CHARACTERIZATION OF A COOPERATIVE TARGET FOR GROUND-PENETRATING RADAR

Christopher T. Allen, Kun Shi, and Richard G. Plumb
Radar Systems and Remote Sensing Laboratory, The University of Kansas, 2291 Irving Hill Road, Lawrence KS 66045, USA
callen@eecs.ukans.edu

ABSTRACT

A cooperative target (CT) has been developed to enhance the ground-penetrating radar (GPR) signal-to-clutter ratio for buried man-made targets. Applications include tagging high-value buried structures and monitoring microtunnelling equipment. Results are presented for a time-domain CT, comprised of a dipole antenna connected to an unterminated delay line. Multiple GPR measurements made from separate positions, together with a priori knowledge of the dielectric properties of the intervening ground, allow good estimation of the position of the tagged target through triangulation. By using several independent time-domain cooperative targets, strategically arrayed about a target, the rotational aspect of the target can also be obtained. Finally, harmonic generation is demonstrated as a technique for a frequency-domain CT.

Key words: Ground-penetrating radar, Excavation

INTRODUCTION

The value of ground-penetrating radar (GPR) as a survey tool prior to excavation is growing. Its ability to detect (and hence avoid) natural obstacles (such as rocks) and man-made obstacles (utility lines, pipelines, vaults, etc.) enables the equipment operator and route planner to perform their tasks more efficiently. Take, for example, the use of microtunnelling (directional boring), a trenchless technology involving the installation of pipes having an internal diameter too small for man entry with steering via remote control. In this operation the detection and avoidance of existing underground structures and obstacles often drives the cost of new service installation. Further, effective steering of the microtunnelling tool head requires precise knowledge of its position and orientation, information GPR could potentially provide.

GPR echoes from subterranean man-made objects (targets in radar parlance) may not be inherently easy to identify or distinguish from echoes of the naturally occurring background (i.e., clutter). For example, a fiber optic cable may present a very weak echo (low backscatter) in the midst of other scatterers such as tree roots, small rocks, buried debris, etc. Or a plastic pipe containing air or some other gas may not be readily identifiable in the presence of other scatterers. In cases such as these, GPR performance is not noise limited; i.e., increasing the GPR sensitivity will not improve its ability to discriminate man-made targets from background clutter. Instead, GPR performance is limited by the weak target signal relative to the background clutter signals; i.e., the signal-to-clutter ratio (SCR). Therefore, to improve the GPR's discrimination capability, techniques that improve the signal-to-clutter ratio are required.

We could, of course, approach this problem by boosting the target signal level by enhancing its radar cross section (RCS). To do this we could introduce a large metallic reflector or perhaps an amplifier connected between a pair of antennas. For this approach to be successful the resultant RCS of the target must be much larger than that of the clutter. This will become difficult when the clutter cross section is substantial. Further, the techniques involved in enhancing the target RCS may be expensive, too large for the application, or unreliable.

We chose another approach to enhance the signal-to-clutter ratio. The cooperative target (CT) concepts reported here improve the target's signal-to-clutter ratio significantly by causing the returned signal from the designated target to have a unique characteristic or signature. Any number of techniques may be applied to provide this target with a unique radar signature. We report two such techniques–one for time-domain GPR systems, the other for frequency-domain GPR systems. In both cases, through careful design, the SCR can be improved by orders of magnitude. In addition, these designs are entirely passive resulting in a more robust design.

TIME-DOMAIN COOPERATIVE TARGET

In time-domain ground-penetrating radar systems, a brief pulse of electromagnetic energy is transmitted followed by an interval during which the receiver records the returning signals.

Signals backscattered from clutter and the target can have comparable power levels and arrival times making it difficult, if not impossible, to distinguish one from the other. The approach we selected to improve the signal-to-clutter ratio is to introduce additional delay in the signal from the target while preserving its nominal signal strength. The cooperative target here is comprised of an antenna connected to an unterminated delay line (the far end of the line is an open circuit) attached to the target. A portion of the incident signal is received through the antenna, coupled into the delay line, and, after traversing the delay line, this signal is totally reflected at the far end, retracing its path through the delay line to be retransmitted back through the original antenna. The signal from the CT is delayed with respect to the target echo and its surrounding clutter. While the signal from the CT experiences minimal attenuation (due to delay line losses), the signal from clutter at the depth corresponding to the round-trip travel time through the delay line is attenuated further by the ground medium, resulting in an improved SCR.

Figure 1 illustrates the concept of the time-domain CT. If we assume uniform clutter throughout the medium, and that the target of interest returns an echo comparable in strength to the clutter, then the received signal power level will decrease with increasing depth due to attenuation through the medium until the signal is below the system's minimum detectable signal level (or noise floor). The signal from the cooperative target is delayed, yet maintains approximately the same signal power. Thus at the depth where the cooperative target appears, the background clutter signal is smaller than the minimum detectable signal level and a significant signal-to-clutter ratio results.

