A new–generation EM system for the detection and classification of buried metallic objects

Erika Gasperikova, Lawrence Berkeley National Laboratory*

Summary

A prime requirement in discrimination between UXO and non-UXO metallic fragments (clutter) is to determine accurately the response parameters that characterize a metallic object in the ground. Lawrence Berkeley National Laboratory has been involved in assessing and comparing existing systems, and designing an optimum system for UXO detection. A prototype of a new electromagnetic system will be built based on the results of this study. The detection and characterization of metallic objects can be considered a two-step process: location and identification. A multi-component transmitter-receiver system is essential for the identifying of the principal dipole moments of a target. The ground response imposes an early time limit on the time window available for target discrimination. Once the target response falls below the ground response, it will be poorly resolved, especially since the ground response itself will be variable due to the inhomogeneous nature of the near surface. For a given range of targets and given ambient noise characteristics, one can optimize system bandwidth so as to maximize the observable signal-to-noise ratio. A sensor with four or more decades of flat frequency response is needed to record the secondary magnetic fields associated with the target.

Introduction

As land previously occupied by military installations is returned to civilian use, it must be cleared of all unexploded ordinance (UXO) before it can be declared safe for passage. This requirement has spurred much new research aimed at the development of new metal locators specifically designed for detecting unexploded buried munitions. These munitions range in size from small machine gun ammunition or artillery shells to large, deeply buried, but still possibly active bombs. Although improved UXO detection is a prime objective, it is equally important to identify the size, shape, and metal content of the object and to discriminate against scrap metal and the effects of magnetic and electric geological inhomogeneities in the ground. Most existing metal locators may be thought of as scaled versions of the electromagnetic (EM) systems that have been used for mineral exploration. The large-scale systems used for detecting deep mineral targets have practical constraints on their configurations, as well as power and bandwidth requirements. However, the small size of the transmitter-receiver (T-R) assembly used for shallow metallic targets offers exciting possibilities for a new-generation of EM systems optimized for these targets.

The system parameters that are variables in the design are: (a) the geometric configuration of the T-R and the way in which it is mounted for given target objectives (the platform), (b) the spatial positioning of the system (profile, grid, single site stand-off, etc.), (c) the transmitter power and waveform, (d) the system and ambient noise, (e) the receiver bandwidth and dynamic range, and (f) the signal averaging time (a function of survey speed). Geologic variables (geologic noise) include the values and variability of the ground conductivity and permeability. This paper discusses some of these design variables.

Transmitter–Receiver Configuration

The detection and characterization of metallic objects can be considered a two-step process: location and identification. As demonstrated by Morrison et al. (2002), any bounded metallic object can be represented approximately by three co-located orthogonal magnetic dipole polarizabilities. Using a simple and robust inversion scheme for determining the location and magnitude of the principal polarizabilities of a bounded object, it is possible to coarsely identify it using narrow-band spatial data acquired with a number of co-located EM transmitters and a multiplicity of associated receiver sensors. The important role of multiple field polarizations at the target is easily seen in Figure 1. One-meter-square transmitter loops were used with a moment of 180 Amp-m^2 and a receiver noise level of 1.97 nT/s in vertical field measurements (simulating an observed noise level), and 5.91 nT/s in horizontal field components, when present, (simulating the larger noise levels observed in horizontal components). A step-function turn-off transmitter current was used, as the most generic of waveforms, and an observation time of 610 μs after turnoff was chosen to simulate the effective center time of the averaging gate for an existing commercial T-R system. For each sphere radius and for each T-R configuration, the relative root-mean-squared (rms) inverted moment uncertainty and depth uncertainty were computed as a function of sphere depth, for spheres directly below the center of a 9 x 9 grid of system placements, with 0.4 m spacing in x and y. The results for the standard horizontal loop with a single vertical receiver are shown for reference as the solid line. The depth of detection for a 10 cm radius sphere almost doubles with the three-component transmitter, but relatively little is gained by adding a triaxial receiver.

