Lawrence Berkeley National Laboratory

Title
A Multisensor system for the detection and characterization of UXO

Authors
Gasperikova, Erika
Becker, Alex
Morrison, H. Frank
et al.

Publication Date
2005-04-01

A MULTISENSOR SYSTEM FOR THE DETECTION AND CHARACTERIZATION OF UXO

Alex Becker, Lawrence Berkeley National Laboratory, Berkeley, CA
Erika Gasperikova, Lawrence Berkeley National Laboratory, Berkeley, CA
H. Frank Morrison, Lawrence Berkeley National Laboratory, Berkeley, CA
J. Torquil Smith, Lawrence Berkeley National Laboratory, Berkeley, CA

Abstract

A prototype active electromagnetic system has been developed for detecting and characterizing UXO. The system employs two orthogonal vertical loop transmitters and a pair of horizontal loop transmitters spaced apart vertically by 0.7 m. Eight vertical field detectors are deployed in the plane of each of the horizontal loops and are arranged to measure offset vertical gradients of the fields. The location and orientation of the three principal polarizabilities of a target can be recovered from a single position of the transmitter-receiver system. Further characterization of the target is obtained from the broadband response. The system employs a bipolar half sine pulse train current waveform and the detectors are dB/dt induction coils designed to minimize the transient response of the primary field pulse. The target transient is recovered in a 40 μsec to 1.0 msec window. The ground response imposes an early time limit on the time window and system/ambient noise limits the late time response. Nevertheless for practical transmitter moments and optimum receivers the size and the ratio of conductivity to permeability can be accurately recovered. The prototype system has successfully recovered the depths and polarizabilities of ellipsoidal test targets.

Introduction

In the search for UXO and for discrimination between UXO and non-UXO metallic fragments (clutter) it is necessary to accurately determine the parameters that characterize a metallic object in the ground. A search system is needed that not only detects the object but can also determine the size, shape, orientation, shell thickness and metal content (ferrous or non-ferrous, mixed metals). The latter properties of a buried metallic object are referred to here as the parameters of the object.

The search for UXO is a two-step process. The object must first be detected and its location determined then the parameters of the object must be defined. The first step is now accomplished with a variety of magnetometer and active electromagnetic (AEM) systems. The AEM systems operate in the transient or frequency domain mode and at present using a single transmitter and up to three receivers. The characterization phase can also be described as a two-step process. A variety of incident fields are used to induce magnetization and current flow in different directions within the object. The moments induced in the body, normalized by the inducing field are known as the polarizabilities of the object. The secondary fields related to these induced polarizabilities as a function of frequency or time, are the measured quantities. Interpretation could stop with the determination of the vector three principal polarizabilities. These polarizabilities and their variation with either time or frequency are the only fundamental data that can be recovered from the inductive excitation of a finite body in the ground if a dipolar representation is assumed. Presumably a catalog of polarizabilities could be constructed from the forward model polarizabilities for a wide range of potential targets and then a look-up table inversion scheme could be used to identify the actual dimensions and physical properties of a target.

We have found that a powerful second step in the characterization process is to directly interpret the polarizabilities in terms of the principal axes of an equivalent spheroid. This step yields the size and aspect ratio of the spheroid that is physically equivalent to the target. Finally, the wideband response itself permits estimation of both the permeability – conductivity ratio and the conductivity – permeability product so that each can be estimated independently. It is unlikely that any better resolution of the shape of an intact UXO than its equivalent spheroid can be recovered using practical system data. A catalog of equivalent spheroidal bodies representing most UXOs would thus be relatively easy to construct for final target identification. This more detailed second step requires the broadband spectral or transient response using frequencies low enough to identify the quasi dc magnetization response and high enough to identify the purely electromagnetic (EM), inductive limit, response which depends only on the size of the object.

