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Passive and Active Low-Frequency Electromagnetic Spectroscopy

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Executive Summary

Electromagnetic (EM) induction techniques can potentially provide information that will contribute to the delineation and characterization of Underground Facilities (UGF) which produce weapons of mass destruction or perform other covert activities deemed threatening to our national security. EM geophysical techniques, used widely in mineral exploration, geo-hydrology, engineering, and environmental assessment, consists of measurements of fluctuating magnetic fields with a loop antenna at the surface of the earth above or in a bore hole near the subsurface target area. The fluctuating fields may be natural (magnetotellurics), excited by a controlled source which is part of the EM instrumentation (active EM), or emitted by an electrically active target (passive EM). Active EM provides information about the conductivity and/or permeability distribution in the subsurface resulting from the scattering of the primary field emitted from the active EM transmitter by the anomalous zones, from induced eddy currents in highly conductive targets, magnetic polarization of permeable targets, perturbation of background current flow in a conductive earth, or a combination of these phenomena. The conductivity and permeability distribution may be associated with man-made structures that include metal and voids which, in turn, may be an element of a UGF. Passive EM provides a means of directly sensing the operation of electrical equipment or of power lines feeding them, with the potential to both locate the equipment or power lines from spatially sampled data and characterize the equipment from the spectral content of the EM signal.

The objective of the research performed under this project was to advance EM induction sensor technology and software for modeling and interpreting EM induction data, and perform experiments testing EM methodology pertaining to UGF.

Hardware development primarily focused on improvements to the GEM-2 instruments, including changes that have been implemented in operational units that have been built, as well as design and module prototyping for the next generation. We also have experimented with new sensor calibration techniques.

An undertaking to derive more rigorous imaging algorithms for active source EM data has been the focus of software research efforts. In an attempt to achieve a practical compromise between the simple, crude Born approximation and the very complex rigorous solution of Maxwell's equations for the general three-dimensional scattering problem, an inversion algorithm based on the "extended Born" approximation has been developed. This scheme accounts for the field alteration generated by the conductivity anomaly in an approximate way that eliminates the need to solve a large matrix equation. The approximation is based on the assumption that the variation of the electric field in the anomalous region is small, which, unfortunately, is not always the case. Efforts to improve the approximation via iterative techniques were successful when the conductivity contrast was low, and for voids - the same criteria that holds for the iterative Neumann series method. The "extended Born", as well as the full matrix integral equation forward models were incorporated into a conjugate-gradient inversion algorithm for imaging. Convergence to a reasonable reconstruction of a simple model used to generate synthetic data degraded rapidly as the number of mesh cells were increased, particularly for the "extended Born" approximation. Incorporating a focusing term into the least square objective function for regularization did not significantly improve convergence or image sharpness. Another approach has been formulated, in which, like the Born approximation, no dyadic

Green's function is computed and no matrix equation solved. In order to account for the frequency response of metallic structures, a parametric scalar response function is applied that accounts for high conductivity and magnetic permeability, and also void and current channeling response modes. A parametric model with the essential frequency response features based on known responses of spheres and voids has been developed using incident magnetic and electric fields within a conductive halfspace excited by a loop current source at the surface. This algorithm could potentially be incorporated into an inversion algorithm for imaging the spatial distribution of buried metal structures and voids.

Passive EM research included an experiment comparing single-loop and coaxial gradient sensors in horizontal and vertical loop orientations. All of the techniques can measure spectral EM radiation from power lines and other man-made sources, but different loop configurations have different spatial resolution and sensitivity to various source orientations and distances. Some simple analyses were done to quantify signal (nearby buried dipole source)/noise (distant power lines) for the various configurations.

1.0 Introduction

The objective of this program is to perform research to advance the science in the application of both passive and active electromagnetic measurement techniques for the detection and spatial delineation of underground facilities. Passive techniques exploit the electromagnetic fields generated by electrical apparatus within the structure, including generators, motors, power distribution circuitry, as well as communications hardware and similar electronics equipment. Frequencies monitored are generally in the audio range (60-20,000 Hz), anticipating strong sources associated with normal AC power (i.e., 50 or 60 Hz and associated harmonics), and low frequency power from broad-band sources such as switching circuits. Measurements are made using receiver induction coils wired to electronics that digitize and record the voltage induced by the time varying magnetic fields. Active techniques employ electromagnetic field transmitters in the form of AC current carrying loops also in the audio frequency range, and receiving coils that measure the resultant time varying magnetic fields. These fields are perturbed from those expected in free space by any conductive material in the vicinity of the coils, including the ground, so that the total measured field is comprised of the primary free-space component and the secondary scattered component. The latter can be further delineated into an average background field (uniform conductive half-space earth) and anomalous field associated with heterogeneous zones in the earth, including both highly conductive objects such as metallic structures as well as highly resistive structures such as empty voids corresponding to rooms or tunnels.

