Predicting GPR Target Locations Using Time Delay Differences

Ali Cafer Gürbüz , James H. McClellan and Waymond R. Scott Jr. *

Georgia Institute of Technology
Atlanta, GA 30332-0250;

ABSTRACT

We describe an efficient approach for finding probable target areas quickly with a minimal number of Ground Penetrating Radar (GPR) measurements. Since a potential GPR target creates a hyperbolic signature in the space-time domain, our approach uses the time delay differences from consecutive GPR A-Scan data to estimate the location of the apex of the hyperbolic signature, thus locating a target. This apex prediction method uses many fewer measurements than a full backprojection algorithm. Regions of low target probability are determined using a Neyman-Pearson detection approach in order to eliminate redundant measurements. In this regard, our approach is especially suitable as a pre-screener: other sensors that are more accurate, but require more measurement time, can then be applied only to high probability-of-target areas to corroborate results, differentiate between targets, or provide more accurate location measurements. Compared to a standard backprojection algorithm more signal-to-noise ratio (SNR) is needed to achieve similar detection performance. This SNR loss can be reduced by using a more conservative algorithm which reduces the step size of the GPR antenna. Results from experimental data collected at a model mine field at the Georgia Institute of Technology show that target positions can be found accurately using less than 10 % of the measurements utilized by conventional imaging algorithms.

Keywords: Time Delay Difference, Adaptive search, Prescreening, minimal measurement number,Ground penetrating radar (GPR), steepest descent, landmine detection

1. INTRODUCTION

Synthetic aperture ground penetrating radar (GPR) techniques have been primarily used for the imaging and detection of subsurface targets. Other applications include the investigation of shallow geological and engineering features on land. In this paper, we consider the problem of detecting and imaging subsurface land mines. The ecologically desirable and non-destructive nature of GPR, as well as its capability of sensing variation in dielectric properties, makes GPR effective for the mine detection problem.[1–4]

The GPR transmissions spanning the region of interest form a synthetic aperture, whose impulse response is a spatially-variant hyperbolic curve in the space-time domain. The total subsurface response, formed from a combination of the responses from all reflectors within the medium, can be inverted using a number of imaging algorithms; e.g. Time Domain Standard Backprojection (SBP),[2,5] Fourier domain Synthetic Aperture Radar (SAR) image formation techniques,[6,7] quadtree imaging[8] etc. However, all of these methods require scanning the entire region prior to imaging. Our paper presents an alternative method for prescreening and detection that does not require scanning the entire area or processing all the data from a comprehensive scan. Instead, subsequent measurement locations are determined based on previous measurement data to minimize the total required amount of data. Thus, an adaptive search strategy for the GPR is generated.

Proposed algorithm depends on the detectibility of the reflected target echo. If a target is detected, then an adjacent data measurement (i.e. separated by only one measurement interval) is also processed. Both of these data points must lie along the hyperbolic signature of the target. Thus difference between the time delays at the two consecutive measurement points can then be used to estimate the target position. Then the antenna

*This work is supported under MURI by the U.S. Army Research Office under contract number DAAD19-02-1-0252
Further author information: (Send correspondence to Ali Cafer Gürbüz): E-mail:alicafer@ece.gatech.edu

Detection and Remediation Technologies for Mines and Minelike Targets XI, edited by
J. Thomas Broach, Russell S. Harmon, John H. Holloway, Proc. of SPIE Vol. 6217,
621731, (2006) · 0277-786X/06/$15 · doi: 10.1117/12.666335

can be directly moved to the estimated target position to verify the target. This method doesn't need the full hyperbolic scan of the target and reduces total number of measurements.

If a target has not been detected from the initial measurement, this means that the probability of being a target in the footprint of the antenna is low. It is both waste of time and resources to scan the entire surface even though there may not be any target present. In the case of no detection, the antenna is moved to another position such that there is no overlap between the areas reached by the antenna and entire scan area is covered (Section 2.2). The antenna moving distance depends on the antenna beamwidth, antenna height and transmitter-receiver distance. This property is independent of time delay difference algorithm (TDD) and further reduces the total number of measurements.