In general, it was found that the object position can be estimated more precisely than the principal polarizabilities. The object position may be determined with only a single orientation of primary field, whereas estimating the full polarizability matrix requires illuminating the object with primary fields in at least three directions, each with a significant component in the direction orthogonal to the other two. Consequently, object depth can be resolved within 10% to greater depths than principal polarizabilities.

Spectral Properties of Target Response

To illustrate the spectral response of a variety of targets, we have chosen to use a simple horizontal loop transmitter with an in-loop vertical receiver deployed directly above the target. This is basically the model for the EM61 commercial system. This configuration, the target size and shape, and the separation of the T-R system from the target are shown to the right of the response plots. The secondary response is normalized by the transmitter moment. The dB/dt response for both the horizontal and vertical orientation of the shell with the aspect ratio of 3:1 is on the right-hand side, while the magnetic field (B) response is on the left-hand side of Figure 2. It is immediately evident that the actual shell response, for both orientations, is larger than the sphere responses. Figure 2 also includes the response from the conductive ground in which the target is immersed. The ground response basically imposes an early time limit on the time window available for target discrimination. Once the target response falls below the ground response, it will be poorly resolved, especially since the ground response itself will be variable due to the inhomogeneous nature of the near surface.

The early time limit imposed by the ground and the later time limit imposed by the noise sets the time window over which the response can be measured. For dB/dt for the horizontal shell, for example, the window is roughly from 2×10^{-5} to 3×10^{-2} s. For B rather than dB/dt, the window where the target response exceeds the ground response widens to 3×10^{-6} s at the low end. Since there are no existing systems that measure B, we have no estimate of when the late time response meets the noise floor. However, the horizontal and vertical responses still differ by a factor of 10 and most importantly, the observed separation (including very early time) is confined to less than 3 decades of amplitude variation. Instrumentally, this is much more manageable than the much higher dynamic range required for a dB/dt system.

In summary, it appears that for step-function excitation, transients from 10 μs to 100 ms are to be detected for a practical range of UXO and a practical range of depths. Overall, B receivers may be more effective than dB/dt receivers.

Wideband Sensor

System bandwidth is an important feature of metal detector design and optimization. Narrow-band systems reject ambient noise but also can severely distort the target signal, rendering it virtually useless for detailed characterization of the target. Wide-band systems, however, require a very high transmitter moment to allow for the extraction of target signals from the ever-present cultural and natural EM noise. An optimal sensor might be an EM induction sensor whose bandwidth is variable. Depending on circumstances, the sensor can be tuned and critically damped so that it shows conventional dB/dt behavior. On the other hand, with the judicious use of feedback, the sensor can be made to have a flat response over many decades of frequency, so that its behavior is more akin to that of a magnetometer that measures B. In either case, the dc target response cannot be recovered.

To illustrate the effects of sensor bandwidth on the response of a typical target, we consider a 37 mm steel sphere. It has a relative magnetic permeability of about 200 and an electric conductivity of about ten million. The target, located 0.75 m below the surface, is energized by a dipole transmitter of unit moment and detected with a collocated, concentric axial sensor. In this case, the target is illuminated with a repetitive boxcar (rectangular) waveform of alternating polarity and 50% duty cycle. The fundamental frequency of about 860 Hz was specifically chosen to maximize the observable transient signal for the 37 mm spherical target. The effects of sensor bandwidth are shown in Figure 3. When the unfiltered theoretical response of this target is compared with the observable filtered transient signal, the effect of limited sensor bandwidth is apparent. In fact, four decades of bandwidth, in this case from 40 Hz to 400 kHz, are needed to properly record the observable transient signal of the target. The loss of two decades of bandwidth by increasing the high-pass frequency to 400 Hz and reducing the low-pass frequency to 40 kHz clearly results in a considerable distortion of the transient. Finally, we note a complete change in the observable transient when a critically damped detector tuned to about 4 kHz is used. Here, the initial, positive part of the observed transient simply corresponds to the impulse response of the sensor. Only its amplitude is related to the target presence. However, a close inspection of the negative part of the transient signal will reveal that the decay rate for this portion of the transient signal is governed only by the properties of the target. In fact, as indicated by the negative sign, it is a replica of the time derivative of the target signal.