The concept of characterizing UXO by their equivalent spheroid parameters is key to distinguishing intact UXO from non-UXO metal scrap. Any UXO is expected to retain its fundamental shape (size, aspect ratio and symmetry about its long axis) with perhaps minor distortion caused by impact. Metal scrap will have distinct polarizability signatures that cannot mimic these of elongated symmetric bodies. Roughly flat sheets will have dipolar responses approaching these of a highly flattened oblate spheroid (close to a loop response), twisted sheets a principal moment orthogonal to some equivalent plane through the sheet with small and highly irregular minor axis polarizabilities etc. These distinguishing polarizabilities, coupled with the size estimates and spatial sampling of the multiple receiver array are more than enough to separate small scrap from deeper targets of concern.

Design Considerations

The analyses developed in this paper are applicable to AEM systems on any scale. We have found in this process that systems scale roughly with depth of burial and size of the target. Thus the dimensions of the transmitter control the field strength at depth and spacing of receivers controls the accuracy of depth estimates. The detection of small near surface objects depends on having sufficient receivers deployed spatially so as not to miss the target's spatially small response pattern. It appears that given the possibility of an arbitrary number of receivers that the overall system dimensions should be set by the size of the transmitter loop and the practicality of moving this loop over the ground.

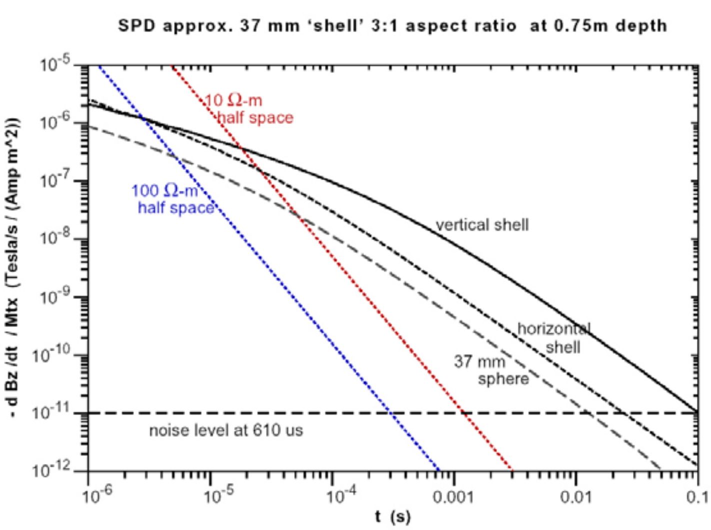
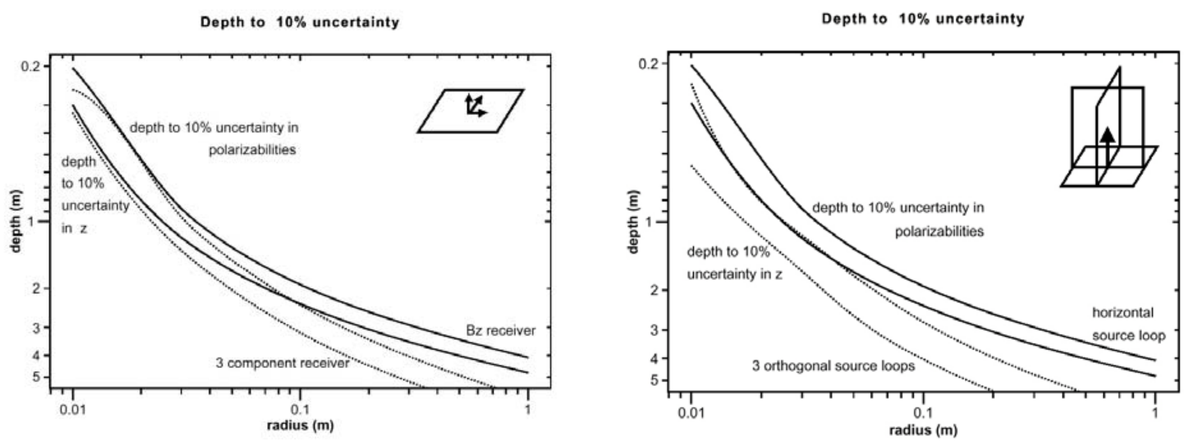


Figure 1: Amplitude of the dB/dt response for both the horizontal and vertical orientation of 37 mm solid steel shell with an aspect ratio of 3:1 and 37 mm sphere 0.75 m below the EM-61 style in-loop system.