Reduction in total measurement number doesn't come without cost. Targets might not be detected in high clutter or high clutter might cause changes in time delay measurements which will result as wrong target position estimates. Performance of the proposed algorithm is tested under high clutter conditions and compared with standard backprojection (SBP) algorithm. It is observed that TDD algorithm needs more signal-to-noise ratio (SNR) to achieve the same performance with SBP. Simulations comparing the algorithm performances in varying noise levels show that for SNR values greater than -5dB both algorithms performs similarly. For SNR below -15dB TDD algorithm has a very poor performance. It is also observed that using a more conservative algorithm which decreases the estimated moving distance of the antenna, SNR loss between TDD and SBP algorithms can be decreased. The proposed algorithm has been tested using data collected from a model mine field located at the Georgia Institute of Technology. Results confirm that target positions can be accurately determined using a minimal number of data measurements.

The next section expands on the theory of the proposed algorithm. Performance comparison between TDD and SBP algorithms are given in Section 3. Experimental results are shown in Section 4.

2. THEORY

The proposed algorithm consists of detecting target reflections, calculating measurement intervals for non-target areas and estimating target position using the time delay difference (TDD) method. Each of these parts are analyzed in more detail in the following subsections.

2.1. Detection of Target Reflections

We can represent the received signal at the GPR antenna as

$$x[n] = \frac{s[n-n_0]}{r} + w[n] \tag{1}$$

where $s[n-n_0]$ is a delayed version of the transmitted signal, $1/r$ is a scaling factor used to account for geometrical spreading, and $w[n]$ is a white gaussian noise (WGN) term that approximates any measurement noise or clutter.[9] The transmitted pulse $s[n]$ is specified by the user. It is desirable to design the transmitted pulse to be as short as possible in time so to increase the target resolution. In our experiments, a double-differentiated Gaussian pulse (Fig. 1 (a)) with frequency response (Fig. 1 (b)) was utilized. If we keep r constant by fixing the target depth we wish to test, then the detection problem reduces to that of detecting a known signal in WGN[10]:

$$\begin{aligned} &H_0 : x_r[n] = w_r[n] \quad n = 0, 1, ...N-1 \\ &H_1 : x_r[n] = s_r[n] + w_r[n] \quad n = 0, 1, ...N-1 \end{aligned} \tag{2}$$

where $s_r[n] = \frac{s[n-n_0]}{r}$ is assumed to be known and $w_r[n]$ is WGN with variance σ_r^2. The Neyman-Pearson (NP) detector decides H_1 if

$$T_r(\mathbf{x}) = \sum_{n=0}^{N-1} x_r[n]s[n] > \gamma'. \tag{3}$$

The threshold γ' depends on the probability of false alarm and is selected as follows:

$$\gamma' = \sqrt{\sigma_r^2 \varepsilon} Q^{-1}(P_{FA}). \tag{4}$$

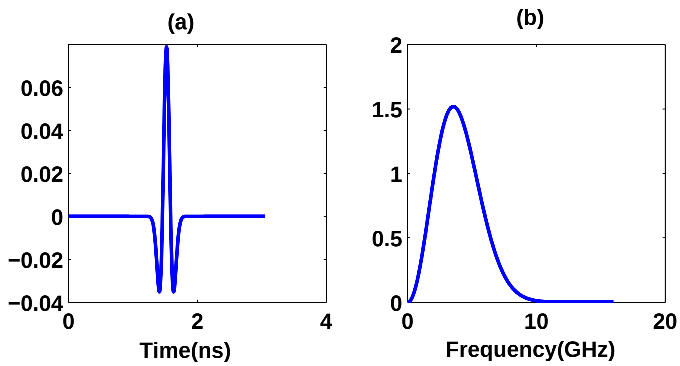


Figure 1. (a) : Theoretical expected target return (b): Frequency response of the target return.

In (4), ε is the energy of the transmitted pulse $s[n]$ and $Q(x) = 1 - \Phi(x)$, where $\Phi(x)$ is the cumulative density function (CDF) of a $N(0, 1)$ random variable. The variance σ_r^2 is usually not known beforehand, but can be estimated from measured data known not to contain any targets.