A new–generation EM system for UXO

Summary and Discussion

A multi-component transmitter-receiver system is essential for the identification of the principal dipole moments of a target.

The ground response basically imposes an early time limit on the time window available for target discrimination. Once the target response falls below the ground response, it will be poorly resolved, especially since the ground response itself will be variable due to the inhomogeneous nature of the near surface.

It appears that for step-function excitation, transients from 10 μs to 100 ms are to be detected for a practical range of UXO and a practical range of depths. Overall, as indicated above, B receivers may be more effective than dB/dt receivers.

The received EM signal related to a particular target will be distorted to a degree that depends on the system bandwidth. It is likely that for a given range of targets and given ambient noise characteristics one can optimize the system bandwidth so as to maximize the observable signal-to-noise ratio. A sensor with four or more decades of flat frequency response is needed to record the secondary magnetic fields associated with the target. On the other hand, in some circumstances it may be more advantageous to use a conventional, tuned, and critically damped dB/dt sensor.

References

Morrison, H.F., Becker, A., Smith, J.M., Gasperikova, E., 2002. Detection and classification of buried metallic objects: EAGE Expanded Abstracts, Florence.

Acknowledgments

This research was funded by the U.S. Department of Defense under SERDP Project #UX1225.

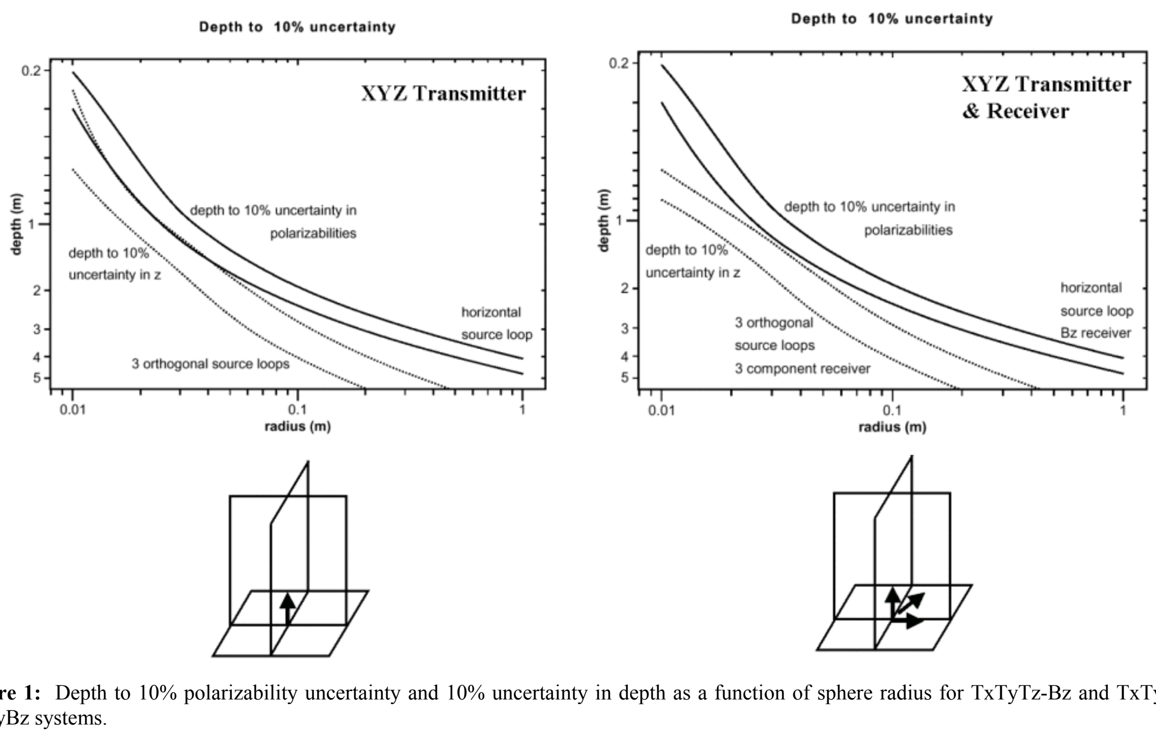

Figure 1: Depth to 10% polarizability uncertainty and 10% uncertainty in depth as a function of sphere radius for TxTyTz-Bz and TxTyTz – BxByBz systems.

