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Prediction of Buried Mine-like Target Radar Signatures using Wideband Electromagnetic Modeling

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ABSTRACT

Current ground penetrating radars (GPR) have been tested for land mine detection, but they have generally been costly and have poor performance. Comprehensive modeling and experimentation must be done to predict the electromagnetic (EM) signatures of mines to access the effect of clutter on the EM signature of the mine, and to understand the merit and limitations of using radar for various mine detection scenarios. This modeling can provide a basis for advanced radar design and detection techniques leading to superior performance. Lawrence Livermore National Laboratory (LLNL) has developed a radar technology that when combined with comprehensive modeling and detection methodologies could be the basis of an advanced mine detection system. Micropower Impulse Radar (MIR) technology exhibits a combination of properties, including wideband operation, extremely low power consumption, extremely small size and low cost, array configurability, and noise encoded pulse generation. LLNL is in the process of developing an "optimal" processing algorithm to use with the MIR sensor. In this paper, we use classical numerical models to obtain the signature of mine-like targets and examine the effect of surface roughness on the reconstructed signals. These results are then qualitatively compared to experimental data.

Keywords: Ground penetrating radars, land mine detection, impulse radar, electromagnetic modeling, diffraction tomography

1. INTRODUCTION

Land mines will continue to pose an enormous military and civilian threat throughout the world until an effective detection and removal strategy is developed. Various detection technologies are currently in use. However, each of these technologies continue to have significant drawbacks including cost, speed, and ability to discriminate. For example, dogs have high ongoing expenses and are subject to fatigue. Metal detectors are sensitive to metal mines and firing pins but cannot reliably find plastic mines. Infrared detectors effectively detect recently placed mines, but they are expensive and limited to certain temperature conditions.

In early attempts, ground-penetrating radar has been sensitive to large mines, had good coverage rate at a distance, and, with signal processing, could discriminate antitank mines from clutter such as rocks beneath the ground surface. This type of radar, however, remains expensive, cannot reliably detect antipersonal mines because its resolution is too low, and frequently records false alarms from clutter sources.

LLNL is developing a ground-penetrating system with advanced image processing and detection algorithms into a practical system called Land-Mine Detection Advanced Radar Concept, or LANDMARC. The LANDMARC system's enabling technology is MIR. MIR was invented at LLNL in 1993 as an outgrowth of the Nova laser fusion diagnostics program. MIR is a battery-operated pulsed radar that is small, inexpensive, has a wide range of frequency bands, and works well at short ranges.

Similar to all radar systems, MIR has degrading performance due to clutter, both from the ground surface and from objects below the surface such as rocks or metal casings. By incorporating sophisticated signal and image processing algorithms, removal of the surface effects and discrimination of these objects is realizable.

In this paper, we investigate the effect of surface roughness on performance of a MIR system. A finite difference time domain (FDTD) simulation is developed which incorporates the experimental MIR pulse. The simulation is used to examine the effect of the surface roughness is examined for various mine depths. Results are then compared to experimental data.

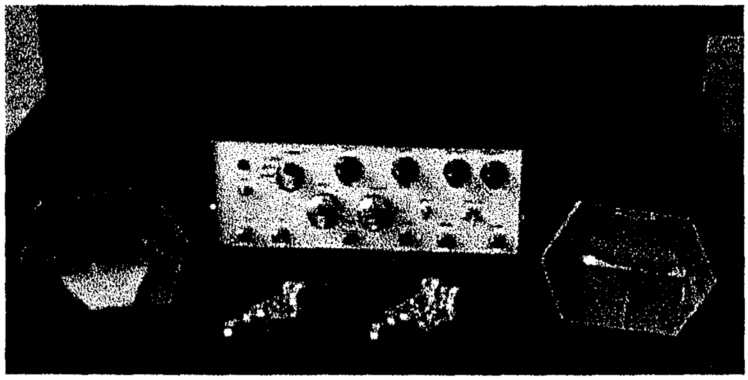


Figure 1. The modular MIR system consists of transmitter module, receiver module, two antennas and the timing and control unit.

