Improved Subsurface UXO Discrimination
with Full-Polarimetric, Ultra-wideband, Ground Based Radar,
Using Space and Frequency Dependent Signal Features

[C POSTER SESSION]

C.-C. Chen, and M. Higgins
Ohio State University Electroscience Laboratory
1320 Kinnear Rd, Columbus, OH, 43212
chen.118@osu.edu

Kevin O'Neill
USA Engineer Research and Development Center - Hanover
72 Lyme Rd, Hanover, NH 03755
Kevin.ONeill@ERDC.usace.army.mil

An ultra-wide bandwidth, fully-polarimetric ground penetrating radar (GPR) system operating between about 10 MHz to 810 MHz has been used in field tests for the classification of buried unexploded ordnance (UXO). Radar signatures such as natural resonance and polarization response were used to separate false alarm objects from UXO-like items, that is, from those having elongated bodies with length-to-diameter ratios greater than three. The inferred late time resonances allowed estimation of the target’s longest dimension. Polarization information from manipulation of the complete late-time scattering matrix produced measures of “linearity,” i.e. preferred directional orientation in the response, and “angular density,” which is basically a measure of consistency or tightness of the response orientation distribution. Additional features such as depth and orientation were also extracted from the data. In one field test, results were based on these features extracted from a single radar position, usually one judged to be approximately directly above the target. Good classification performance was obtained for UXO-like items with inclination angles less than 45 degrees from the horizontal. More than 50% false alarm rejection was achieved with a detection rate of approximately 90% for the UXO-like targets. These early efforts showed promising use of estimated target length to improve classification. However it was determined that this single-position approach contributed to many of the false alarms, particularly for classification of UXO’s with large inclination angles.

To deal with these difficulties, a new measurement approach was developed in which GPR data were processed from multiple positions along a transect line which crossed over the presumed target location. This approach exploited very near field, early time information as well as the late time data. It has the particular advantage that changes in the signal features can be tracked as a function of position along the transect, over which subsurface observation angle changes. This is designed to help deal with steeply inclined targets and also to eliminate the problem of positional uncertainty of the target along the scan direction. The abundance of information from position dependent scattering has allowed discrimination of vertical UXO-like objects from other rotationally symmetric objects, such as plates or spheres. In part, false alarms can be caused by these targets when they are very near the surface, due to unbalanced excitation of the antenna arms, as happened in some instances during the previous field tests. Such false alarms can now be discarded, based on combined spatial and frequency analysis of the scattered signals.
The Problem

Unexploded ordnance (UXO) presents an urgent problem worldwide, at sites of previous conflict or military practice. Sufficient means of subsurface detection and discrimination are urgently needed. Currently, applicable sensor resolution is limited by the fact that only low frequency (< 1 GHz), low resolution signals penetrate the ground sufficiently to be useful for surveying. This means that lack of ability to discriminate UXO from widespread clutter complicates the cleanup problem greatly and increases costs. Fig. 1 shows the not-untypical breakdown of costs at a particular large cleanup site in the US.

- Heavily Contaminated 5000 Acre Site
- Mortar and Artillery

![Pie chart showing cost allocation](image)

Total Cost:
US$30,000,000

Figure 1. Illustration of cost allocation at a fairly typical UXO cleanup site in the US, showing how most of the cost is expended on addressing spots designated by current sensors but not containing actual UXO.

To address this matter we have developed full-polarimetric, ultra-wideband, ground based radar system. Results are obtained by exploiting space and frequency dependent signal features in the
processing. Controlled field tests are performed using prototype objects (Fig 2), as well as objects more representative of real-world clutter.

Figure 2. Fundamental target shapes buried at a GPR test site for subsurface discrimination testing.

Figure 3. UXO site clutter items emplaced at GPR discrimination test site
New Ground Contact GPR System and Processing

The innovative radar system consists of a horn-fed, dielectric loaded, “bowtie” antenna, pictured in Figure 4. With two sets of opposing "arms" on the antenna, the system is fully polarimetric, registering amplitude and phase for co-polar and cross-polar responses. Essential is the ultra-wide band, maximally from 10 MHz – 810 MHz.

The antenna is towed by a small tractor or inexpensive all-terrain vehicle (Fig 5). An onboard network analyzer (rear) produces signals over the frequency band at 2 MHz intervals, while an on-board computer (front) is for control, real-time monitoring of data, recording and rotation of full scattering matrix.

Figure 4.
UWB horn fed, dielectrically loaded, crossed-bowtie antenna, for fully polarimetric GPR measurements between 10 MHz – 810 MHz.

Figure 5.
Tractor for towing the antenna, with network analyzer (rear) and computer (front).
This radar systems allows increasingly sophisticated processing of signals over both space and time. Figure 6 shows the basic parameter extraction algorithm. Most of the steps shown are explained briefly below. Overall, frequency bands deemed representative of target resonance in late time are used to filter the signal; then characteristic hyperbolic arcs from discrete targets are located both to use as spatial filters and to identify subsequent time as "late time."

The basic parameters extracted are:

- Estimated linearity factor (ELF), indicating degree of predominance of axially polarized response in late time;
- Estimated target orientation (ETO);
- Complex natural resonance (CNR), a key to identification of target length;
- Angular density of signal (DEN), indicating the extent to which the target has a dominant axis.

