

# REPORT DOCUMENTATION PAGE

Form Approved  
OMB NO. 0704-0188

Public Reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comment regarding this burden estimates or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188,) Washington, DC 20503.

1. AGENCY USE ONLY (Leave Blank)		2. REPORT DATE 4/30/2004	3. REPORT TYPE AND DATES COVERED Final 01 Sep 02 - 30 Nov 03	
4. TITLE AND SUBTITLE Rapid Calculation of EMI Responses of Metallic Objects and Implementation in Inversion Schemes			5. FUNDING NUMBERS DAAD 19-02-1-0399	
6. AUTHOR(S) Keith D. Paulsen				
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Dartmouth College, Hanover, NH 03755			8. PERFORMING ORGANIZATION REPORT NUMBER None	
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) U. S. Army Research Office P.O. Box 12211 Research Triangle Park, NC 27709-2211			10. SPONSORING / MONITORING AGENCY REPORT NUMBER 44485.3 - EV	
11. SUPPLEMENTARY NOTES The views, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy or decision, unless so designated by other documentation.				
12 a. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release; distribution unlimited.			12 b. DISTRIBUTION CODE	
13. ABSTRACT (Maximum 200 words) Broadband electromagnetic induction (EMI, 10's of Hz to ~ 100's of kHz) is emerging as one of the most promising technologies for discriminating subsurface unexploded ordnance (UXO) from widespread clutter. We have succeeded in performing detailed numerical simulations of EMI responses by a considerable variety of representative objects and UXO. Nonetheless, signal inversion schemes are impeded by a lack of rapid means for calculating the responses of possible target types in a great variety of depths and dispositions relative to the sensor. In this project we have developed a reduced source set (RSS) formulation of target response, which is essentially a modified and simplified method of auxiliary sources. In the RSS approach we express the same target response as would be obtained by a full-fledged, detailed, first-principles numerical solution but using only a small number of equivalent responding entities (e.g. charges, currents, surface field components, etc. We have shown that as long as the observer is at distance that is at least some significant fraction of the smallest dimension of an object of interest, the complete and the RSS responses are essentially indistinguishable.				
14. SUBJECT TERMS EMI, UXO, Reduced Source Set, Auxiliary Sources, Signature Inversion			15. NUMBER OF PAGES 12	
			16. PRICE CODE	
17. SECURITY CLASSIFICATION OR REPORT UNCLASSIFIED	18. SECURITY CLASSIFICATION ON THIS PAGE UNCLASSIFIED	19. SECURITY CLASSIFICATION OF ABSTRACT UNCLASSIFIED	20. LIMITATION OF ABSTRACT UL	

NSN 7540-01-280-5500

Standard Form 298 (Rev.2-89)  
Prescribed by ANSI Std. Z39-18  
298-102

---

**REPORT DOCUMENTATION PAGE (SF298)**  
**(Continuation Sheet)**

---

**TABLE OF CONTENTS**

**1. THE PROBLEM STUDIED..... 3**

**2. RESULTS: COMPLETE SOLUTION USING THE STANDARDIZED EXCITATIONS APPROACH (SEA)..... 4**

**3. BIBLIOGRAPHY ..... 10**

**4. PUBLICATIONS..... 11**

    4.1 JOURNALS:..... 11

    4.2 CONFERENCES (FULL PAPER PUBLISHED):..... 11

**5. PARTICIPATING PERSONNEL ..... 12**

**FIGURES**

Figure 1. Transmitted magnetic field patterns corresponding to two of the lowest excitation modes, around a hypothetical target shape. Edge labels correspond to space coordinates (arb) on two sides of a plane through the target axis..... 8

Figure 2. GEM-3 measurements (markers) compared to two modeling approaches. .... 9