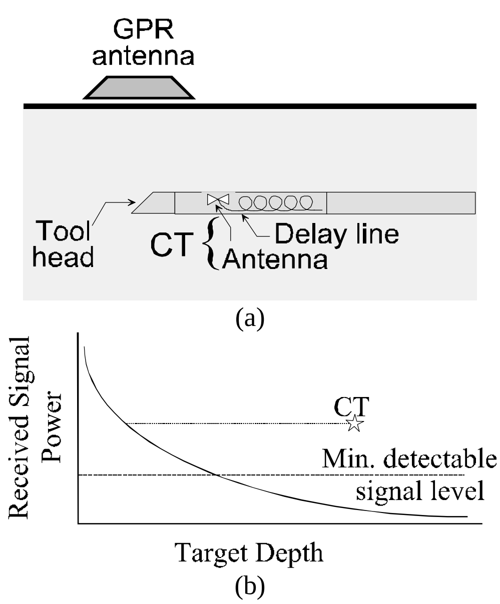
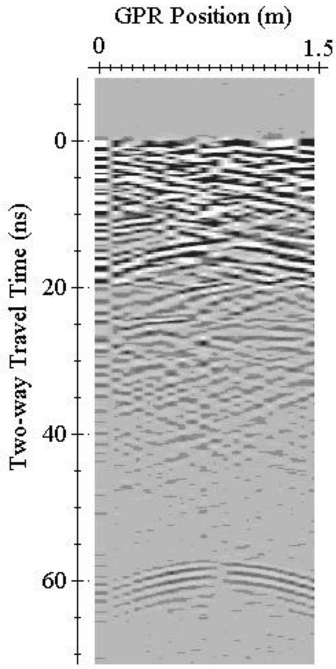
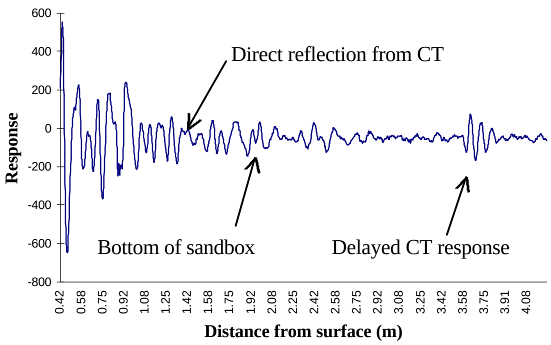


Figure 1. Concept of the time-domain CT. (a) The geometry of the CT and GPR in a microtunnelling application; (b) an illustration of how the signal-to-clutter ratio is improved.

To demonstrate this concept, a time-domain cooperative target was assembled and tested. The CT (a dipole antenna connected to an unterminated coaxial delay line) was fastened to a plastic pipe to maintain the desired geometry. This assembly was then inserted into the indoor ground-penetrating radar test tank (the sand pit) at the Radar Systems and Remote Sensing Laboratory of The University of Kansas (Goodman and others, 1996). This test tank, a reinforced concrete enclosure measuring approximately 3.6 m x 5.2 m and 1.8 m deep and filled with sand, has access ports near the bottom of the tank enabling the insertion of the CT into the deepest sand without digging. The time-domain GPR used was a Sensors and Software pulseEKKO 1000 system operating at a center frequency of 900 MHz. The measured data were collected as the GPR moved along the surface, passing directly above the position of the cooperative target. The polarization of the CT dipole was aligned with that of the GPR antennas (which is perpendicular to the GPR travel direction). In Figure 2(a), the GPR travel distance was about 1.5 m with new traces collected about every 7.6 cm.



(a)



(b)

Figure 2. Measured time-domain CT performance. (a) A gray-scale graph of the radar response; (b) a close-up look at a single time-domain trace.

The received signal is composed of reflections from both the target and clutter; i.e., reflections from the walls and bottom of the sand pit, as well as from inhomogenieties within the sand. The direct reflection from the target lies in the upper part of the graph and is difficult to distinguish from the clutter. In the lower part of the plot, where the clutter is attenuated further, we can clearly see the characteristic hyperbolic response from the cooperative target.