The simulated results for an EM-61 style in-loop system over a typical 37 mm ellipsoidal body 0.75 m below the system are shown in Figure 1. The shell is solid, steel, and has an aspect ratio (length/diameter) of 3:1. The plot shows the dB/dt response for both the horizontal and vertical orientation of the shell. For comparison the response of the 37 mm sphere is included. In Figure 1 we have also plotted the response from the conductive half-space (ground) in which the target is immersed. The responses for two ground resistivities, 10 and 100 Ohm-m, are plotted. 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. For a conservative design approach we assumed a ground of 10 Ohm-m.

An inversion program was written to determine the optimal configuration of transmitters and receivers to best recover the depth and polarizabilities of a buried target. Using realistic values of ambient noise it was quickly discovered that three orthogonal loop transmitters yielded significantly better results that multi-component receivers with a single horizontal loop transmitter. The results in Figure 2 show comparison of these configurations as a function of depth and size of target. Moreover, it was found that a three-component transmitter with eight vertical receivers could recover depths and polarizabilities from a single position of the multi-element system.



(a) (b)

Figure 2: Depth to 10% polarizability uncertainty and 10 % uncertainty in depth as a function of sphere radius for (a) three-component receiver and (b) three-component transmitter.

Figure 3: 9 inch (23 cm) long and 3 inches (7.6 cm) in diameter steel ellipsoid.

There are also a number of other technical issues that need to be addressed. The first one of these is a dynamic range and a primary field transient related to a receiver bandwidth. For these reasons we have elected to use a critically damped induction sensor. For the initial laboratory tests we used a 100 turn, 3 inch diameter flat coil with a resonant frequency of 20 kHz, which effectively measured dB/dt – the derivative of the magnetic field. Numerical simulation results for the ellipsoidal test target depicted in Figure 3 are presented in Figure 4. Here the target was placed 30 cm below the vertical axis of a square 1 m x 1 m 32 turn transmitter coil. The half-sine excitation current was 18 A. It had a fundamental frequency of 270 Hz and a duty factor of about 15%. The primary and secondary fields were computed at the center of the transmitter.

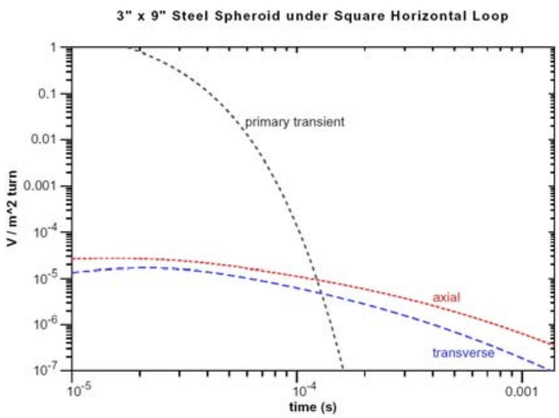
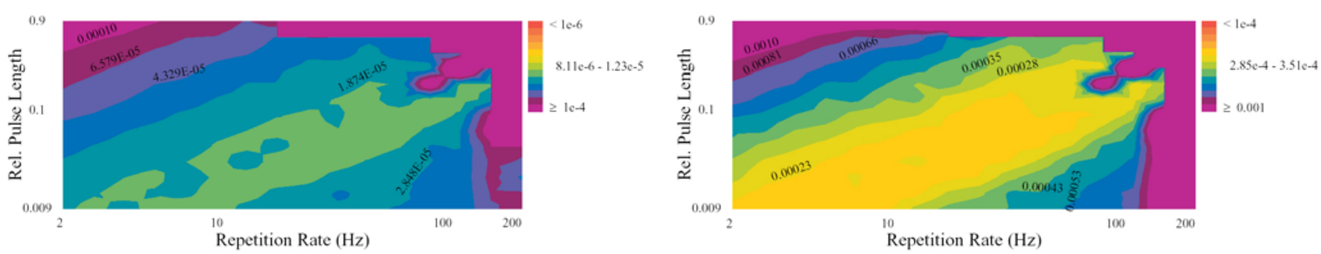


