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Detecting Antipersonnel Mines with a Handheld Parabolic Reflector Transmitter/Multistatic Receiver Impulse GPR

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DETECTING ANTIPERSONNEL MINES WITH A HANDHELD PARABOLIC REFLECTOR TRANSMITTER / MULTISTATIC RECEIVER IMPULSE GPR

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Abstract

A novel handheld time-domain array GPR antipersonnel mine detection system using an offset paraboloidal reflector antenna is described. The reflector collimates rays from an ultra-wideband transmitting feed, directing the microwave impulse forward, in front of the antenna structure. As such, much of the ground reflected wave is directed further forward, away from the operator, the reflector, and the receiving antennas, and thereby reducing the major source of clutter. The wave transmitted into the ground that interacts with the target, generating significant backscatter returning toward the receiving antennas. These receiving antennas are configured in a 2 by 2 array to provide spatial focusing in both the along- and cross-track directions.

This system has been built and tested at both Lawrence Livermore National Laboratory, and GeoCenters, Inc. In both cases, custom-built wideband antenna elements generate narrow pulse shapes, which allow for resolving small non-metallic targets buried at shallow depths. The LLNL's Micro-Power Impulse Radar (MIR) operates in the 1.5 to 5 GHz range a very narrow pulse shape. The Geo-Centers wideband TEMR antenna elements have higher power, though lower frequency range (850 to 1700 MHz), and generate less residual ringing in the time signal.

Preliminary measured data from both systems indicate that the surface clutter is indeed reduced relative to the target signal, and that small non-metallic anti-personnel mines can be reliably detected at burial depths as shallow as 1 inch in both dry sand and dry vegetative clay loam soil.

Introduction

The Northeastern University Multidisciplinary University Research Initiative (MURI) demining effort, sponsored by the Army Research Office, has been investigating novel sensing systems and processing algorithms to detect small, shallow buried, low metal content antipersonnel mines. Finding buried plastic mines with conventional electromagnetic induction metal detectors is problematic, due to the relatively low amount of metal (just in the firing pin) relative to surrounding metallic clutter. Ground penetrating radar (GPR) has been shown to be effective in detecting shape anomalies characteristic of buried mines [1,2]. However, identifying buried target signals amid rough ground clutter is particularly difficult for small mines buried close to the ground surface. To address this problem, it is essential that the GPR sensor minimize the strongest scattering contribution: the ground surface reflection.

A new GPR system designed at Northeastern University, and fabricated at both Lawrence Livermore National Labs (LLNL) and Geo-Centers, Inc. reduces this ground clutter by illuminating the sample ground surface with a forward propagating, quasi-planar wave, and receiving the scattered signals with a two-dimensional multistatic array. Since the scattering by a small target is relatively isotropic, while scattering by the ground is primarily specular, a planar transmitted signal is well suited for shallow GPR detection. Plane wave illumination has another advantage beside clutter reduction compared to point source excitations: for a given target burial depth, the wave incident on a target from a plane wave source will always scatter the same way. For a point source, the incident wave on a given target will be illuminated from the side for one transmitter position and directly above for another. This constant exposure angle for the planar wave makes processing the returned signals more straightforward.

In both the LLNL and Geo-Centers systems, the excitation signal is sufficiently short in time duration to resolve small targets and discriminate the ground surface from a shallow buried target. The multistatic array concept provides for additional clutter rejection and time-domain focusing [3]. This focusing is accomplished by measuring, comparing, and summing the backscattered signals at each receiver in the narrow time window between the times when the residual ground reflected wave passes the receiver and before this wave re-reflects from the reflector components.

The finite-difference time-domain (FDTD) [4] method has been used to electromagnetically model the novel GPR configuration. We implemented the 2-D FDTD code to simulate the generation of the non-uniform plane wave, the scattering by the modeled dispersive soil ground surface, the scattering by the target, and the retransmission back into the air, confirming the clutter minimizing characteristics of this mine detector.