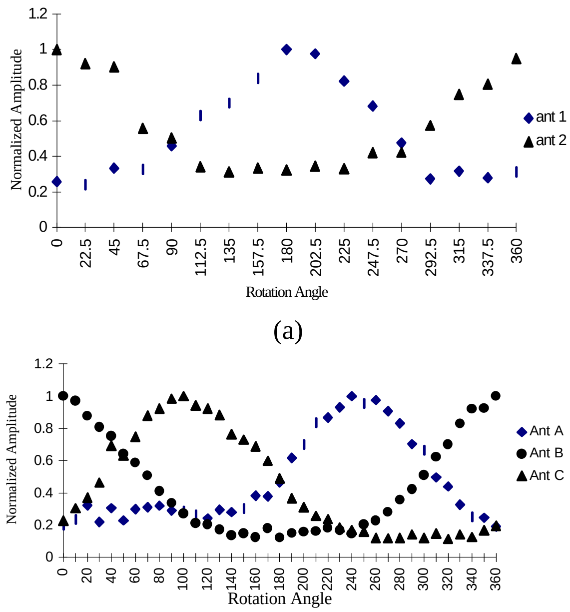
To obtain the true position of the CT, the depth offset due to the delay line (a constant) can be removed. We can determine the depth of the target attached to the CT from the two-way travel time. The CT echo begins at about 57 ns on the time axis, representing the round-trip time to the target plus the known time delay through the delay line of 40.3 ns, yielding a round-trip time to the target of about 16 ns. The relative dielectric constant of the sand was measured and found to be 4.7; therefore, the depth of the cooperative target is about 1.1 m. From the sample scan trace shown in Figure 2(b), we see that the delayed response of the CT corresponds to a depth of 3.7 m. At this distance, well beyond the bottom of the sandbox at about 1.8 m (27 ns of round-trip time), the clutter signal is greatly attenuated. The improved SCR is clearly in evidence, comparing the direct response (i.e., the echo from the target) at time 16 ns (about 1.1 m of depth) with the delayed response (via the CT) at time 57 ns. Note that while the signal level remained about the same, the clutter level is significantly decreased at the greater depths.

Accurate determination of the CT location can be determined through triangulation using GPR measurements made from multiple locations on the surface. With this approach the accuracy of the location estimate is limited by the accuracy of the GPR measurements and the knowledge of the dielectric properties of the material between the GRP and the CT. Our experiments have shown that the accuracy of this method is within about 2 cm when the CT is buried at a depth of about 1 m in dry sand.

Target Orientation

To apply this concept to the microtunnelling application, information about tool head orientation is also desired. To demonstrate how this technique can be used to determine rotational orientation we extended the concept to two (and later three) separate cooperative targets, each comprised of its own dipole antenna attached to independent delay lines of different lengths. In this arrangement, the response from the target will be composed of two distinct time-delayed responses corresponding to the two CTs. Assuming the nominal antenna characteristics and the attenuation through the delay lines are similar, variations in the amplitudes of the two time-delayed responses will depend on variations in the antenna gains, which depend on the aspect angle of each CT and the GPR. From the variations in the amplitudes, information on the rotational orientation of the target is obtained.

Figure 3(a) shows the variation of received CT signal amplitudes measured at different target rotational angles for a two-CT configuration and Figure 3(b) shows this for a three-CT configuration. For the two-CT configuration, the antennas are located on opposing sides of the target, (i.e., while one is on top, the other is on the bottom) and, as the target is rotated, the signal strength varies due to changes in the antenna gain. We see from the graph that the rotation angles where the two CT responses peak are 180° apart. In Figure 3(b), the maxima are separated by 120° as the antennas were located 120° apart in this configuration. [Note that the responses are normalized; their absolute amplitude can be different corresponding to their delay.] With the three-CT configuration, we estimate the target rotational angle can be unambiguously determined to within ±10°.



(a)

(b)

Figure 3. Normalized response at different rotation angles for (a) the two-CT configuration and (b) the three-CT configuration.

FREQUENCY-DOMAIN COOPERATIVE TARGET

In frequency-domain ground-penetrating radar systems, a sequence of narrow-band, relatively long-duration electromagnetic tones are coupled into the ground and the returned signal is sampled. Through spectral analysis, range and radar-cross-section information regarding subsurface targets is obtained. A cooperative target for this type of GPR has also been developed. To obtain the enhanced SCR in this scheme, a frequency shift is introduced in the signal returned from the CT. Clearly echoes from naturally occurring subsurface targets will have the same frequency as the transmitted GPR signal. The only source of a frequency-shifted signal will be the CT; hence, for a GPR designed to detect this frequency-shifted signal as well as the fundamental (unshifted-frequency) signal, an enhanced signal-to-clutter ratio is obtained.

One technique for achieving this frequency shifting is to generate a harmonic of the original signal. This can be performed with devices exhibiting a non-linear transfer characteristic. One such device is a simple diode. When properly stimulated, harmonics of the stimulating signal are developed. This is the approach we followed for the frequency-domain CT.