2. DATA ACQUISITION

Successful nondestructive evaluations have been performed using the MIR including the imaging of subsurface objects and the interior of civil structures.[1–4] Modular MIR[5,6] can be integrated into systems, and it provided the flexibility required for multistatic implementations (see Figure 1). Separate transmitter and receiver modules provide bistatic capability allowing the transmitter and receiver to be positioned independently. The operational bandwidth of this radar is approximately 1 to 5 GHz with 10 MHz pulse repetition frequency, a peak power of 1090 mW and a scan rate of 40 Hz.

We have developed a calibrated radar testbed for land mine detection shown in Figure 2 (a), which is a mobile platform consisting of an MIR sensor, a linear translational stage, and a portable computer for control, acquisition and image processing. The translational stage provides antenna motion in one dimension while a computer-controlled motor drives the stage forward providing a platform for accurate 2D planar aperture synthesis with data suitable for 3D imaging.

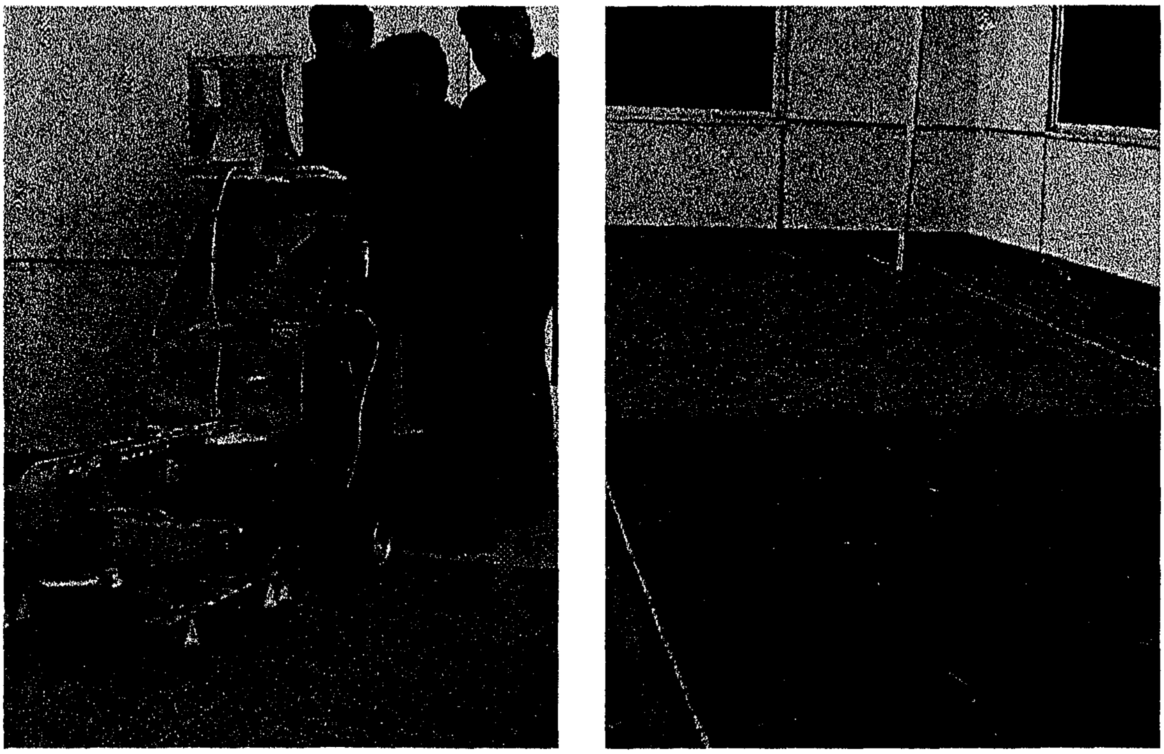
A test mine field was constructed for evaluation of the system and is illustrated in Figure 2 (b). The test bed is approximately 10m x 1m with a depth of 1m. Wood was place around the edge of the bed to help minimize scattering from the sides. In addition, the bottom is sloped and laid with gravel to ensure drainage. Currently, the test bed is divided into three sections to allow testing on various soil conditions. For this paper, we are going to restrict our experimental results to sand.

3. SIGNAL PROCESSING APPROACH

One factor that significantly reduces the effectiveness of radar based systems for land mine detection is noise from various clutter sources including the ground surface and scattering objects such as rocks below the surface. In order to reduce the effect of clutter, LLNL has adopted a signal processing approach.