Parabolic Reflector Transmitter GPR

The quasi-planar transmitted wave is generated using an offset paraboloidal reflector antenna. The resulting wave is incident at 45 deg. to normal, and is fairly uniform over the portion of ground being investigated. Because the transmitted wave diverges very little from reflector to the ground, most of the power incident from the illuminating feed is transferred to the ground. Much of the ground reflected wave is directed further forward, away from the operator, the reflector, and the receiving antennas, reducing clutter. In addition, the wave transmitted into the ground is incident on the target in the same manner for any antenna position: always as a plane wave with constant soil path length and incident angle. Since the scattering from an electrically small buried target is primarily isotropic, there will be a significant backscattered signal, propagating opposite to the surface clutter signal, returning toward the receiving antennas.

Figure 1 shows the geometry of the parabolic reflector and the way it directs rays from the transmitting feed to the ground. Diverging rays leaving the transmitter reflect from the paraboloidal surface, emerging as parallel rays, in such manner as to keep the path length from the feed to an inclined wavefront constant. The inclined wavefront is perpendicular to -- and propagates along -- the axis of revolution of the parent paraboloid, which includes the parabola focus and vertex. Also, the reflector produces a beam of microwave energy with an abrupt drop in power outside the ray tube bounded by the perimeter of the reflector. As long as the distance from reflector to ground S is comparable to the reflector diameter D, the rays representing the transmitted wave will be parallel, and the wave will be planar. The governing equation for the nearfield of the reflector is: $S << 2 D^2 / ($, so when the reflector is positioned close to the ground, the radiated wave are in the nearfield and concepts of antenna gain and radiation pattern are irrelevant.

An offset section of the paraboloid is selected to avoid blockage of rays by the feed structure. In contrast to offset reflectors used in communications applications, this offset section is particularly deep, extending from the vertex past the focal point by twice the focal length, giving an F/D ratio of the parent paraboloid of about 0.15. The best offset section extends from 45 deg. to about 115 deg. from the symmetry axis, which ensures that the front and rear edges are at the same height above ground. For a parabolic focal length of 20 cm, the projected aperture diameter of the reflector is about 47 cm, which nominally illuminates an elliptical spot of ground with axes 47 and 67 cm. For a reflector positioned 33.5 cm above the ground, the center of this elliptical region is immediately below the front edge of the reflector, and all of the collimated rays from the reflector would reflect from a flat ground just missing the front of the reflector.

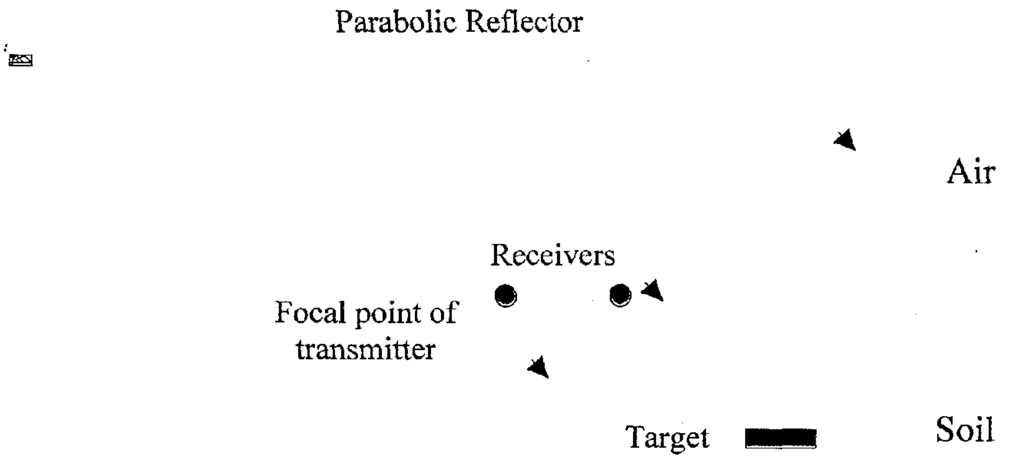

Figure 1. Geometry of the offset parabolic reflector

The receivers are positioned under the reflector, but behind the point on the ground at the center of the illuminated spot. The 4 receivers are arranged in a rectangular 2 by 2 array, with the forward pair separated by about 40 cm, and the backward pair by the same distance, 20 cm behind the forward pair. Since the receivers are displaced from the centerline, they do not appreciably block any of the wave from the reflector to the ground.