Time delay for the target response is the time value where the correlation $T_r(x)$ is peaked while it is above the threshold value. Since there might be more than one target at one measurement point at different depths, there might be more than one peak in $T_r(x)$. Each time delay value corresponding to each peak is stacked in a time delay vector for that particular measurement point to be used in TDD algorithm.

2.2. Detecting non-target areas

Normally an entire surface area is scanned by the GPR antenna even though no targets may be present. This wastes both time and resources. We propose that the GPR antenna be moved intelligently so that the radar avoids searching for targets in an area where there is a very low probability that any targets are present. From Fig. 2 it can be seen that if no target reflection is detected at a given measurement point then it can be concluded that there is no target in the shaded region - more specifically, the region in which the transmitter and receiver antenna footprints overlap. Here we assume that the antennas have a limited beamwidth, as represented by θ in Fig. 2, and that the antennas can only send power to or receive echoes from the area spanned by the beamwidth.

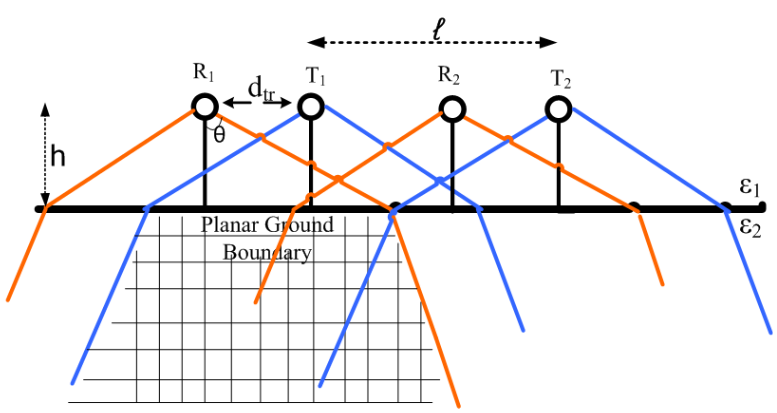


Figure 2. Detection Region of the antenna pair at the measurement point.

In Fig. 2 T1-R1, and T2-R2 represent the transmitter-receiver pairs used to take measurements at points that we will label 1 and 2, respectively. If a target is not detected at Measurement Point 1, instead of making unnecessary measurements for the non-target area, antennas can be moved by the amount

$$l = 2h \tan\theta - d_{tr} \tag{5}$$

to Measurement Point 2, as shown in Fig. 2.

2.3. Time Delay Difference Method

2.3.1. Search In One Dimension

The response of a point target to GPR is a hyperbola in the space-time domain. When the detection test turns out positive it means that the measurement point is on the hyperbola created by the target. The Time Delay Difference (TDD) Method estimates the target position, given by the peak of the hyperbola, from two aperture point measurements using the difference in the target echo delays. In this way, the antenna can be moved directly to the target location without scanning the entire hyperbolic response or doing any imaging. Another advantage of this algorithm is that it is real time. The entire area does not need to be scanned prior to making a detection decision; rather, decisions are made as measurements are taken, and subsequent measurement points are determined based on these decisions.

Figure 3 represents a monostatic GPR antenna taking measurements in a single homogeneous medium. The