## 1. The Problem Studied

Broadband electromagnetic induction (EMI, 10's of Hz to ~ 100's of kHz) is emerging as one of the most promising technologies for discriminating subsurface unexploded ordnance (UXO) from widespread clutter. We have succeeded in performing detailed numerical simulations of EMI responses by a considerable variety of representative objects and UXO [1-6]. Still, signal inversion schemes are impeded by a lack of rapid means for calculating the responses of possible target types in a great variety of depths and dispositions relative to the sensor. Progress in the above-referenced articles has pointed the way towards a reduced source set (RSS) formulation of target response, which will be essentially a modified and simplified method of auxiliary sources (see above references). In the RSS approach one contrives to express the same target response as would be obtained by a full-fledged, detailed, first-principles numerical solution but using only a small number of equivalent responding entities (e.g. charges, currents, surface field components...). As long as the observer is at distance that is at least some significant fraction of the smallest dimension of an object of interest, the complete and the RSS responses are essentially indistinguishable. The key to application of the RSS lies in obtaining RSS solutions for each member of a set of fundamental target excitations. The fundamental excitation modes are constructed so that a simple (and readily calculated) superposition of them can describe the field actually transmitted by a real sensor. Thus the complete response (received signal) under any prospective circumstances will just be the same superposition of corresponding responses to the fundamental excitations. That is, a given linear combination of inputs corresponds to the same linear combination of outputs. The key lies in properly defining the fundamental excitation modes, parameterizing the target response to each, and determining the best way to obtain those parameters.

## **2. Results: Complete Solution Using the Standardized Excitations Approach (SEA)**

Our approach here has been much like what has been done in radar problems for a long time, but which has not been possible heretofore for EMI. In radar work, one might determine the response of an object to a collection of unit-magnitude plane waves, each striking the object from a different angle. Any real incident beam can be constructed by some particular superposition of plane waves. The result (output, scattered field) will be the same superposition (same linear combination, same weighting) of responses to each of the constituent waves. The problem in EMI is that there are no waves. Otherwise put: There has been no immediately obvious way to express arbitrary EMI excitation fields as a sum of basic, universal, or standardized components. Our investigations have produced two ways to perform effective field decompositions in EMI realm. These are in many ways simpler than those for radar, possibly requiring fewer terms. In our initial investigations, the response of a target to each basic excitation mode was determined first from detailed numerical modeling, including all interactions, near field effects, then saved. The same kind of thing has recently been carried out based on measurements only (see papers published under this grant). That is, the response of objects to individual standard excitations has been inferred from measurements in which the primary field contained a number of these excitation components simultaneously (the normal state of affairs). Given a sufficient variety of sensor-object arrangements, one can extract the response associated with each individual excitation component. Essentially no idealization of the object or its response is required.

The first version of this approach, which we have as yet explored in the most detail, involves expressing the primary field in terms of fundamental spheroidal modes (FSM) for the standardized excitations. In particular, these are solutions in spheroidal coordinates to the Laplace equation that governs the primary (transmitted) magnetic potential field. The origin is taken to be located at the target, not the sensor, and the superposition of modes expressing the primary field is valid throughout the domain. Spheroidal modes are chosen simply because spheroidal enclosing shapes and coordinate systems conform more readily to the kinds of shapes

we are interested in, therefore fewer terms will be required. The primary magnetic potential field is expressed as

$$\Psi^{\text{PR}} = \sum_j b_j \Psi_j = \sum_{j=\{n,m\}} b_{mn} P_m^n(\xi) P_m^n(\eta) \begin{cases} \cos m\phi \\ \sin m\phi \end{cases} \quad (1)$$

where  $\xi$ ,  $\eta$  and the angle  $\phi$  are just the standard “radial,” “angular,” and circumferential spheroidal coordinates, respectively; the subscript  $j$  indicates all admissible combinations of  $n$  and  $m$ ; and  $P_m^n$  is the standard associated Legendre function of the first kind. These are easily calculated. The lowest modes, for each of  $m = 0$  and  $m = 1$ , correspond just to uniform (H field) axial and transverse excitation. Higher modes provide more detail for more non-uniform excitations. For a given primary field, the key is to determine the coefficients  $b_j$  that apply when the object is in any contemplated position. This also is easily done, either by integrations that exploit the orthogonality properties of the Legendre functions, or by a simple point matching scheme.