For FDTD modeling the dispersive soil, several modeling methods have been proposed to avoid convolution in the time domain [6,7]. Our method makes use of the Z-transformation. We approximate the frequency dependent conductivity using the (2-2) Pade' approximant

$$\sigma(Z) = \frac{b_0 + b_1 \cdot Z^{-1} + b_2 \cdot Z^{-2}}{1 + a_0 \cdot Z^{-1}} \tag{1}$$

and assume a constant average dielectric constant, With the a1, b0, b1, b2 parameters in (1) chosen to match the experimental data, such as Puerto Rican clay loam [8] with density 1.4 g/cc and moisture 10%, we have a1 = -0.88, b0 = 0.9162, b1 = -1.6766, b2 = 0.7611, and $\varepsilon = 4.2$. The perfectly matched layer (PML) absorbing boundary condition is used in the FDTD model to terminate the computational grid [9,10]. Computational models of the parabolic reflector system indicate that the wave reflected by the offset parabola do indeed remain planar over the illuminated region of ground, and that the scattering by rough soil surface is primarily specular. In addition, the mine scattered signal appears to be circular, showing that the electrically small target scatters almost isotropically.

Lawrence Livermore National Laboratory System and Results

The Lawrence Livermore National Laboratory (LLNL) Micro-Power Impulse Radar (MIR) was used as the transmitter source for one of fabricated systems. This radar source generates an impulse with pulse width of about 300 ps and frequency range from about 1.5GHz to 5GHz (see Figure 2), and has the particular advantage of being small and extremely low cost: both important features for mine detectors used in developing countries [5]. This source was assembled with a custom-built metallic offset paraboloidal reflector. Figure 3 shows the full mine detector prototype; Figure 4 show the device performing measurements at the test site at LLNL. In this test, a non-metallic antipersonnel mine simulant was buried in dry sand 1 in. below a very rough surface. This is a particularly challenging detection problem, because the dielectric constants of the plastic body TNT filled mine and the surrounding soil are very close. In addition, the random rough surface height variation is of the order of the height of the mine, and its burial depth. Thus, the anomaly detection is frustrated by low signal to clutter both in terms of size and contrast.

The result of processing the measured signals is shown in Figure 5, with bright areas signifying anomalies. Although there is still appreciable clutter from the rough ground, the target is still visible in the center of the image. The extent of the rough ground variation precludes clutter suppression using purely signal processing means. However, by ensuring that the ground scattered signal specularly reflects away from the receivers, the target signal can be discriminated from the clutter.