The feasibility of this approach depends on the diode conversion efficiency, defined as the ratio between the power received at the cooperative target and the second-harmonic power reradiated by the target. Numerical models suggest conversion efficiencies may range from -10 to -30 dB depending on various diode parameters. While Schottky diodes are superior to p-n junction diodes in many aspects, for GPR applications that use the lower end of the microwave frequency range, silicon p-n junction diodes are of comparable efficiency and are available at a lower cost.

Preliminary Measurements

To evaluate the feasibility of this approach and to measure the second-harmonic power reradiated by the CT (a diode), an experiment was carried out with a network analyzer serving as the signal source and a spectrum analyzer serving as the receiver, as shown in Figure 4.

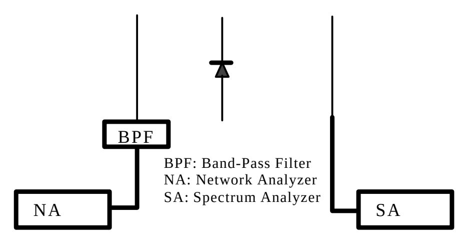
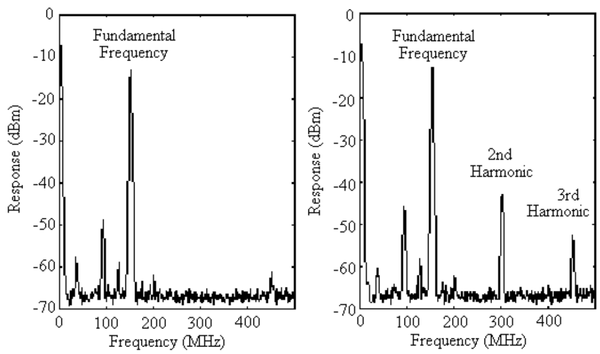


Figure 4. Experimental setup used to evaluate the feasibility of the frequency-domain CT concept.

To minimize the interference caused by the harmonics generated within the signal source, a narrow-band, band-pass filter centered at 150 MHz was used between the source and the transmitting antenna. The transmitting and receiving antennas are both simple monopole antennas, while a 1N23C silicon mixer diode was attached to a dipole antenna placed between the other two antennas.

The distance between the transmit and receive antennas was about 1 m, and the distance from the transmit antenna to the diode was about 0.5 m. The network analyzer generates about 20 dBm of CW power at 150 MHz. Figure 5(a) shows the received signal without the diode. We can see the fundamental frequency component is about 32 dB down from the signal source power due to transmission losses. This is due in part to the fact that the antenna lengths are much shorter than the half wavelength (1 m) and, therefore, the radiation efficiency of the antennas is not optimized. Figure 5(b) shows the received signal with the diode present. It can be observed that a significant amount of second-harmonic power is generated when the diode is present. The second-harmonic signal level is about -30 dB relative to the fundamental signal level, which is within expectations. Next we buried the diode in the sand and measured its response; we observed a response essentially identical to that shown in Figure 5(b), as expected.



(a) (b)

Figure 5. Emulation of a frequency-domain CT through second-harmonic generation in a free-space measurement: (a) without diode and (b) with diode.

The generation of the second-harmonic signal with a diode demonstrates the feasibility of this technique for a cooperative target with a frequency-domain GPR.

CONCLUSIONS

We have presented the results of a cooperative target for the time-domain GPR employing a simple dipole antenna connected to a delay line terminated in an open circuit. We have further demonstrated how the three-dimensional location of the time-domain cooperative target can be determined from a few, separate GPR measurements and a priori knowledge of the ground dielectric properties. By using an array of independent time-domain cooperative targets, strategically placed about the target, the rotational aspect of the target can also be obtained. That such a system is compatible with commercially available, time-domain GPR systems has also been demonstrated.

We have also demonstrated the feasibility of using harmonic-frequency generation as a basis for a cooperative target in the frequency domain. This approach holds the promise of more simplicity and reduced cost (over the time-domain CT) in that the CT may consist of a diode with leads. The drawback to this approach is that we are unaware of any commercially available frequency-domain GPR systems having the signal purity required for this approach.

Regardless of the approach (time-domain or frequency-domain) we believe this development offers a solution to a problem encountered daily by those involved in excavation; i.e., how to detect, identify, and locate buried man-made systems, such as fiber optic transmission lines or high-pressure gas pipelines, the disruption of which would have severe consequences.

ACKNOWLEDGEMENTS

This work was funded by Vermeer Manufacturing Co., Pella, IA. Key elements of this work are protected under U. S. Patent 5,720,354 with other patents pending.

REFERENCE

Goodman, N., C. Leuschen, R. Plumb, and C. Allen, "Subsurface Imaging Techniques Applied at a Ground-Penetrating Radar Test Facility," *Proceedings of the 6th International Conference on Ground Penetrating Radar (GPR '96)*, 30 September to 3 October 1996, Sendai, Japan, pp. 395-397, 1996.