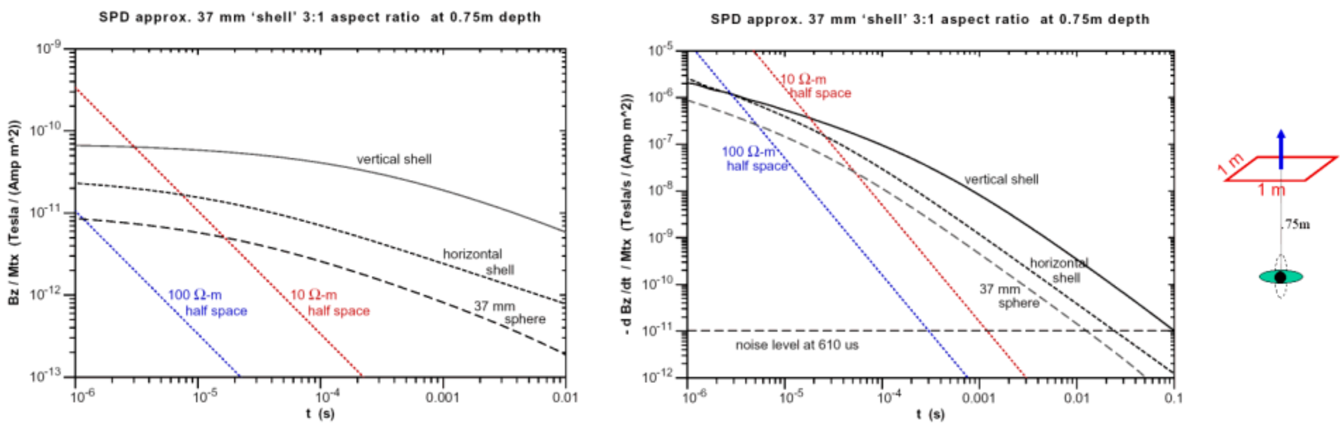

Figure 2: Amplitude of B and dB/dt response for 37 mm sphere, horizontal and vertical shells 3:1 aspect ratio at the depth of 0.75 m as a function of time together with responses for 10 Ω-m and 100 Ω-m half-space.

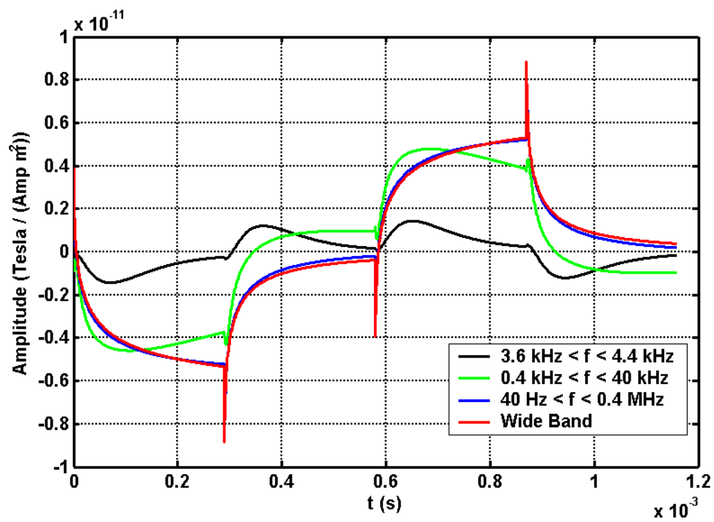

Figure 3. Effect of system bandwidth on the observable target signal.