The signal processing approach currently used at LLNL for land mine detection is illustrated in Figure 3. Once the raw data is collected, a surface removal algorithm is applied to the data. The topography of the surface is obtained using an algorithm based on correlations of the peak of the surface return. Currently, our surface removal algorithm consists of aligning the peaks from the ground return by appropriately shifting each row. The shift is performed in the frequency domain to provide subpixel accuracy. Once the data is aligned, the mean of each column is subtracted from each point. The data is then reconstructed using an image processing algorithm that forms a spatial image using the coherent backward propagation of the received reflected wavefield.[7]

Because of the large number of variables that exist in this problem, from environmental conditions such as surface roughness, material properties, and subsurface clutter to radar parameters such as frequency of operation and pulse shape, simulated data allows for a more complete parametric study. For this paper, we will focus exclusively on the effect of surface roughness and qualitatively compare the results to experimental data using a MIR radar pulse.



(a) (b)

Figure 2. (a) The MIR radar acquisition system includes a mobile platform, with an MIR sensor, a linear translational stage, and a portable computer and is tested on a (b) simulated land mine field.

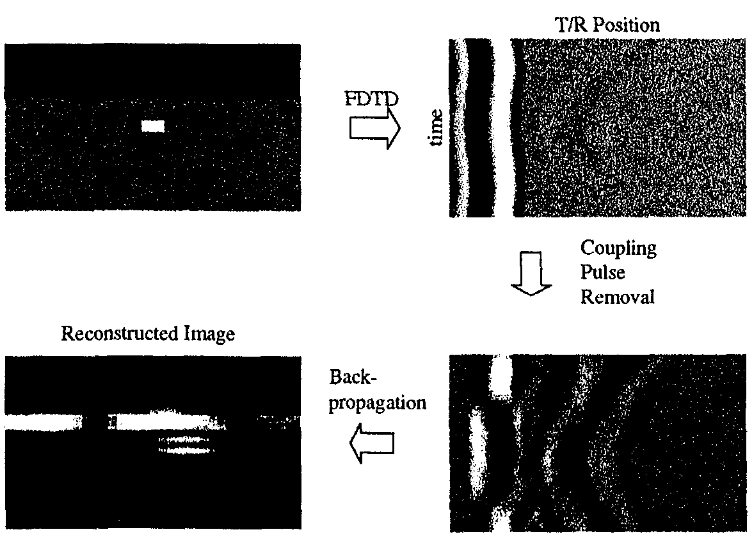


Figure 3. The signal processing approach consists of of data acquisition (through FDTD or simulation), surface removal and backpropagation.

The simulated data is obtained using a FDTD code to calculate the scattered fields. The FDTD algorithm provides a direct solution to Maxwell's time-dependent curl equations.[8] For this analysis we restrict the computations to the two dimensional scattering case. However, full three dimensional scattering from buried objects have been performed at LLNL and by other research groups.[9] The simulation pulse is a windowed MIR pulse that was obtained experimentally and has a spectrum in the 1-6 GHz range as shown in Figure 4.

The effect of scattering from a small mine for several depths was examined for the two geometries illustrated in Figure 5, a perfectly smooth surface and a surface with a small amount of roughness. Our simulation region is 45cm x 80cm with a 3cm x 6cm sized mine at mine depths of 1cm, 2cm, and 5cm. Material properties considered in this simulation are given in Table 1.

	soil properties	mine properties
relative permittivity	3.5	4.0
conductivity	0.01	0

Table 1. Material properties for the soil and land mine.

The surface removal algorithm consists of first estimating the surface using a correlation of the peak return. This method of estimating the surface provides an excellent correspondence to the model surface (see Figure 6). Once the topography of the surface is estimated, the algorithm aligns the peaks from the ground return by appropriately shifting each row.

In Figure 7 (a)-(b) the raw data and surface removal data are shown for a smooth surface. For this case the algorithm very effectively removes the effects of the surface. Similarly in Figure 7 (c)-(d) the raw data and surface removal data are shown for a rough surface. Although the waterfall is clearly present, there are significant surface effects present in the data. The effect of the surface could be reduced by windowing the data in the region were the surface is present. However, this must be carefully applied because it may remove the signature of shallow mines.