Figure 4: The response of a typical induction sensor for a half-sine pulse and 9 inch (23 cm) steel target.

As shown in Figure 4, the primary field response dominates the smallest measurable target signal by about 170 dB, way beyond the range of any amplifier. Without some sort of dynamic range compression it is difficult to recover accurately the target transient. A solution to this problem is presented in a gradient arrangement used in the field prototype described below.



(a) (b)

Figure 5: Uncertainties in (a) log(r) and (b) log(s/m) for 160 mm sphere, resonant frequency of 33 kHz, and critically damped receiver.

We have also examined the choice of period and duty factor for the transmitter waveform. These parameters were optimized by minimizing the expected error in experimental data inversion by considering the ambient noise. Typical results are shown in Figure 5. These were obtained for a critically tuned receiver with a resonant frequency of 3.2 kHz. The results are displayed as contours of the uncertainty in the estimates of log(r) (Figure 5a), and log(σ/μ) (Figure 5b) as a function of the repetition rate (on the horizontal axis) and relative pulse length (on the vertical axis). The product σ·μ is not well resolved from practical transient data because the transient cannot be obtained at times large enough for the exponential decay to have occurred. However, for large σ·μ even if roughly estimated, the radius, r, and the ratio of σ/μ is well determined. The determination of σ/μ is very weakly dependent on the value of σ·μ. The results suggest that an optimum repetition rate is in the 10 – 100 Hz range for relative pulse lengths from 0.03 to 0.1 respectively.

Laboratory Results

The laboratory prototype had a 32 turn 1 m^2 transmitter loop carrying a peak current of 19 Amperes for a moment of about 600 Am^2. The current waveform was a repetitive bipolar half-sine. We synthesized the results for an orthogonal three-loop system by simply moving a single loop to the three positions in the jig shown in Figure 6. Various target objects were placed beneath the system. As an example, a 9 inch (23 cm) steel ellipsoidal target is shown in Figure 3. This object was placed directly below the center of the transmitter at a depth of 30 cm, with its long axis horizontal (dip = 0°) and at an angle of 45° to the principal coordinates of the system (azimuth). The interpreted location (x, y, z) (Figure 7a), the orientation of the three principal axes (Figure 7b), and the three principal moments (Figure 7c) are plotted as a function of time. The estimates are plotted as solid, colored, lines. Dashed lines of the same color indicate the variability of the estimate. The true value of the parameters plotted is listed on each plot. The invariance of the interpreted center position with time is indicative of a symmetric homogeneous object.