The secondary field response  $\Psi_j^{\text{s}}$  to the  $j^{\text{th}}$  standard excitation ( $\Psi_j$ ) is

$$\Psi_j^{\text{s}} = \sum_k S_{j,k} \Psi_k^{\text{s}} \quad (2)$$

where the  $S_{j,k}$  are coefficients scaling the basis  $\Psi_k^{\text{s}}$ . The latter can likewise consist of spheroidal Laplacian eigenfunctions

$$\Psi_{k=\{m,n\}}^{\text{s}} = Q_m^n(\xi) P_m^n(\eta) \begin{cases} \cos m\phi \\ \sin m\phi \end{cases} \quad (3)$$

where  $Q_m^n$  is the associated Legendre function of the second kind and, as for  $j$ , each value of  $k$  indicates different admissible combinations of  $m$  and  $n$ . In this case (spheroidal response modes) we write  $S_{j,k}$  as  $B_{j,k}$ . Alternatively, the  $S_{j,k}$  can represent hypothetical magnetic charge or current strengths, in which case each  $\Psi_k^s$  is the potential field produced by the  $k^{\text{th}}$  such source. In this case we write  $S_{j,k}$  as  $q_{j,k}^s$ , to distinguish the source based system from the spheroidal eigenfunction system for the scattered field.

We have concentrated our efforts thus far on the source-based system for the scattered field. It has the advantage that we can determine a greatly reduced source set (RSS) that produces essentially the same scattered field as a more complete, numerous set of sources, for each input FSM. Altogether, while we have pursued many variants and continue to do so, the FSM excitation system with RSS response parameters (FSM-RSS) is the approach we have formulated and tested in this project. However one parameterizes them, one can combine the relations above so that the complete secondary (scattered) field can be written as

$$\Psi^s = \sum_j b_j \Psi_j^s = \sum_j b_j \sum_k S_{j,k} \Psi_k^s \quad (4)$$

The basic ideas sketched above can be recast simply as a procedure. This produces the complete EMI response of an arbitrarily complex metallic object, including all near and far field effects, and internal interactions:

1. In any sensor-target configuration, express the primary field as a linear combination (weighted superposition) of pre-defined, fundamental, standardized excitation fields;
2. Determine the basic responses of the object, i.e. to unit magnitudes of each of these basic excitations;
3. Under any particular circumstances (e.g. sensor-object geometry), obtain the complete solution by forming a linear combination of the basic responses using the same weights  $b_j$  as produced the primary excitation. That is, a given linear combination of inputs will produce the same linear combination of corresponding outputs.

In practice, we are generally solving for the response coefficients  $S_{j,k}$  here. The basic building blocks of the response,  $\Psi_k^s$ , are just defined functions attached to those coefficients, and the input spheroidal Laplacian eigensolutions are often intuitively graspable - and physically informative - field patterns. For the lowest excitation mode  $j = 0$ , the primary field is just a uniform axial H field of magnitude  $b_0$  (Figure 1). The corresponding response coefficients  $S_{0,k}$  are just equivalent source magnitudes that produce the response to such a primary field. Note the next higher mode shown in the lower plot in the figure. At one end of the object the field is vectorially positive in one direction, passes through zero magnitude at the center of the object, then increases with the opposite sign. That is, at least around the axis of the target, it supplies a  $\sim$  linear variation of the primary field that can be superposed on the uniform background of the lower mode. Higher modes bring to bear more detailed and varied patterns, to accommodate any real field, especially when sinusoidal azimuthal variation is included (see (3) ).

Figure 2 shows results of a test of our system against UWB EMI measurements with the Geophex GEM-3 sensor, compared to results using the next most complete approach, namely multiple offset, anisotropic dipoles. The fundamental difference between the  $S_{j,k}$  we solve for here and magnetic polarizability coefficients in the commonly used single or multiple dipole models is that these  $S_{j,k}$  represents the response of the *entire* target, including all internal interactions. Linked to this, the secondary field expressed through these  $S_{j,k}$  are valid in near, middle, and far field. This is the reason for the accuracy of the green line in Figure 2 as opposed to that for the displaced dipoles.