Work performed during Phase I included the development of the prototype GEM-2H instrumentation, collection of data at several test sites in the passive mode and a single site in the active mode, development of processing and interpretation software.

The technical objectives of Phase II were to: 1) continue to develop and improve EM instruments; 2) develop new software for analysis and inversion of electromagnetic induction measurements for both passive and active surveys; 3) Perform experiments to test EM induction methodology.

2.0 Instrumentation Development

2.1 GEM-2 Instrument Description

The GEM-2 is a hand-held, digital, multi-frequency electromagnetic sensor operating over a frequency band of 90 Hz to 23 kHz (Won et al., 1996). The unit is capable of transmitting and receiving any digitally synthesized waveform by means of the pulse-width modulation technique. The GEM-2 sensor contains a transmitter coil and a receiver coil separated by about 5.5 feet. It also contains a third "bucking coil" that removes (or bucks) the primary field from the receiver coil. All three coils are molded into a single board, dubbed the ski, in a fixed geometry, rendering a light, compact, and portable package. The electronics/processing console is attached directly to the ski, which provides current to the transmitter coil and also digitizes, processes and records the signal from the receiver and bucking coils. The GEM-2 has two recording channels: one from the bucking coil (called the reference channel) and the other from the bucked receiver coil (called the signal channel). Both channels are digitized at a rate of 24 kHz (half the transmitter rate) at 16-bit resolution. To extract the in-phase and quadrature components, the measured time-series is convolved with a set of sine series (for in-phase) and cosine series (for quadrature) for each transmitted frequency. This convolution renders an extremely narrow-band, match-filter-type, signal detection technique. A single computer (DSP chip) coordinates all controls and computations for the transmitter and receiver channels. The in-phase and quadrature data derived through the convolution are converted into a part-per-million, or ppm, unit defined as the ratio of the secondary magnetic field divided by the primary magnetic field as observed at the receive coil.

2.2 GEM-2H Instrument Description

The GEM-2H was designed to be an evolutionary advancement of the GEM-2, not a completely new, untested sensor. A comparison between the coil designs of the two sensors is shown in Figure 1, and the GEM-2 in use. The desired modifications included higher transmitting and receiving dipole moments for increased depth of exploration, and the option to operate in a passive mode (i.e., with the transmitter turned off). The transmitter coil has a switch selectable option of 12 or 24 turns, the former optimal for high frequency when the current is limited by the inductive load, and the latter optimal for low frequency when the current is limited by the power supply maximum output current. The electronics console is essentially the same as the standard GEM-2, except for two transmitter voltage settings for the two winding settings, and the option to record passively.

GEM-5P Instrument Description

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2.3 GEM-2 Hardware Improvements

Improvements to the GEM-2 receiver (Rx) and bucking (Bx) coils implemented in the current instruments include reduction in the number of windings, use of teflon insulated wire, and addition of polystyrene Q-dope to coat the wires in place of epoxy. The reduction in windings increases the coil resonance frequency well above the operating band, resulting in a more stable sensor frequency response. The new wire and coating reduces the dielectric temperature sensitivity associated with the coil capacitance, which in turn improves sensor stability.

Improvements in the electronics have been made to prototype modules. The hybrid components in the transmitter (Tx) switching bridge have been replaced with high-speed, low resistance MOSFET components. The reduction in resistance reduces power waste and self-heating, eliminating the need for large heat sinks. The increase in switching frequency (from 48 kHz to 800 kHz) improves the fidelity of the transmitted waveform, concentrates the power in the desired frequencies, and moves the switching power out of the operating frequency where it can be easily filtered out. An added benefit is the elimination of the need for de-spiking circuitry, which is expected to improve sensor stability. Preamplifiers have been built that will be attached directly to the coils, so that the analog signals carried over the wires from the coils to the console will be amplified, improving signal/noise (i.e., reducing the impact of noise picked up in the cables). Design work for future improvements includes replacement of the 16-bit A/D with a faster 24-bit A/D, increasing the dynamic range and doubling the frequency bandwidth.