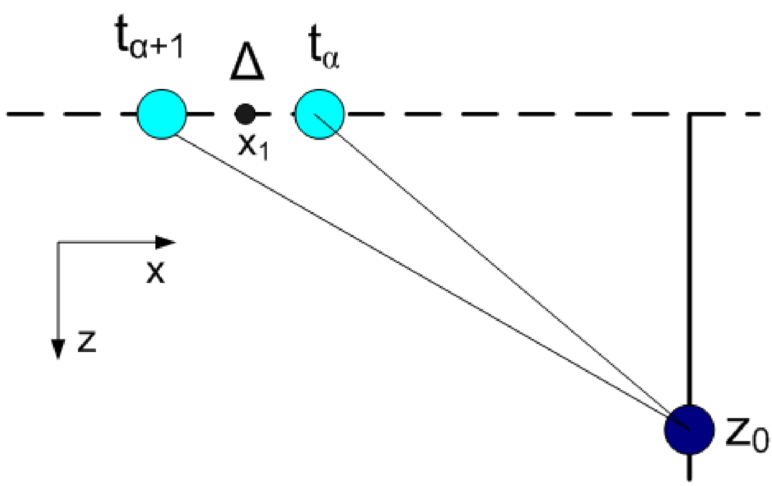


Figure 3. Measurement setup of a monostatic GPR in one homogeneous medium

target is located a distance z_0 below the level of the antenna. Δ represents the step size of the antenna movement in the x direction. t_α and $t_{\alpha+1}$ represent the time delays of the transmitted pulse that are received at the aperture points; in other words, the aperture points are located $\alpha\Delta$ and $(\alpha+1)\Delta$ away from the x position of the target. The TDD algorithm uses the difference in delay times to find α, the number of aperture points the antenna is away from the target.

The time delays for the target returns at the two consecutive aperture points can be written as follows:

$$\begin{aligned} t_\alpha &= \tfrac{2}{c}\sqrt{z_0^2 + (\alpha\Delta)^2} \\ t_{\alpha+1} &= \tfrac{2}{c}\sqrt{z_0^2 + ((\alpha+1)\Delta)^2} \end{aligned} \tag{6}$$

By taking the difference in squared time delays α can be found as in (7)

$$t_{\alpha+1}^2 - t_\alpha^2 = \tfrac{4}{c^2}(2\alpha+1)\Delta^2 \quad \Rightarrow \quad \alpha = \tfrac{1}{2}\tfrac{c^2}{4}\tfrac{t_{\alpha+1}^2 - t_\alpha^2}{\Delta^2} - \tfrac{1}{2} \tag{7}$$

From (7), it can be seen that the difference in squared time delays between two aperture points only depends on the step size of the antenna and the number of aperture points between the antenna and the target. It does not depend on the target depth. For any target at any depth, α can be calculated by (7).

2.3.2. Searching In Two Dimensions:

Generally, a GPR system searches for the targets on a two-dimensional (2D) area (x and y dimensions). In this case two measurements are not sufficient to find the target position, instead three measurements making pairs of two both in x and y directions are used two find the position of the target on x and y dimensions consecutively. First measurement point is the position of the antenna where the reflection of the target is detected. The second and third measurement points are next aperture points on x and y dimensions. Denoting target position with (x_T, y_T, z_T) and the three measurement points as $(x_A, y_A, 0)$, $(x_A + \Delta, y_A, 0)$, $(x_A, y_A + \Delta, 0)$, the squared time delay values for each measurement point is given as

$$\begin{aligned} t_{D1}^2 &= \tfrac{4}{c^2}(x_T - x_A)^2 + (y_T - y_A)^2 + z_T^2 \\ t_{D2}^2 &= \tfrac{4}{c^2}(x_T - x_A - \Delta)^2 + (y_T - y_A)^2 + z_T^2 \\ t_{D3}^2 &= \tfrac{4}{c^2}(x_T - x_A)^2 + (y_T - y_A - \Delta)^2 + z_T^2 \end{aligned} \tag{8}$$

When the difference of the squared time delays are taken on both x and y dimensions the target position can be found as follows;

$$\begin{aligned} t_{D1}^2 - t_{D2}^2 &= \tfrac{4}{c^2}(2\alpha_x + 1)\Delta^2 \quad \Rightarrow \quad \alpha_x = \tfrac{1}{2}\tfrac{c^2}{4}\tfrac{t_{D1}^2 - t_{D2}^2}{\Delta^2} - \tfrac{1}{2} \\ t_{D1}^2 - t_{D3}^2 &= \tfrac{4}{c^2}(2\alpha_y + 1)\Delta^2 \quad \Rightarrow \quad \alpha_y = \tfrac{1}{2}\tfrac{c^2}{4}\tfrac{t_{D1}^2 - t_{D3}^2}{\Delta^2} - \tfrac{1}{2} \end{aligned} \tag{9}$$

From (9) it can be seen that the 2D search problem can be seen as two independent 1D search problems which can be solved separately. Next section compares the TDD algorithm performance with SBP for varying clutter levels.