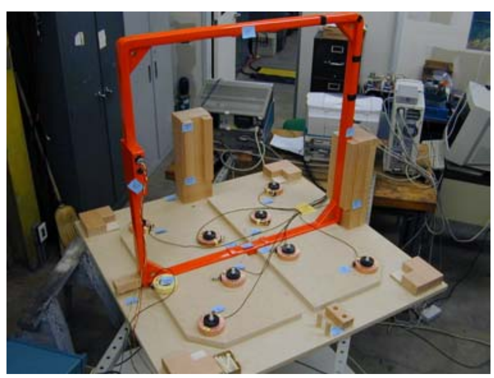
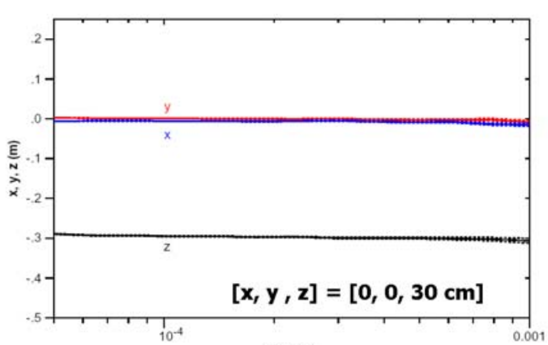
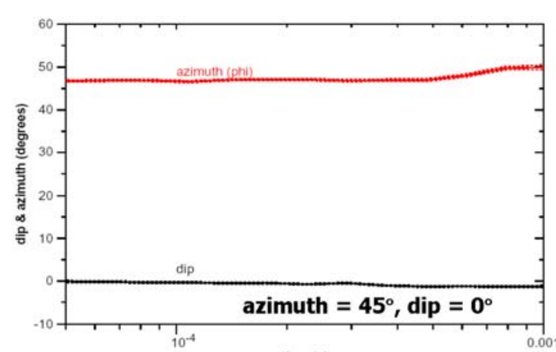


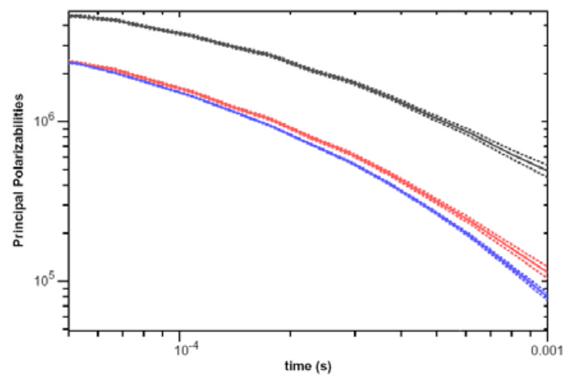
Figure 6: A laboratory prototype system.



(a)



(b)



(c)

Figure 7: Inversion results for (a) the position, (b) the moment orientation, (c) the principal moments of 9 inch (23 cm) steel ellipsoid.

These results clearly show that the multi element system can detect the object and more importantly, determine its principal polarizabilities and their directions. Moreover, it is evident that these quantities can be obtained over a time window that will allow subsequent inversion for the true physical aspect ratio, the size and the ratio of σ/μ.

Field Prototype

The laboratory prototype had to sacrifice target sensitivity to accommodate the dynamic range requirements imposed by the primary transient. However, if we compensate the receiver by nulling the primary field induction then we see that the target signal amplitude range is only 40 dB so that it can be readily observed and recorded. We have solved the dynamic range problem by using displaced pairs of coils in a gradient configuration. Horizontal receiver coils are placed in the upper and lower planes of two horizontal transmitter coils. The sensor coil pairs (Figure 8a) are located on symmetry lines through the center of the system so as to see identical primary fields (for all three transmitters) during the on-time of the pulse. They are wired in opposition to produce a null output. Secondary fields from the target have a large gradient that is easily measured in the differenced output. The final configuration has eight pairs of receiver coils placed as shown in Figure 8b.

(a) (b)

Figure 8: A configuration of receiver coils for a field prototype system.

The field prototype instrument is shown in Figure 9. It consists of a triaxial transmitter where each axis is excited in sequence with a waveform shown in Figure 10. We note that the vertical axis transmitter is split into two identical parts. This was done to achieve the symmetry needed for receiver compensation. The field prototype sensors are critically damped and resonant at about 20 kHz. The resonant frequency allows a 270 Hz waveform repetition rate and a duty factor of about 20%.