2.4 GEM-2 Calibration

An ideal measurement is not realizable with any real hardware – electronic and mechanical limitations result in an instrument response that distorts the measurement to some extent. Two system response parameters can be accounted for if they are known as a function of frequency. The first is the system transfer function that describes a multiplicative amplitude and phase distortion, generally important at high frequency when the receiver loop resonance and anti-alias filter have effects, and the second is an additive free-air offset arising out of imperfect bucking. Corrections for these system effects are made in real-time by the GEM console firmware by application of compensation coefficients. These coefficients must be measured in a controlled calibration procedure where the ideal measurements are known. We have enhanced the calibration methodology. The focus was development of an inversion algorithm that would simultaneously extract both the frequency dependent free-space offset errors and the system transfer function while accounting for the presence of a conductive (half-space) earth. This would enable a single systematic and accurate procedure to be employed for complete system calibration. Details of the compensation equations and calibration methodology, with examples of calibration data and fit to theory, are provided in Appendix A.

3.0 Software Development

Interpretation of EMI data requires software tools that enable the user to delineate the underground model that accounts for the observed excursions from normal background. These software algorithms include programs that predict observations for an assumed model (forward modeling), as well as programs that use the data to generate a consistent model (inversion).

3.1 Active-Source EM Software Development

Interpretation of GEM-2H data (or any EM data) in an environment with large spatial variations in the conductivity within the subsurface remains somewhat problematic due to the lack of modeling and inversion tools for general structures. Algorithms that have been developed in the geophysical community tend to be either limited in scope (e.g., layered earth, sphere), extremely complex and computer resource demanding (e.g., 3-d finite difference inversions), or overly simplistic and inaccurate (e.g., Born approximation based inversion). In particular, these algorithms (including the more rigorous ones) perform poorly when man-made metal structures are involved. The goal in our effort is to compromise between accuracy and computational requirements to obtain a more practical data interpretation tool, and to find an approximation scheme that is tailored to coping with metal structures that respond in the inductive limit (i.e., frequencies are above the target quadrature peak response).

3.1.1 EM Data Inversion – Imaging

The focus of the software development effort has been on the development of an improved imaging algorithm. Two approaches have been pursued: the first employs the “extended Born approximation” (Habashy, et. al., 1993), and the second a parametric frequency response model incorporated into a Born approximation type algorithm with the goal of accounting for the intrinsic response of metal targets as well as weak scattering targets including voids. The first has been incorporated into a non-linear inversion algorithm in an attempt to develop an imaging algorithm, and the second has been developed as far as the forward algorithm.

3.1.1.1 EM Extended Born Forward Model Development

By replacing the forward algorithm based on the Born approximation, which assumes weak scattering (generally not the case), with the extended Born approximation to the electric field integral equation, a more accurate representation of the conductivity structure can be attained. Also, the incident and scattered fields in the new algorithm take into account the air-earth interface.

The volume integral equation for the EM scattering problem is written:

$$\vec{E}(r) = \vec{E}^0(r) + \iiint_V \overline{G(\omega; r, r')} \cdot \vec{J}^s(r') dv' \quad (3-1)$$

where $\vec{J}^s(r') = (\sigma - \sigma_0)\vec{E}(r') \Rightarrow 0$ in the background

$\vec{E}^0(r)$ = incident (background) field

$\overline{G(\omega; r, r')}$ = tensor Green's function for conductive medium

Note that the unknown fields within the region of anomalous conductivity appears both on the left of the equal sign and under the integral operator (i.e., inhomogeneous Fredholm equation of the second kind), and thus a general solution requires an approximate numerical technique.

The tensor Green's function can incorporate any background conductivity that has an analytic solution for an electric dipole current source (e.g., layered or uniform half-space). Except for shallow, flat lying structures, the terms that modify the conductive whole-space to account for the air-earth interface are not too important and are thus ignored – an approximation that greatly simplifies the program as well as reducing computational load. Since the transmitter and receiver coils are very close to the air-earth interface, the incident fields do include those terms, as well as the emf computed from the scattering currents. This is a reasonable compromise between efficiency and accuracy.