The reconstructions for smooth and rough surfaces are shown in Figure 8 (a)-(f) for mines at 1cm, 2cm, and 5cm in depth. For the smooth surface, shown in the left column, a distinct mine signature is observed at all depths. The signature reduces in intensity as the depth increases; however, the signature is roughly the same. For the case of the rough surface, shown in the right column, the mine is present all cases. However, the noise of the surface disguises the full mine signature in the 1cm and 2cm cases. In addition, the mine signature for the 5 cm case, although clearly visible, is slightly distorted.

An experiment with a mine placed roughly 2cm and 5cm below the surface was performed. The raw data and processed data is shown in Figure 9 for the 5cm depth mine. Although the mine signature waterfall is clearly present, there is a significant amount of noise below the surface not directly due to the surface interaction. This noise may be caused by inhomogeneities in the soil or multiple reflections in the electronics and antennas not accounted for in the model. The source of this noise and its statistics are currently under investigation. The mine reconstruction is shown in Figure 10. In both cases, the mine is clearly visible. However, for the deeper mine the exact signature of the mine is more defined.

4. DISCUSSION AND SUMMARY

A complete MIR system for land mine detection which includes data acquisition and signal processing was presented in this paper. In addition, the framework for EM modeling of a land mine scene was presented and qualitatively confirmed by experimental observations. It was shown that the roughness of the surface significantly degrades the image quality in the raw data. A simple surface removal algorithm was performed before reconstruction. However, the effect of the surface was still significant especially for shallow mines. Although the results, both from experiment and modeling, are preliminary, this system has shown encouraging results for the detection of antipersonal land mines.

The effect of the rough surface is a severe limiting factor for the MIR system for land mine detection. Currently a simple algorithm for surface detection has been applied to the land mine problem. Although this algorithm has provided a good estimate of the surface topology and improved the image quality, the surface still remains the

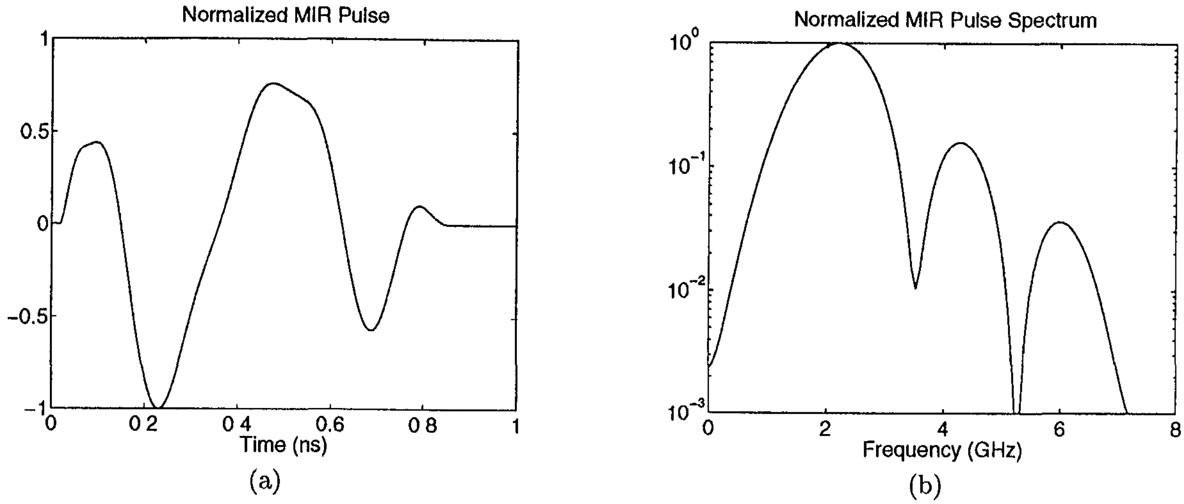


Figure 4. The (a) simulation pulse and (b) spectrum are obtained experimentally using the MIR system.