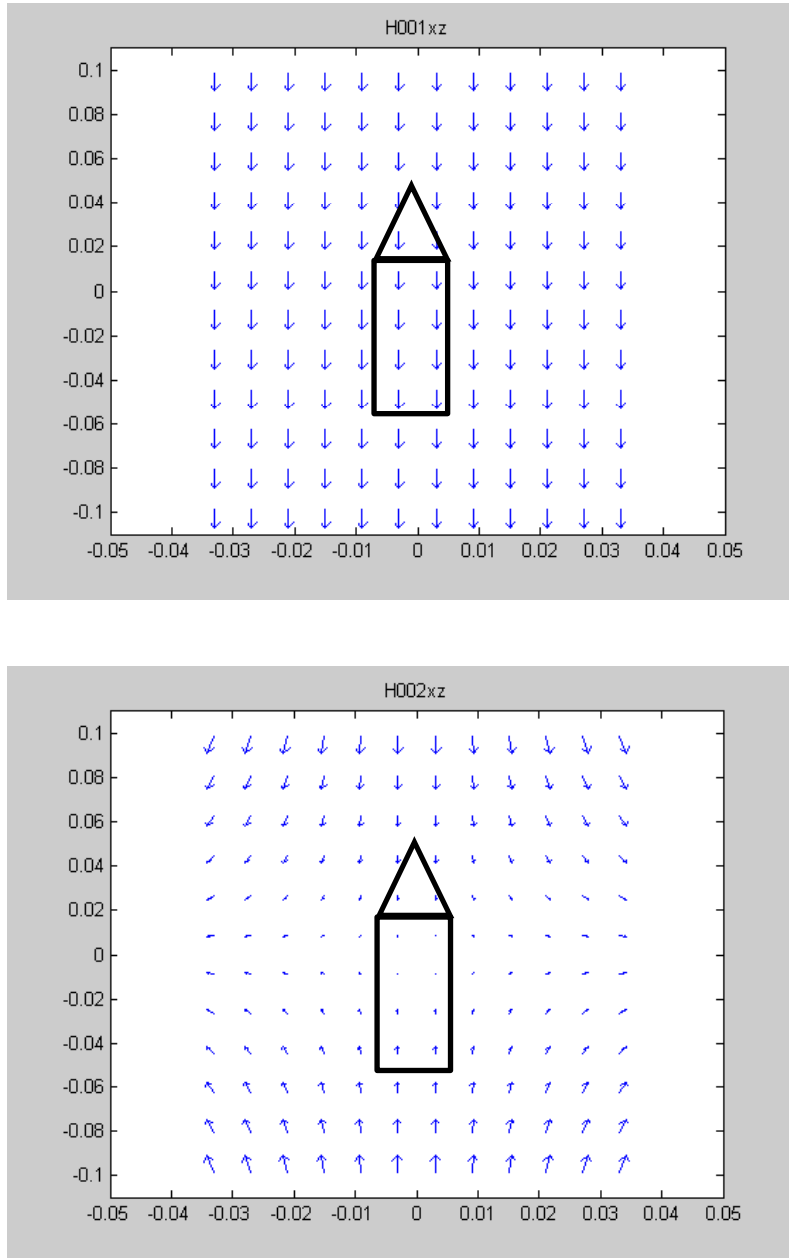


Figure 1. Transmitted magnetic field patterns corresponding to two of the lowest excitation modes, around a hypothetical target shape. Edge labels correspond to space coordinates (arb) on two sides of a plane through the target axis.

