actual and modeled data track well. A difference in parameters of the medium easily explains the dissimilarity. A geological survey was not conducted of the Forest Lodge site to determine the specific composition of the medium, we assumed Sand.

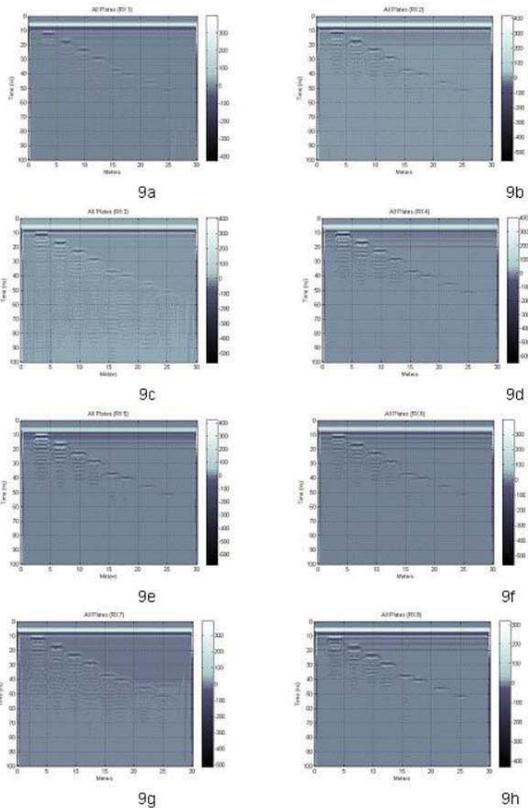
## 5.0 CONCLUSIONS

Ground Penetrating Radar can identify objects buried in different soil types. What we have attempted to show here is that modeling can identify simulated buried objects. One key that is prevalent in the modeling process is that the more accurate the model the better the end result corresponds to the data. A comprehensive knowledge of the area to be modeled strengthens the accuracy of the analysis engine. Our 2-D case had some unexplained outcomes when attempting to compare the real data to the modeled data. Both real and modeled analyses indicated that besides the broad outline of the target there exists a reflection underneath the illuminated object closely associated with just one object at a time. This was an unexpected outcome. For the 2-D case the actual data response was taken over a site that was not well known below 4 meters and appears to have other unexplained voids or objects. The 3-D data bears out that within 4 meters the site content is known. The 3-D analysis shows the buried object more clearly without other artifacts over 4 meters. Part of the difference between the 2-D and 3-D analyses is that one used 25 MHz (2-D case) while the other used 200 MHz (3-D case) center frequencies. Inherent in using 25 MHz is the fact that one will have much less resolution of objects but one will see to a greater depth. Using 200 MHz increases the level of resolution greatly but to a shallower depth. Both models demonstrate that. For the 3-D case, modeling the multistatic sensor platform in its currently defined configuration is challenging. The reason is that the multistatic radar is configured such that 16 channels of data

are returned by a process in which TX and RX communication is controlled. For our model, we took the first step and modeled the 9 TXs and 8 RXs and presented the result. At most we had 8 channels of data where the adjacent TXs added to one RX. The output demonstrated the promise of using modeling as a tool. In general what has been demonstrated is that one can successfully use GprMax to model test sites.



**Figure 8.** FDTD analysis results from GprMax for 2-D model at 25 MHz, simulating buried roof sheets at Forest Lodge. Scans are of each tin sheet, 8 in all. Tin sheet (a) represents a buried sheet at 0.5 meters, (b) represents 1.0 meter buried sheet. It follows that (c), (d), (e), (f), (g), and (h) represent 1.5, 2.0, 2.75, 3.0, 3.5 and 4.0 meter buried sheets.



**Figure 9. FDTD Analysis results at 200MHz. Plots (a) through (g) depict the software results at each RX modeled in the 3-D GPR model. All 8 of the simulated buried tin sheets are shown. There are unexpected differences from receiver to receiver.**

## 6.0 ACKNOWLEDGMENTS

The Authors thank Dr. Willard H. (Bill) Wattenburg for providing the use of the Forest Lodge facilities; Chico State University Mechatronic Engineering Department for their assistance with field experiments. This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344. LLNL-CONF-482511

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