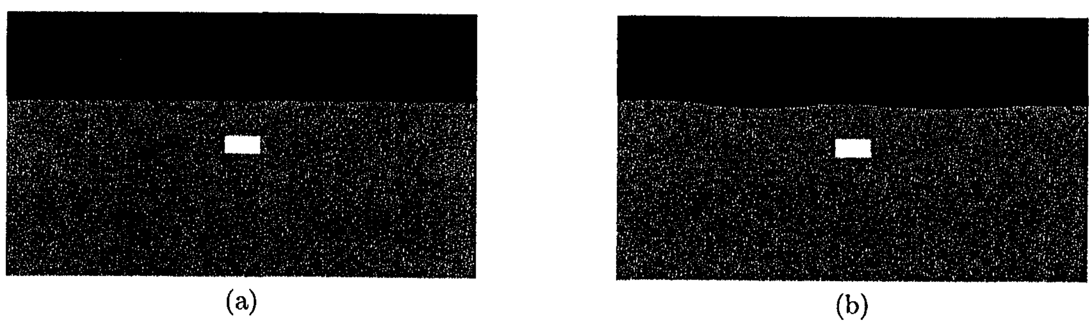


Figure 5. The simulation regions considered are 45cm by 80cm with (a) a smooth surface and (b) a rough surface. The land mine shown is at a depth of 5cm.

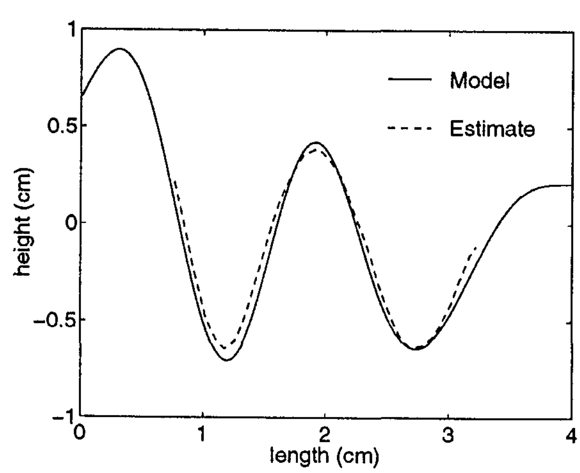


Figure 6. An estimate of the surface topography is obtained using the correlation algorithm.