The next approximation utilizes a scheme proposed by Habashy, et. al., (1993) attained with the following manipulation of the above expression:

$$\vec{E}(r) = \vec{E}^0(r) + \iiint_V \overline{G(\omega; r, r')} \cdot \gamma(r') \vec{E}^s(r') dv' + \iiint_V \overline{G(\omega; r, r')} \cdot \gamma(r') [\vec{E}^s(r') - \vec{E}^s(r)] dv' \quad (3-2)$$

where $\gamma(r') = \sigma(r') - \sigma_0$ and the prime designates source (integration variables) point, unprimed field point coordinates. Thus the fields under the integral sign in the first integral can be taken out from the integral, leaving an integral that is not directly dependent on the solution. The second integral includes a factor proportional to the variation of the field throughout the source region relative to the value at the field point. The extended Born approximation assumes that the field variation is small compared to the overall field value (i.e., slowly varying), and ignores this term. By doing so, the solution decouples for different field points and can be solved independently at each point. Once the electric fields in the anomalous region of the subsurface are known, the measured emf at the receiver is computed using the expression based on reciprocity (Norton, 1995, Norton et.al., 1999):

$$emf = emf^0 - \iiint_V \vec{E}(r') \bullet \vec{E}^{Rx}(r') \gamma(r') dv' \quad (3-3)$$

where emf^0 is the background (half-space) response and $\vec{E}^{Rx}$ is the incident field that would be generated within the structure if the receiving loop acted as a one amp transmitter (termed "reciprocal" incident field).

The next step is to formulate a numerical algorithm to approximate the field distribution in the subsurface region having a conductivity different than the background value. The method employed is the Method-of-Moments (MoM) using pulse basis functions over rectangular prismatic cells and delta-function weighting. In other words, the zone in the subsurface containing structures of interest is divided into a grid of blocks each having a constant conductivity, and the fields approximated as constants within each block, and the field points of evaluation are at the center of each block.

The integral equation is then discretized via integration over each cell, forming a matrix equation for the field values in each cell. Note, this can be done with the full equation, or with the extended Born approximation – the former results in a large system of equations with coupling between the different cells, the latter in a decoupled set of 3x3 systems for the vector field in each cell. We have coded both forward algorithms, and each have been incorporated into the inversion algorithms described below. Integration of the tensor Green's function terms follows that of Hohmann (1987), in which the gradient/divergence operator terms are replaced by finite differences of the retarded scalar potential for a spherical charge distribution centered at cell boundaries. Rectangular cells are constructed numerically from cubic sub-cells. Each coupling term between cells is generated and stored, and then the field solution solved for each cell (a 3x3 system) by adding column elements from the (full) stored matrix. The measured *emf* is computed by adding the contributions from each cell as/per the above expression, noting that for the small Tx-Rx separation of the GEM, the Tx incident field (already computed) can be used as an approximation to the Rx incident (reciprocal) field. For comparison purposes, a program that does not use the extended Born approximation is easily made by modifying the program to perform the full matrix equation solution (computations of the matrix elements, incident fields, and *emf* are the same, however a system of equations $3n \times 3n$, where n is the number of cells in the grid, must be solved).

Testing the forward algorithm is critical to evaluate its model range of applicability and overall accuracy. The prototype model for testing was a prismatic conductor buried in a conductive half-space, as/per Hohmann (1975); the target is a 1.0 S/m tabular prism 120 m in strike length, 90m depth extent, and 30 m thick, buried 30 m in .01 S/m earth, and .00333 S/m earth. The horizontal loop EM system consisted of dipole Tx and Rx coils separated by 150 m (data points referenced to midpoint) operating at 1000 Hz. Since this test refers to a similar volume integral equation algorithm, it is not a test of the basic MoM scheme for such an algorithm, but rather for a check on our particular approximations (i.e., only including air-earth interface effects for the incident and scattered fields and not the cell coupling; the extended Born approximation, and the code implementation). Also, the algorithm used by Hohmann (1975) in this model did not incorporate the scalar potential difference scheme referred to above, which he developed at a later time. A comparison of the scattered field (does not include background response) results for two positions – centered over the target (i.e., loops straddling the target, producing the peak negative response along the profile), and centered at 105 m ("side lobe" positive peak) is summarized in Table 1.