3. EFFECT OF CLUTTER LEVEL ON TDD ALGORITHM

The effect of clutter on the performance of the TDD algorithm relative to time-domain backprojection is evaluated using simulated GPR data. White Gaussian Noise (WGN) with varying variance levels is added to the simulated point target response. The signal-to-noise ratio (SNR) is defined as the highest signal power of the A-scans divided by the average total noise power of one A-scan. The proposed TDD algorithm, a more conservative TDD algorithm which goes half the estimated distance and the standard backprojection algorithm are applied to the test data. This procedure is continued 200 times and the positive detection results for each algorithm

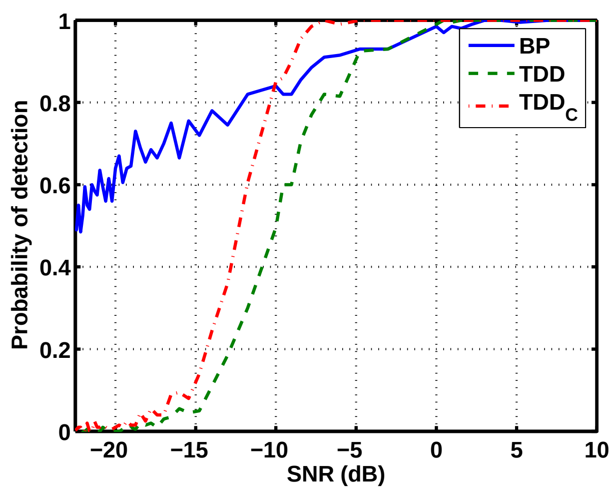


Figure 4. Simulated space-time response of a point like target.

is counted. If the estimated target position for TDD algorithms is in ±4 cm region of the true target position, positive detections for TDD are increased by one. Similarly, if the maximum point in the migrated image for SBP is ±4 cm and ±1 cm region of the true target position in x and depth dimensions respectively, positive detections for SBP are increased by one. Figure 4 shows the normalized probability of detection vs. SNR plot for each algorithm.

One important point that can be seen in Fig.4 is that there are not much difference in the performance of TDD and SBP algorithms when the SNR is bigger than -5 dB. The probability of detection is close to 1 for all algorithms when SNR is bigger than -5 dB. Another important point is that TDD algorithms don't work at all for very high clutter situations specifically for SNR values less than -15dB. For these SNR values SBP algorithm still gives good detection of the target. For SNR values less than -5dB but bigger than - 15dB SBP has a bigger P_D compared to all TDD algorithms. Also in this SNR region it can be seen that the conservative TDD algorithm has better P_D values compared to TDD and TDD has nearly 3dB SNR loss to have the same detection performance as conservative TDD algorithm.

4. RESULTS

The TDD method is tested using experimental data collected from a model mine field at the Georgia Institute of Technology.[4] Following scenarios are tested:

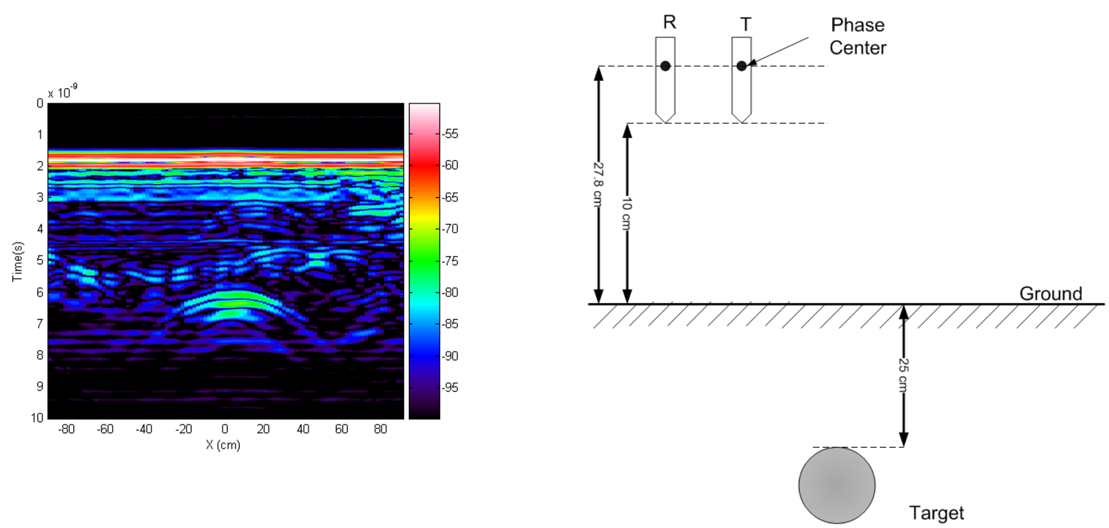
1) A single target (11 cm diameter metal sphere) buried in a sandbox at a depth of 25 cm, processing with the 1D TDD algorithm (Figure 5);

2) Multiple targets (including mines, rocks and other reflectors) buried in a sandbox at a variety of depths (Figure 7), processed with the 2D TDD algorithm.

The phase centers of the antennas are elevated 27.8 cm. Transmitter receiver distance is 12 cm . The beamwidth of each antenna is taken as 30°. Results for each configuration are presented next.

Configuration 1: Single Buried Target, 1D Processing

In Figure 5(a) below, an example of a line scan taken over the buried target is shown. The hyperbolic response of the target as well as the nearly flat ground reflection can be clearly seen. The scan is comprised of a total of 91 measurements with a step size of 2 cm. However, as will be seen by our processing results, in fact only 14 data points are required for successful detection of the target and determination of its position.



(a) (b)

Figure 5. (a) Buried Target Line Scan, (b) Buried Target Measurement Setup.

We begin by taking the first data measurement and applying the detection test described in Section 2 to determine whether a target is present or not. If no detection is made, then (5) is used to calculate what distance the antennas will be moved. Given the configuration sketched in Fig. 5(b) , we find $l = 20.1cm$, which corresponds to an increment of 10 aperture points.

Table 1. TDD Algorithm Results for Buried Target

TDD Algorithm Results		
Measurement Point	Time Delay(ns)	Estimate (α)
41	5.7397	6
42	5.7092	
48	5.6482	-2
49	5.6421	

After advancing the antenna by 10 aperture points, the detection test is repeated on the new data point. In this case, the first 4 measurements yield no detection. At the 5th data point, however, a detection is made, thus, the antenna is advanced only by only one more step to collect a second data point, which will be used in the TDD algorithm. The results of these detection tests are shown in Fig. 6.