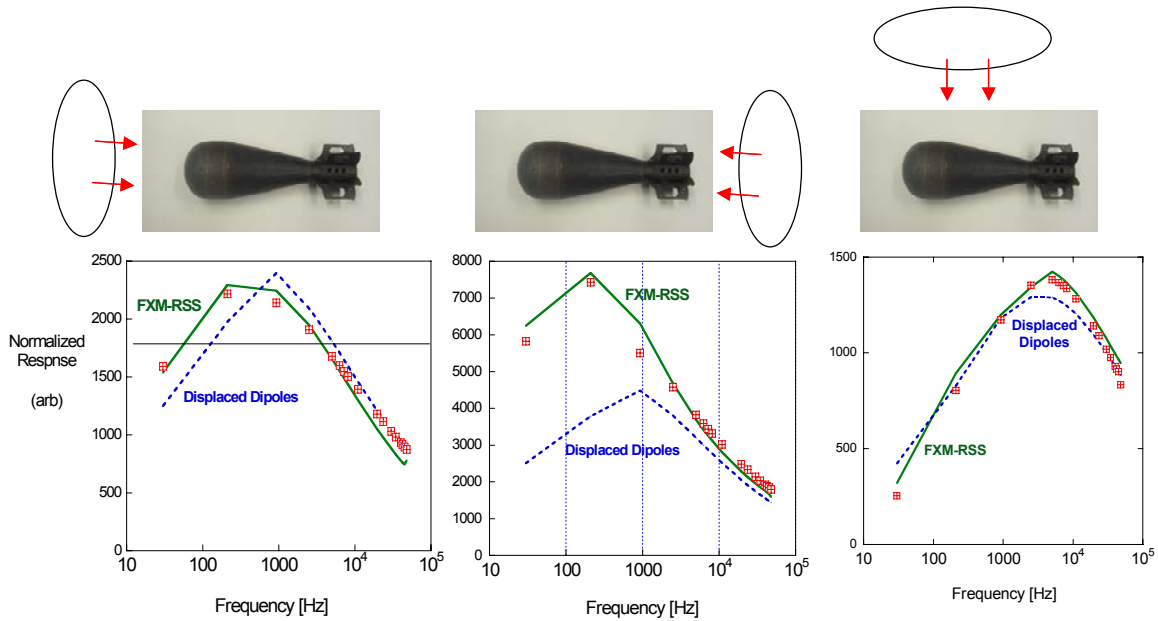


Figure 2. GEM-3 measurements (markers) compared to two modeling approaches.

This is written as if assuming a monostatic, frequency domain system. The generalization to a bistatic and/or time domain system is straightforward. In the latter case, with step function (in time) input, equation (1) would refer to the initial condition and the stored modal responses would cover the entire time period of interest.

Details of the results in this project appear in a number of publications listed in Section 4 below. These include treatment of the definition of the fundamental spheroidal excitations; computation and processing for their coefficients; ill-conditioning issues surrounding that computation and various treatments thereof; testing against other modeling approaches and measurements; implementation in inversion schemes including Bayesian, weighted least squares, and pattern matching classification variants.

### 3. Bibliography

1. K. Sun, K. O'Neill, S.A. Haider, and K.D. Paulsen (2002). Simulation of electromagnetic induction scattering from targets with negligible to moderate penetration by primary fields, *IEEE Trans. Geosci. Remote Sensing*, vol 40, No 4, 910-927.
2. K. Sun, K. O'Neill, F. Shubitidze, and K. D. Paulsen (2002). Treatment of broadband and multi-object electromagnetic induction scattering using high frequency approximations, *Proc. IGARSS'02, Toronto, June 24-28, 2002*.
3. F. Shubitidze, K. O'Neill, S. Haider, K. Sun, and K.D. Paulsen (2002). Application of the method of auxiliary sources to the wideband electromagnetic induction problem, *IEEE Trans. Geosci. Remote Sensing*, vol 40, No 4, 928-942, 2002.
4. F. Shubitidze, K. O'Neill, K. Sun and K. Paulsen (2002). Application of broadband EMI responses to infer buried object's aspect ratio, *Proc. IGARSS'02, Toronto, June 24-28, 2002*.
5. F. Shubitidze, K. O'Neill, K. Sun, and K.D. Paulsen (2002). Investigation of broadband electromagnetic induction scattering by highly conductive, permeable, arbitrarily shaped 3-D objects, accepted for publication, *IEEE Trans. Geosci. & Remote Sens.*
6. K. Sun, K. O'Neill, F. Shubitidze, I. Shamatava and K.D. Paulsen (2002). Theoretical analysis of TSA formulation and its domain of validity, accepted for publication, *IEEE Trans. Geosci. & Remote Sens.*

## **4. Publications**

### **4.1 Journals:**

K. Sun, K O'Neill, I. Shamatava, F. Shubitidze, K. D. Paulsen (2003). A fast forward model for simulating EMI scattering with realistic sensors and elongated objects, ACES J., vol 18, no 4, p 97-106.