	<u>Hohmann</u>	<u>New IE</u>	<u>extended Born IE</u>	<u>Born IE</u>
.01S/m half-space:				
x=0				
IP	-146,000ppm	-211,000ppm	-141,000ppm	-860,000ppm
Q	-200,000ppm	-222,000ppm	-169,000ppm	-2,110,000ppm
x=105				
IP	+60,000ppm	+75,000ppm	+67,000ppm	+690,000ppm
Q	+54,000ppm	+64,000ppm	+52,000ppm	+866,000ppm
.00333S/m half-space:				
x=0				
IP	-31,000ppm	-80,000ppm	-67,000ppm	-362,000ppm
Q	-108,000ppm	-152,000ppm	-92,000ppm	-2,430,000ppm
x=105				
IP	+12,000ppm	+24,000ppm	+18,000ppm	+313,000ppm
Q	+35,000ppm	+46,000ppm	+37,000ppm	+1,200,000ppm

Table 1. Comparison of the different approximation algorithms for the integral equation solution of the VMD response of a 1.0 S/m target buried in a conductive halfspace.

The "New IE" refers to our full integral equation solution without the extended Born approximation. This algorithm tends to predict a somewhat higher response than Hohmann's original algorithm. Convergence testing done by Hohmann (1987) showed that this is consistent with the scalar potential-difference scheme; when the target discretization is refined (i.e., smaller cell size), the response in general increased as it converged, and the scalar potential-difference change "improved" the algorithm by pushing the results towards convergence (increased the response with the same cell size). However, another contribution to the difference in our results can be attributed to the neglected air-interface terms in the tensor Green's function. For the 10/1 and 33/1 conductivity contrasts (considered low to moderate in geophysical applications), the Born approximation grossly overestimates the response. Because the Born approximation is linear in conductivity contrast, the solution never saturates, which is not physically reasonable for contrasts of about 5/1 or more.

In examining the neglected (error) term in the extended Born approximation, it can be anticipated that for a model geometry in which the incident (and thus total) field varies substantially over the target, the solution would be a poor approximation. A flat lying slab under the transmitter is such a case, and indeed the agreement with the full IE is much worse than the above case. Examining the extended Born form of the integral equation, it appears that for varying incident field geometry, a correction using the first pass results to evaluate the second integral can be added into the first pass solution. An iterative scheme can be formed by repeating this process, and this was tried, but unfortunately it does not converge for conductivity contrasts greater than about 3/1. The iteration scheme not only converges for low contrasts (and voids), it matches the full integral equation solution. Comparison of an iterative Neumann series solution showed the same convergence criteria holds for the extended Born (and when they

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converge, they agree). Algorithms to transform the Neumann series to a convergent form have been published (e.g., Avdeev et al., 1998), however the forms are more complex to implement and require hundreds of iterations to converge when the conductivity contrasts are 100/1 or more. Such an algorithm is not practical for an imaging application based on generalized inversion.

There is a problem with highly varying fields in the full IE, as well as for very high conductivity contrasts (i.e., 500/1), in which the true currents consist of closed eddy currents confined in the highly conductive zones. It is clearly apparent when comparing the IE solutions with analytic layered earth solutions for a conductive slab sandwiched between resistive layers. Also, the 3-d IE algorithms using only pulse basis functions always fail to asymptote to the response of a conductor in free-space when the background conductivity is reduced. This problem has been discussed and addressed by Lajoie and West, (1976); and SanFilipo and Hohmann, (1985), but their solutions were applicable only to models with simple geometry, and are too computational demanding for generalized inversion. Another aspect that must be considered for metal structures is the contribution of ferrous susceptibility. A parametric modeling approach for metal objects has been investigated and is discussed in a later section.

3.1.1.2 Inversion Algorithms using the extended Born approximation

The inversion scheme of Hanson and Witten et al, (1997) utilized regularization, and Norton (1995) used singular value decomposition. Both of these approaches applied a two dimensional Fourier transform scheme to the Born approximated IE that allows decoupling the problem so that a separate, small inversion is performed for each horizontal wavenumber value to get the depth variation of conductivity. The resultant spectra for all of the depth samples are then inverse Fourier transformed to get the lateral variation at each depth interval. This method yields a very computationally efficient algorithm; however, a side effect is that nonphysical negative conductivities result and there is no straightforward way to impose a positive conductivity constraint. Also, the Born approximation, as discussed above, can be grossly inaccurate. In particular, all of the phase shift in the response is attributed to propagation through the background media, so that any self-inductance effects will be erroneously accounted for via conductor location (i.e., the depth estimates will tend to be biased). This will be a problem particularly when encountering man-made metal structures, often having an inductive response (inphase > quadrature) at low (< 1 kHz) frequencies.