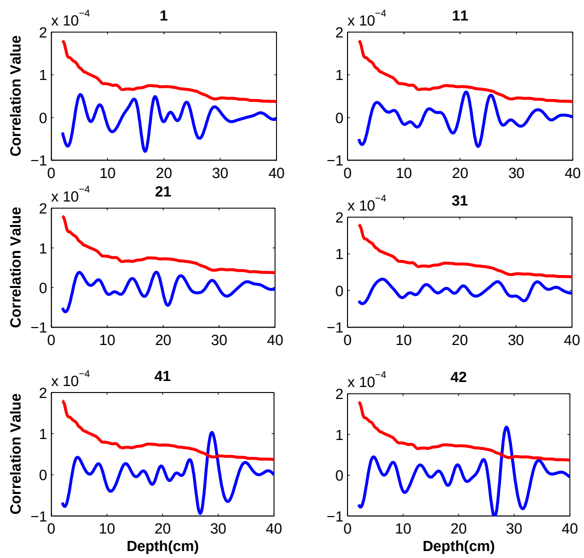
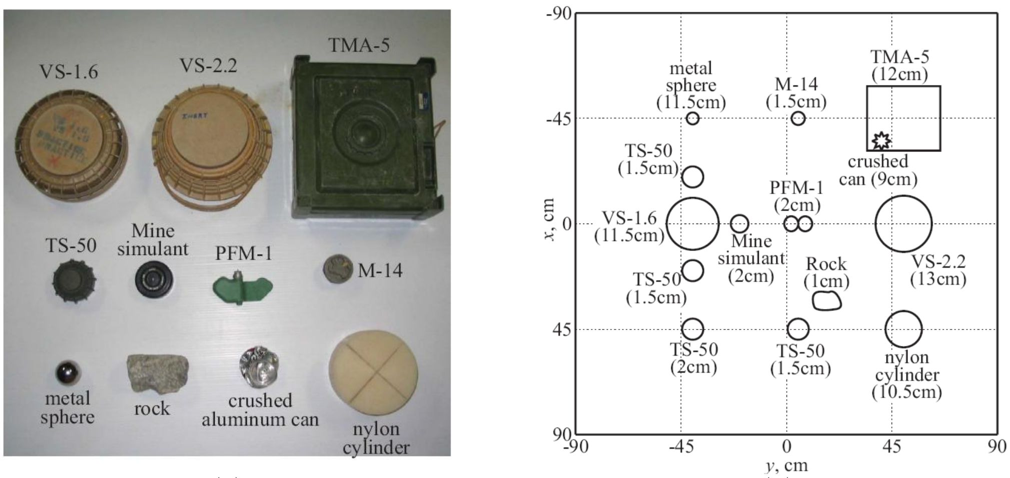


Figure 6. Buried Target Detection Results

The TDD algorithm will use the difference in the time delays measured from the data collected at aperture points 41 and 42 to estimate the location of the apex of the hyperbola. Notice that for buried targets, the signal in fact travels through two mediums (air and ground); therefore, the travelled path will be affected by the diffraction of the wave as given by Snell's Law. Nevertheless, for simplicity, we will continue to use the straight line approximation and the target position estimate given by (7) as working in a single homogeneous medium. We thus find that the target is 6 aperture points away from the antenna's current position. As confirmation of this result, we advance the antenna and repeating the process, find a detection at aperture point 48. Applying the TDD method on data points 48 and 49, we find that we have now passed the target location by 2 points. The Table 1 summarizes the TDD method results. Note that a negative alpha implies that the target is behind the current position of the antenna. Thus, we have found that the target is located over data point 47. The true location of the target center is at point 46; however, the target has a diameter of 11 cm so that in fact the target spans measurement points 43 to 49. Thus, in only 8 measurements, we have found the target.

Since it is in general possible that there are multiple targets present, we continue taking measurements at intervals of 10 aperture points until the entire region has been evaluated. If a detection is made, again we apply the TDD algorithm and check to see whether a new target has been found. In the case of this configuration, however, no more targets are present. Thus, our final result involves taking a total of 14 measurements. This is a significant savings over taking an entire line scan, which has 91 measurements.

Configuration 2: Multiple Targets, 2D Processing In this configuration, multiple targets - such as antipersonnel and antitank mines, metal spheres, nylon cylinders and mine stimulants - are buried in a sandbox with an area of 180cm x 180 cm. A picture of the buried targets is shown in Fig. 7(a). Figure 7(b) shows the burial locations, types and depths of the targets.



(a) (b)

Figure 7. (a) Picture of Buried Targets, (b)Burial map of targets in sand. The numbers in the parentheses are the buried depths of the targets.

We again start the process by applying the detection test on the first data measurement. For the event of no detection in 2D, antenna moving distance from (5) is scaled by $1/\sqrt{2}$ not to leave any unscanned areas in the region. In this case, we find $l = 7$ aperture points on both x and y directions. The antenna is continued to be advanced by this interval until a positive detection is made. The target location can then be computed using (9). Confirmation of the target location may be obtained by repeating the TDD algorithm at the target position.