K. Sun, K. O'Neill, F. Shubitidze, I. Shamatava, and K.D. Paulsen (2004). Fundamental spheroidal excitation modes for fast inversion of EMI survey data, to be submitted, June 2004.

F. Shubitidze, K. O'Neill, K. Sun, I. Shamatava, and K.D. Paulsen (2004). Source-based fundamental excitation and response modes for inversion and classification of buried metallic objects, to be submitted July 2004.

### **4.2 Conferences (full paper published):**

K. Sun, K O'Neill, I. Shamatava, F. Shubitidze (2003). Application of prolate spheroid solutions in simulation of EMI scattering with realistic sensors and objects, Proc. Appl. Comput. EM Symp (ACES), 2003, Monterey CA, 24-28 Mar 2003, p.531-537.

F. Shubitidze, K. O'Neill, K. Sun, I. Shamatava and K.D. Paulsen (2003). Analysis of EMI scattering to support UXO discrimination: heterogeneous and multiple objects, SPIE'03, Orlando, 21-25 April 03.

K. Sun, K. O'Neill, Lanbo Liu, F. Shubitidze , I. Shamatava and K.D. Paulsen (2003). Analytical solutions for EMI scattering from general spheroids with application in signal inversion for UXO discrimination, SPIE'03, Orlando, 21-25 April 03.

K. Sun, K. O'Neill, L. Liu, F. Shubitidze, I. Shamatava (2003). Application of Bayesian inversion of electromagnetic induction data for UXO discrimination, Proc. Symp. Applic. Geophys. Engg & Environ. Problems (SAGEEP), San Antonio TX, 6-10 Apr 2003, p1469-1478.

K. Sun, K. O'Neill, L. Liu, F. Shubitidze, and I. Shamatava (2003). Application of Bayesian inversion of scatterer shape from EMI data, 2003 IEEE AP-S Int'l Symp. & USNC/CNC/URSI Nat'l Radio Sci. Mtg, Columbus, OH, June 22-27, 2003.

F. Shubitidze, K O'Neill, K. Sun , I. Shamatava and K. D. Paulsen (2003). Fast direct and inverse EMI algorithms for enhanced identification of buried UXO with real EMI data, Int'l Geosci. & Remote Sens. Symp, 21-25 July 2003, Toulouse, Vol 7, 4160-62.

K. Sun, K O'Neill, F. Shubitidze, I. Shamatava, K. D. Paulsen (2004). Fundamental mode approach to forward problem solutions in EMI scattering - Inferring fundamental solutions from training data, Proc. Appl. Comput. EM Symp (ACES), Apr 2004.

F. Shubitidze, K O'Neill, I. Shamatava, K. Sun and K.D. Paulsen (2004). A new numerical procedure for efficient and accurate representation of low frequency EM responses for a heterogeneous object, Proc. Appl. Comput. EM Symp (ACES), Apr 2004.

F. Shubitidze, K O'Neill, I. Shamatava, K. Sun and K.D. Paulsen (2004). Use of standardized source sets for enhanced EMI classification of buried heterogeneous objects, SPIE Defense & Security Symp., 12-16 April 2004, Orlando, FL.

K. Sun, K O'Neill, F. Shubitidze, I. Shamatava, K. D. Paulsen (2004). Fast data-derived fundamental spheroidal excitation models with application to UXO identification, SPIE Defense & Security Symp., 12-16 April 2004, Orlando, FL.

## **5. Participating Personnel**

Professor Keith D. Paulsen, Thayer School of Engineering at Dartmouth

Dr. Fridon Shubitidze, Research Scientist, Thayer School of Engineering at Dartmouth

Dr. Keli Sun, Senior Research Associate, Thayer School of Engineering at Dartmouth

Ms. Irma Shamatava, Research Engineer, Thayer School of Engineering at Dartmouth