Because only the Born approximation is linear in response with respect to subsurface conductivity, all the more rigorous forward models require a new, iterative inversion scheme. Unfortunately, computer resource demands increase drastically for any improvement in accuracy. The extended Born scheme described above has been incorporated into several inversion schemes and testing with synthetic data has been undertaken. The algorithms include Marquardt-Levenberg, (described extensively in the literature; we have used a modified algorithm based on routines from Press et.al., 1992), steepest-descent, and conjugate-gradient (Luenberger, 1984).

All of the algorithms are chi-squared (weighted squared error) minimization based, and require calculation of the data/parameter sensitivities (partial derivatives of the model data with respect to the model parameters). We have implemented the scheme for computing Frechet derivatives as described by Norton and Bowler (1993) and Norton et.al. (1999), and similar to the layered earth case example in the latter, the data/parameter sensitivities become the integral of the internal total electric field dot product with the adjoint field (field generated by transmitting at the receiver location – for small Rx-Tx separations, approximated as the solution internal field):

$$\frac{\partial(emf)}{\partial\sigma_i} = - \iiint_{v(i)} \vec{E}(r') \bullet \vec{E}^{adj}(r') dv' \quad (3-4)$$

where σ_i is the conductivity in the i th cell and $v(i)$ the volume defined by the i th cell. This formulation precludes the need to compute finite difference forward models, and the fields are already computed in the forward model data generation (for the GEM instruments with short loop separations the adjoint field is replaced by the normal solution), which drastically reduces the computational costs from traditional algorithms. During the course of testing the inversion code, it was found that performance improved if the vertical component in the above expression for the sensitivities was explicitly excluded, since the vertical component of the source field is zero, and thus the vertical component of the solution field (not zero) does not contribute to the measured emf. Inverting a full 3-D mesh requiring 2-D surface data coverage poses a very large problem, so the current algorithm is written to constrain the conductivity within the mesh to vary only in x (profile) and z (depth) directions. The strike length of the model is finite as set by the input cell mesh and the forward model is 3-D. Also, a single line of data (multiple frequency) is inverted. The starting model is always a homogeneous half-space, i.e., the conductivity of all cells set to the background. The conjugate-gradient method was implemented initially with no regularization penalty function, and then a “focusing” penalty function (Portniaguine et al., 1999) was added to the chi-squared objective in an attempt to improve the inversion convergence and resolution. The full integral equation forward model was also incorporated into a conjugate-gradient inversion algorithm, as was the Born approximation, for comparison.

3.1.1.2.1 Evaluation of Inversion Algorithms.

We started with very small models to assess the potential for large problems, initially using synthetic data from the same forward algorithm to focus on invertability issues (i.e., convergence, regularization for underdetermined cases, etc.).

Test 1 – prismatic horizontal slab, inversion cell mesh matching forward model

The simplest test performed was a model consisting of a 0.1 S/m prism 60 m x 120 m x 30 m, buried 30 m to the top in a .005 S/m half-space, constructed out of 30 m cubic cells (two parameters to invert since there are two cells in x and one in z). The geometry mesh in the inversion matched the model mesh, so that the inversion only had to find the correct conductivity of the cells. A profile of GEM-2H type data with horizontal loops from –100 m to 100 m at 10 m spacing and two frequencies – 1000 Hz and 10000 Hz was inverted. For this case all of the inversion algorithms worked well without regularization.

Test 2 – prismatic vertical slab, inversion cell mesh matching forward model

The next test performed was a similar model except that it was 30 m thick and 60 m depth extent (two parameters to invert since there is one cell in x and two in z). Data were as above except extended to ± 120 m. This seemingly simple inversion proved much more difficult than the first, because the bottom cell conductivity is not as easily determined.

The Marquardt-Levenberg algorithm performed poorly – after two iterations it was not able to further reduce the chi-squared objective even though it was well above the data variance, with conductivity of the top cell at .08 S/m and bottom cell at 0.3 S/m (with the Marquardt damping factor .001 to .01; at .1 performance degraded). The chi-squared was reduced from the starting value by only a factor of six. At this point we abandoned the Marquardt-Levenberg technique.