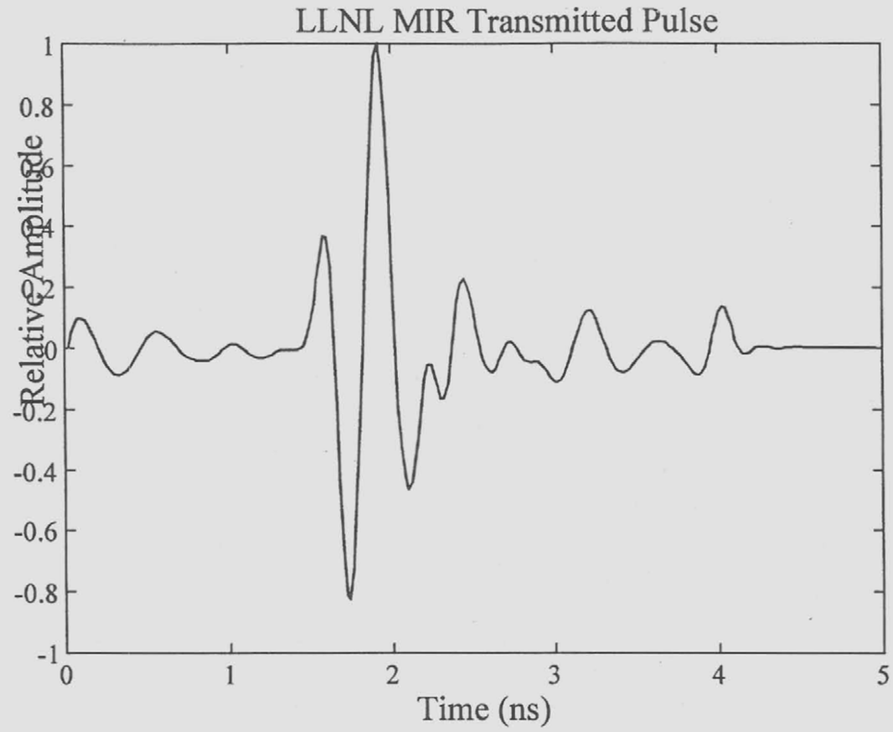

Figure 2 LLNL MIR pulse shape

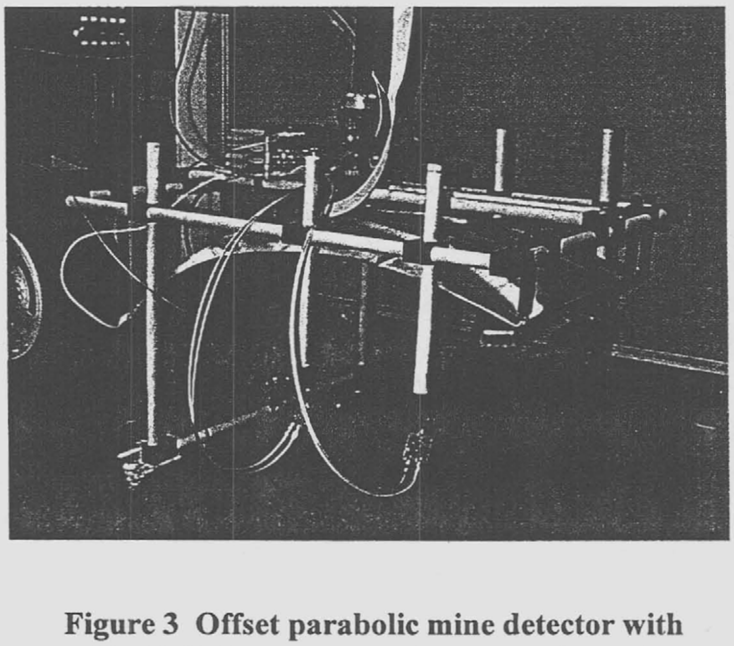

Figure 3 Offset parabolic mine detector with LLNL MIR sources and antenna elements