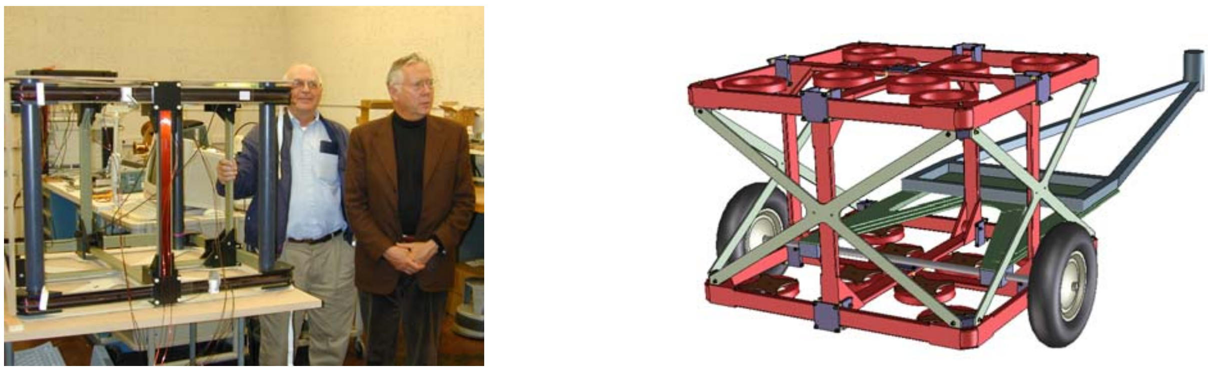


Figure 9: A field prototype system.

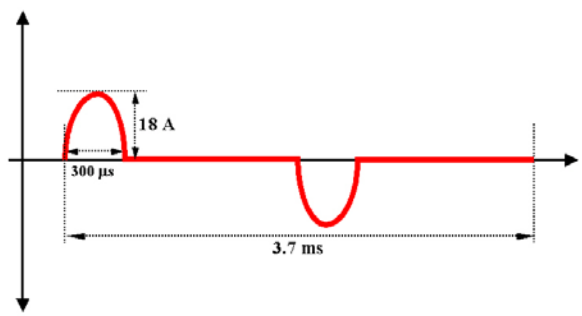


Figure 10: A half-sine waveform of 270 Hz repetition rate, 20% duty cycle and 18 A peak current.

Conclusions

Our numerical simulations and experimental laboratory data show that targets can be accurately located and characterized. Stand-alone equipment can be used to recovers all target parameters from observations at a single position. To do this we need a triaxial transmitter and a multiplicity of receivers in an optimal pattern. The detectors are dB/dt induction coils designed to minimize the transient response of the primary field pulse. The ground response imposes an early time limit on the time window and system/ambient noise limits the late time response. Nevertheless for practical transmitter moments and optimum receivers the size and the ratio of conductivity to permeability can be accurately recovered.

Acknowledgements

This research was funded by the U.S. Department of Defense under SERDP Project # UX1225 and ESTCP Project # 200437.

References

Gasperikova, E., 2003, A new-generation EM system for the detection and classification of buried metallic objects: SEG Expanded Abstracts, pp. 2379-2382.

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

Smith, J.T., and Morrison, H.F., 2004a, Estimating equivalent dipole polarizabilities for the inductive response of isolated conductive bodies: IEEE Trans. Geosci. Remote Sensing, 42, pp. 1208-1214.

Smith, J.T., and Morrison, H.F., 2004b, Optimizing receiver configurations for resolution of equivalent dipole polarizabilities in situ: IEEE Trans. Geosci. Remote Sensing, submitted.

Smith, J.T., and Morrison, H.F., 2004c, Approximating spheroid inductive responses using spheres: Geophysics, submitted.

Smith, J.T., and Morrison, H.F., 2004d , Worse case objects for characterization using magnetic induction: IEEE Trans. Geosci. Remote Sensing, to be submitted.

Smith, J.T., Morrison, H.F., and Becker, A., 2004a, Resolution depths for some transmitter receiver configurations: IEEE Trans. Geosci. Remote Sensing, 42, pp. 1215-1221.

Smith, J.T., Morrison, H.F., and Becker, A., 2004b, Parametric forms and inductive response of a permeable conducting sphere: Journ. Environ. Engin. Geosci., in press.