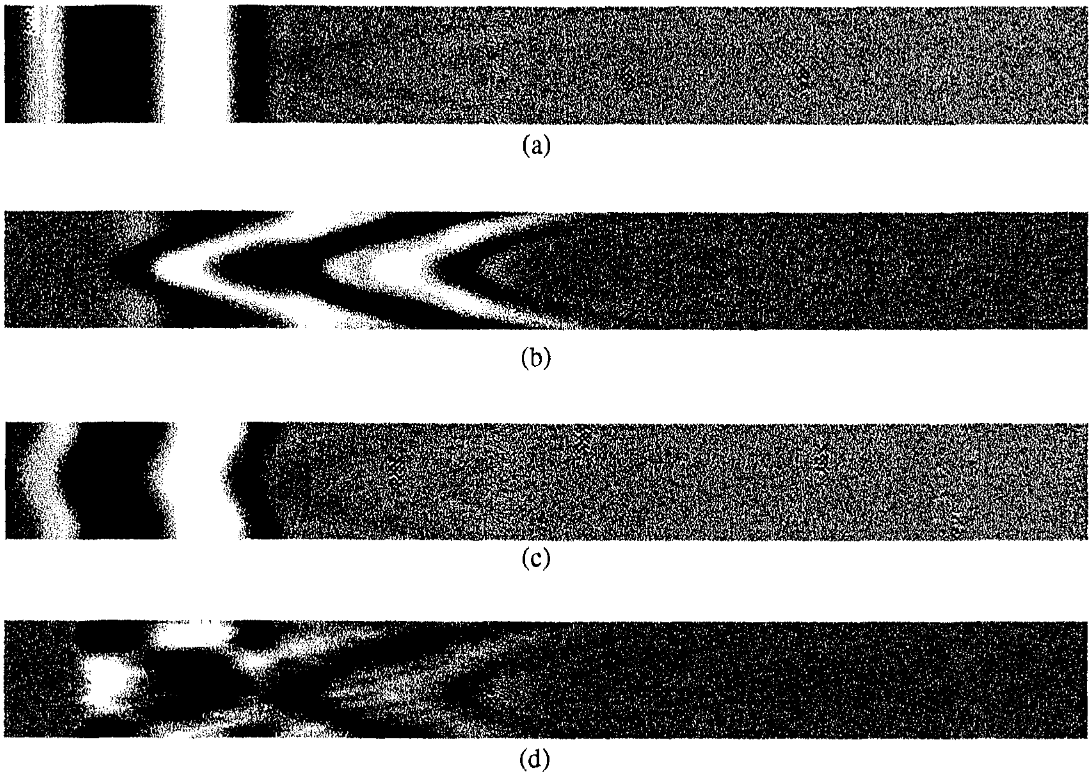


Figure 7. Raw data obtained using simulation for (a) smooth surface with (b) surface removal and (c) rough surface with (d) surface removal.

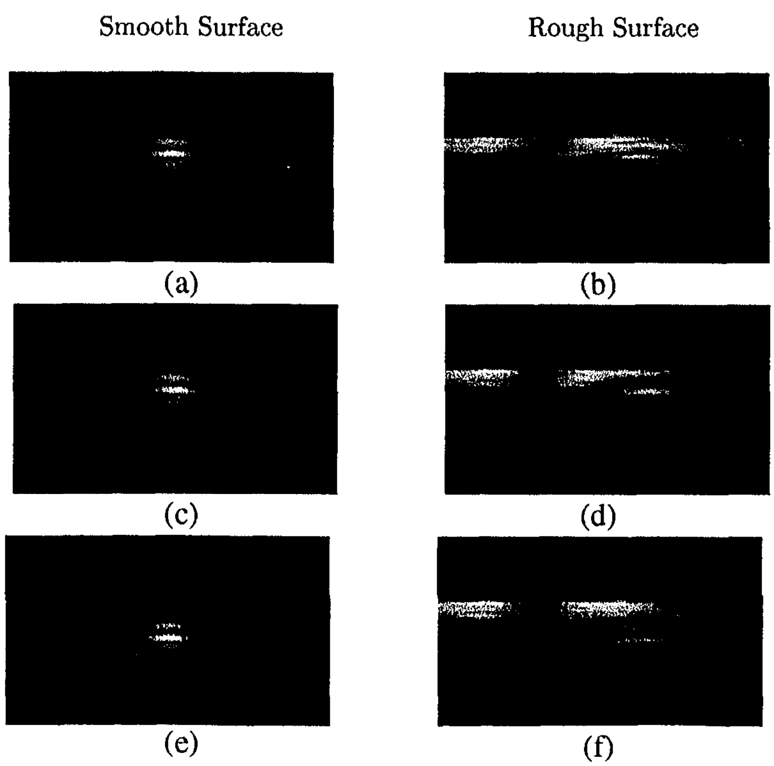
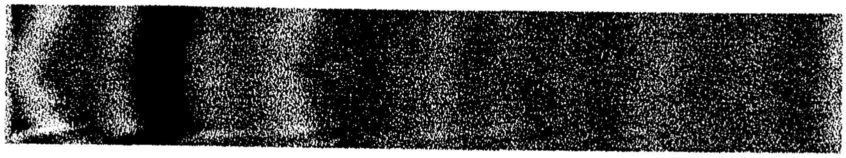


Figure 8. Reconstruction of simulated data for mines at depths of 1cm, 2cm, and 5cm.



(a)

(b)

Figure 9. Raw experimental data and (b) surface removal.

(a)

(b)

Figure 10. Reconstructed Experimental data for (a) 2 cm deep mine and (b) 5 cm deep mine

predominant noise source, both in simulation and experiment. A more advanced algorithm is needed to help reduce the effect of the surface. Because a good estimate of the surface was demonstrated, a possible algorithm which incorporate an EM simulation of the expected scatter from the surface into the model might be feasible. In addition, a signal processing algorithm which incorporates careful windowing of the data near the surface may reduce its effect. Another approach to minimize the effect of the surface is to examine other frequency bands. Preliminary work at LLNL has shown that shallow mines are much easier to detect at higher frequencies.

In addition to surface removal techniques, an optimal detection algorithm could improve the performance of the MIR system. For example, we have obtained signatures for land mines, both with simulation and experimentation. These signatures could be combined with the noise statistics to develop an optimal detection procedure.

5. ACKNOWLEDGMENTS

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