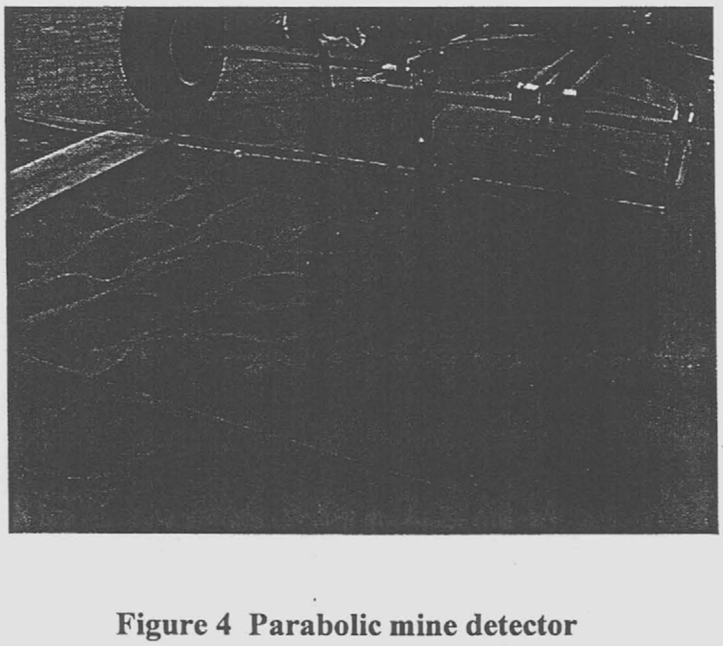

Figure 4 Parabolic mine detector under test at LLNL test site

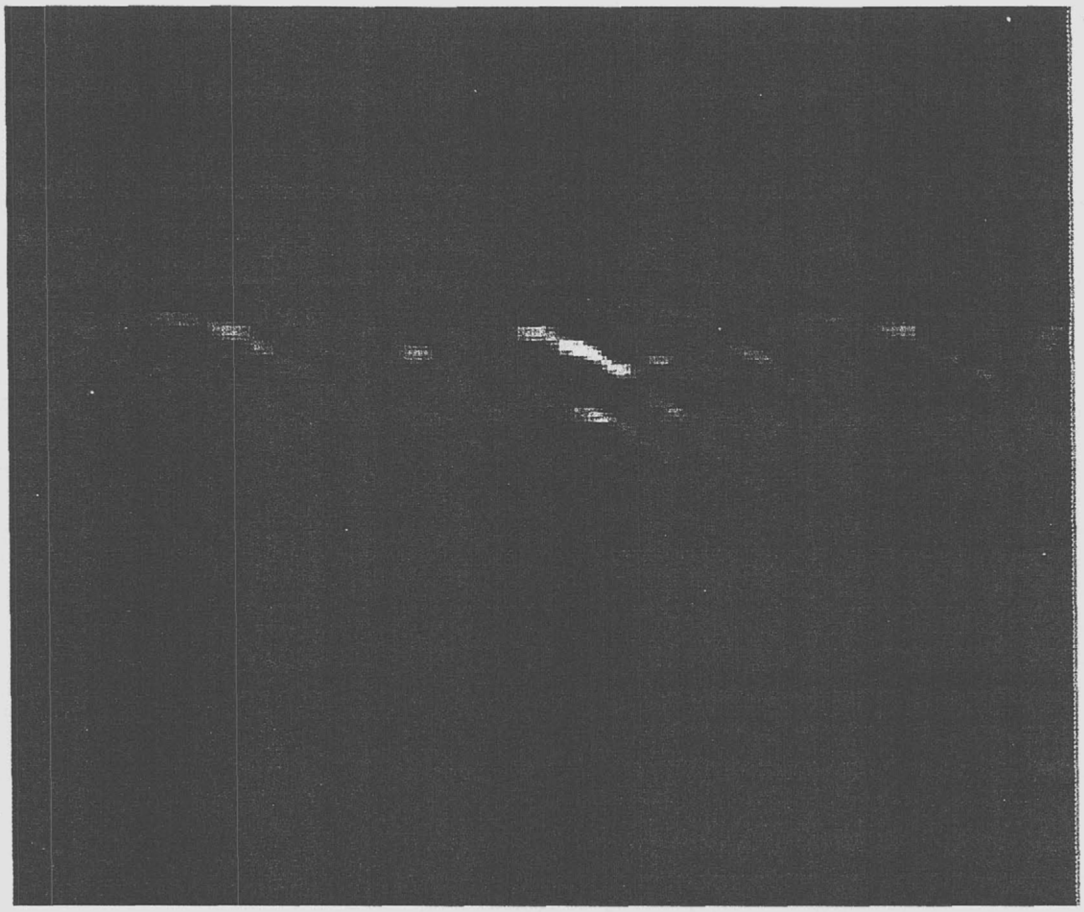

Figure 5 Detection results for the LLNL MIR system for rough sand with AP mine buried 1 in.

Geo-Centers System and Results

Another mine detection system based on the offset parabolic reflector tranmitter was fabricated by GeoCenters, Inc. The reflector consists of metallized fiberglass, and the antenna elements are proprietary Transverse Electromagnetic Rhombus (TEMR), fed by a 1 ns impulse shown in Figure 6.

The system is shown in Figure 7 as it is configured for measuring signals on the Northeastern University test track. The targets in this test were seven non-metallic anitpersonnel mine simulants buried 1 in. in moist loam, with naturally occuring vegetation. While this soil surface was not as rough as in the LLNL test, there is significant realistic clutter from long grass. The seven targets were spaced roughly 60 in. apart.

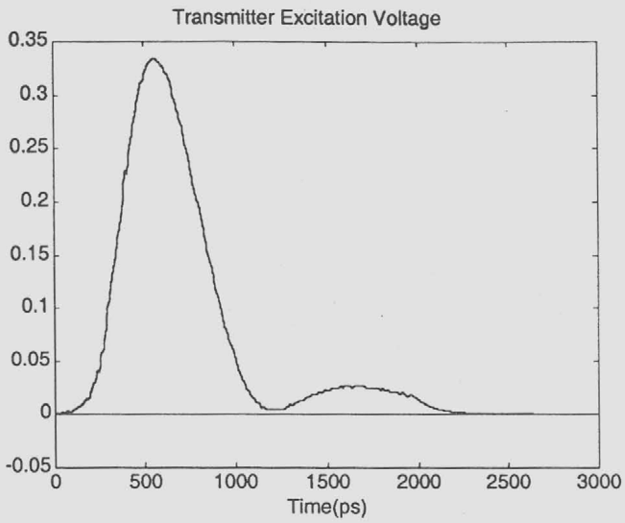

Figure 6 Time signal used by the TEMR element in the Geo-Centers system.