Figure 6. Flow chart showing steps in signal parameter extraction, potentially over all observation points.
Elongated objects, such as we seek, are good resonators in late time, as induced currents bounce back and forth between the ends (Fig. 7). This forms a basis for much of the processing as we identify complex natural resonances (CNR), with dominant center frequencies and characteristic exponential decay patterns. This late time resonance in elongated produces strongly linearly polarized scattering in late time, as only the length dependent resonance survives in that time range. Given the dielectric constant of the soil, which we measure, the frequency of the CNR provides an estimated target length (ETL).

Figure 7. Currents induced on the target by the incident field run back and forth between the ends in late time (top), decaying exponentially in time (bottom; semi-log plot). This approximates a resonating electric dipole, with length equal to half the electromagnetic wavelength. Higher modes are at frequencies where the target length is higher multiples of the half wavelength.
After the late time scattering region is determined, polarization features are examined. Because the system is fully polarimetric, the scattering matrix can be rotated arbitrarily and the eigenvalues obtained. If the scattering matrix has a dominant direction (polarization) in late time (Fig. 8, left), then the signal suggests the presence of orientable (elongated) object, with high angular density of response (DEN). Ratio of late time signal in this dominant polarization to that in transverse polarization gives estimated linearity function (ELF). If the eigenvalue analysis shows no dominant direction, then it is assumed that the object does not have a predominant axis or orientation feature.

![Figure 8. Left: High angular density response (DEN), with high linearity (ELF). Right: Low angular density response (DEN), with low linearity (ELF)](image)

**Space-Space vs Space-Time Views.**

Signals must make longer round trips between the target and the sensor for offset antenna positions. The upper plots in Figure 9 illustrate this, showing a horizontal axis corresponding to antenna position in space and the vertical axis indicating depth in space (space-space view). Below these plots are corresponding space-time views, i.e. in with the horizontal axis is again spatial location of the antenna, but the vertical axis is time at which the signal was received. The later is the form in which data are necessarily obtained. Thus discrete subsurface targets produce hyperbolas in a space – time plots, as has long been recognized in seismic surveying. Note that, proportionally, the distance to a shallow target (left) changes more rapidly as the antenna position shifts along the ground. In a space – time plot this means that the hyperbola is flatter for the deeper target (right).
Figure 9. Horizontal axes are space (antenna position) in all plots. Top: space-space view. Bottom: Space-(arrival) time view. Left: shallow target. Right: Deeper target, showing gentler slope of characteristic hyperbola from discrete object scatterer.

Integration of Spatial Signal Patterns into Polarimetric Processing.

Once a characteristic hyperbola is space-time is identified which may correspond to a target of interest, the signal is filtered over space so that predominantly only signals forming this hyperbola in space-time are retained (figure 10).

Figure 10. Space time view of data from a discrete metallic buried target before (left) and after adaptive filtering. Region below the hyperbola contains "late time."
Changes in signal properties over space can reveal much about the target and, in particular, can help avoid previously inevitable near-field problems. For example, a compact, very shallow target excites nearby antenna arms as the antenna passes over. Because in this scenario one set of antenna arms (one receiving polarization) responds much more strongly than the other, the signal shows apparent linearity, as from an elongated object. But there are telling features of the signal in space-time which prevent such an interpretation: The apparent linearity is approximately the same no what orientation the survey scan (transect) is, i.e. it is always aligned with the scan direction; the signal strength and linearity are weak at the center location compared to the sides of the hyperbola. See Fig. 11 below.

Figure 11. As the antenna scans along the survey transect on the ground surface, a relatively small, compact target passes beneath, in the very near field. As it passes close to one set of antenna arms those are excited preferentially, mimicking linearity as for an elongated target. However the center of the hyperbola is weak, as is signal linearity there.
A vertical elongated object also shows weaker signal directly above the target, but may produce two scattering arcs, with different slopes, from the top and bottom of the target (Fig. 12). These different slopes are explained above with reference to Fig. 9. Further, for a typically tilted elongated target, the signal will not be approximately the same along all transect orientations (antenna paths). Thus the signal pattern shown can help distinguish an elongated, vertical target from a near-surface compact one.

![Diagram](image)

Figure 12. The weak peak of the hyperbola in this space-time plot indicates an object quite near the antenna. The two stronger tails of the hyperbolas show higher linearity but also different slopes, corresponding to separate end reflections from an elongated object.

In contrast to this, a horizontal flattened object produces a strong signal with low linearity at the central location. See Fig. 13 below. Possible increased linearity near the sides of the main response, due to edge effects, only occurs within a region of weaker signal relative to the peak. Altogether this helps distinguish a shell wall fragment from a UXO.
Figure 13. A flattened metal surface facing the antenna produces a strong response at the central antenna location. Even if this response contains significant resonance it will likely show poor linearity, unless the target is elongated. Sides of the main response may show stronger linearity but only with weak magnitude.

Complete Processing Sequence.

The complete processing sequence makes use of spatial information together with frequency information, integrating the concepts and approaches explained above. Fig. 14 diagrams the ultimate flow of classification processing, utilizing the signal parameters shown in Fig. 6 and explained in the subsequent text.
Conclusion

UWB, fully-polarimetric GPR data collected at multiple positions provide abundant scattering features, allowing one to discriminate a vertical UXO-like object from other clutter such as plates, fragments, and other compact metallic forms. False alarms caused by such targets due to unbalanced excitation of the antenna in the very near field, as encountered during the previous field tests, can now be discarded based on spatial and scattering features. Use of the characteristic space-time hyperbola produced by a near field discrete target also allows adaptive filtering to reduce other clutter, such as that due to near surface ground disturbance and layering.