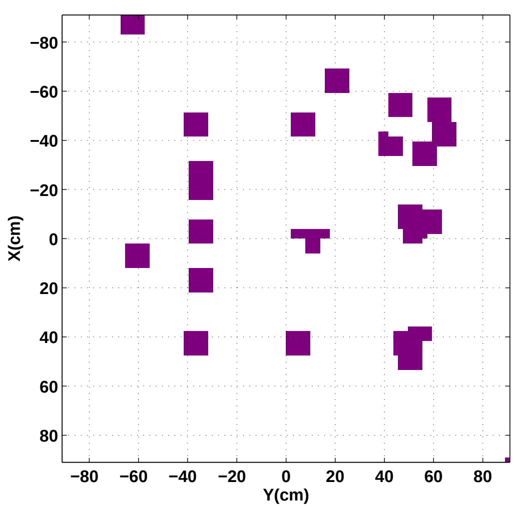


Figure 8. Detection image for 2D processing of TDD algorithm on the experimental data.

Once a final result has been obtained, a 10 cm x 10 cm area (roughly the size of the smallest anti-personnel mine) around the aperture point is marked off. We then return to the location of the antenna before the confirmation step and continue the search. It is of course possible for a target to be detected multiple times during the course of a search. However, a given target location need only be confirmed once. On subsequent detections of the same target the antenna can simply continue in its normal scanning direction.

Applying the TDD process on the experimental data yields the target detections shown in Fig. 8. A total of 398 measurements were done. This is a substantial improvement in comparison to the 91x91=8281 A-scan measurements.

5. CONCLUSION

A novel approach for finding GPR targets easily and fast is demonstrated. The method makes the detections on the measured data and skip the measurements for non-target areas and tries to estimate the target positions from the consecutive aperture point measurements. Results from several data sets show that while the algorithm is more sensitive to clutter as compared to the time-domain backprojection algorithm, the total number of measurements taken can be significantly reduced while maintaining target detection and location performance. Another advantage of the proposed method is that the algorithm is real time, doesn't need any imaging algorithm and data-driven. Method doesn't need the whole scan of the area before making any target detection decisions and well suited for pre-screening purposes.

REFERENCES

1. P. Gader, M. Mystkowski, and Y. Zhao, "Landmine detection with ground penetrating radar using hidden markov models," *IEEE Transactions on Geoscience and Remote Sensing* **39**, pp. 1231 – 1244, 2001.
2. X. Feng and M. Sato, "Pre-stack migration applied to gpr for landmine detection," *Inverse Problems* **20**, pp. 99 – 115, 2004.
3. K. Ho, L. Collins, L. Huettel, and P. Gader, "Discrimination mode processing for emi and gpr sensors for hand-held land mine detection," *IEEE Transactions on Geoscience and Remote Sensing* **42**, pp. 249 – 263, 2004.
4. K. Kim, A. C. Gurbuz, J. H. McClellan, and J. Waymond R. Scott, "A multi-static ground-penetrating radar with an array of resistively loaded vee dipole antennas for landmine detection," in *Detection and Remediation Technologies for Mines and Minelike Targets X, Proc. of SPIE*, **5794**, pp. 495–506, June 2005.
5. S.-M. Oh, *Iterative space-time domain fast multiresolution SAR imaging algorithms*. PhD thesis, Georgia Institute of Technology, Atlanta, GA, 2001.
6. R. Stolt, "Migration by fourier transform," *Geophysics* **43**, pp. 23–48, 1978.
7. J. Gazdag, "Wave equation migration with the phase shift method," *Geophysics* **43**, pp. 1342–1351, 1978.
8. A. C. Gurbuz, J. H. McClellan, and J. Waymond R. Scott, "Subsurface target imaging using a multi-resolution 3d quadtree algorithm," in *Detection and Remediation Technologies for Mines and Minelike Targets X, Proc. of SPIE*, **5794**, pp. 1172–1181, June 2005.
9. D. J. Daniels, *Surface-penetrating radar*, London : Institution of Electrical Engineers, 1996.
10. S. M. Kay, *Fundamentals of Statistical Dignal Processing Detection Theory*, Prentice Hall, 1998.