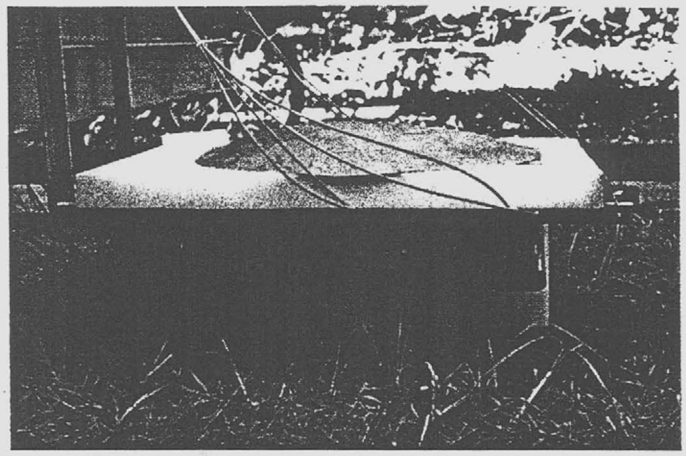

Figure 7 Geo-Centers TEMR-based detection system

Figure 8 shows the detection results by combining the registered signals from the four receivers each with the moving average background signal removed. It is apparent that six of the seven targets are detected (note the proximity to the indicated true postions), and only one false alarm is generated.

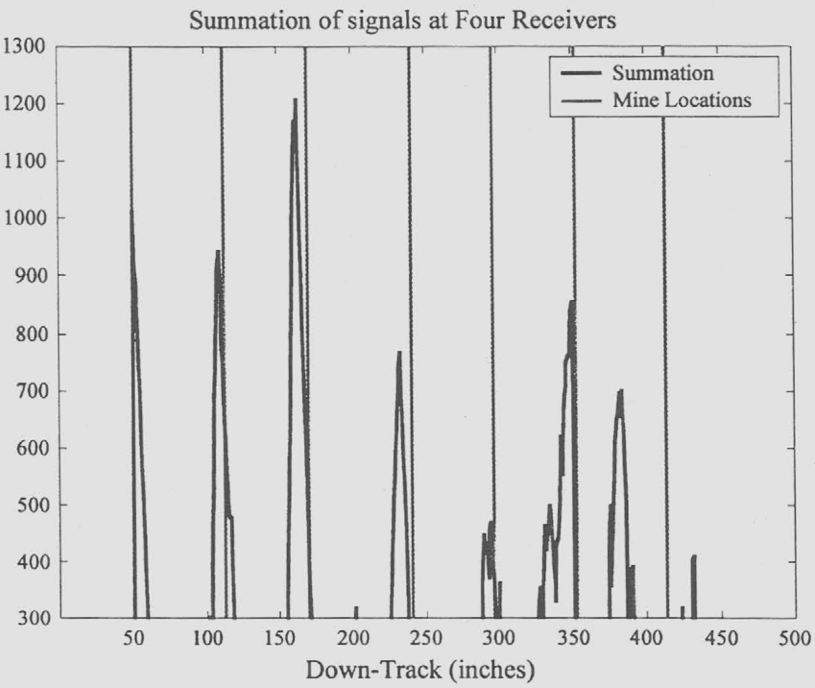

Figure 8 Detection results for the Geo-Centers TEMR system for vegetated moist loam with AP mine buried 1 in.

Conclusions

A novel GPR mine detection system which reduces ground surface clutter has been developed and tested. The detector uses an offset parabolic reflector to generate a forward propagating plane wave to illuminate the ground and a 2-dimensional multistatic array to focus and enhance the received backscattered signal. Numerical simulations support the concept of specular ground reflection with more isotropic target scattering.

Measured signals using both the LLNL MIR and the Geo-Centers TEMR radars for rough dry sand and vegetated moist loam indicate that small non-metallic targets can be detected and discriminated from the cluttered background, even when shallow buried to a depth of 1 in.

Acknowledgement

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