The conjugate gradient algorithm performed much better, reducing the chi-squared by a factor of 20,000, after eight sets of conjugate iterations (two conjugate steps/iteration for a two-parameter model). Convergence slowed drastically after four iterations but did continue to improve the model. The final conductivity values were .098 S/m top and .093 S/m bottom if an unrealistically small ($<.0001 \text{ ppm}^2$) data variance was used. With a more realistic data variance model, the chi-squared convergence criteria is met with greater error in the conductivity values.

Test 3 – The above tests were intended to verify the functional integrity of the inversion algorithms – the conjugate-gradient technique will converge to fit data for a model having the minimum number of required parameters. An inversion model was next designed to over parameterize the subsurface relative to the forward model used to generate the data to assess the potential for imaging targets within a mesh. The model is schematically shown below:

Without regularization, the conjugate-gradient inversion reduces the chi-squared objective rapidly for a few iterations, but then stops improving at the following cell conductivities (S/m):

.007	.008	.007
.060	.069	.060
.039	.041	.039
.023	.023	.023
.015	.015	.015

Conductivity resolution is poor, the estimates low, and the data fit was poor.

Data were generated using the more rigorous full integral equation, and inverted using the same conjugate-gradient algorithm as above but incorporating the full integral equation forward model. The performance is significantly better – the chi-squared error continues to decrease with more iterations, though slowly, and the parameter estimates continue to improve. The cell conductivity estimates (S/m) reached these values after 165 iterations:

.010	.011	.010
.007	.485	.007
.013	.168	.013
.047	.063	.047
.040	.037	.040

Execution required about 6 hours on a 266 MHz K2-6 personal computer.

A test with an expanded grid (7x7 cells in the x/z plane) using the “focusing” regularization function with multiplier set to 1000, showed that convergence degrades as the number of free parameters increases, with the final results for the cell conductivities (S/m) as follows:

.006	.014	.007	.006	.009	.013	.006
.013	.020	.026	.102	.026	.020	.012
.014	.022	.037	.050	.037	.022	.013
.017	.023	.028	.031	.028	.023	.017
.017	.019	.021	.022	.021	.019	.017
.015	.015	.016	.017	.016	.015	.015
.013	.013	.013	.014	.013	.013	.013

The chi-square objective was reduced by an order of magnitude (from 5650 to 520) with this model, after which point there was no improvement. This test revealed that the performance of the more accurate forward model also breaks down when a large number of free parameters is used.

3.1.1.3 Parametric Modeling of EM Scattering – A New Approach

Although the extended Born approximation provides a compromise between the simple Born approximation and the rigorous full integral equation, the above results indicate that a practical imaging algorithm that can approximate the geometry of man-made UGF elements that contain metal based on it is difficult to achieve. Also, the performance of an inversion based on the full integral equation solution has not been significantly better, and the computational costs grow dramatically with model complexity. For that reason, we have begun investigating another modified Born type scattering algorithm that could potentially be incorporated into an imaging

routine. The concept is to formulate a parametric model for the complex EM frequency response of a structure buried in a conductive half-space that describes the internal field behavior used to compute the measured scattered fields. We included both electric and magnetic field contributions, the former useful for voids and background current channeling type responses, the latter for confined eddy current and magnetic (ferrous) polarization type responses, describe by the following equations:

$$emf = emf^0 - \iiint_V \vec{E}^{Tx}(r') \cdot \vec{E}^{Rx}(r') \alpha(f, r') dv' - \iiint_V \vec{H}^{Tx}(r') \cdot \vec{H}^{Rx}(r') \beta(f, r') dv' \dots\dots\dots (3-5)$$

where emf^0 is the background (half-space) response, $\vec{E}^{Tx}$ and $\vec{E}^{Rx}$ are the incident electric field generated by the transmitter and the incident electric field that would be generated within the structure if the receiving loop acted as a one amp transmitter (termed "reciprocal" incident field), and, $\vec{H}^{Tx}$ and $\vec{H}^{Rx}$ are similar incident and reciprocal magnetic fields. The parameters $\alpha(f, r')$ and $\beta(f, r')$ are complex frequency dependent parameters that describe the response characteristics of a volume element in the earth that contains EM scattering material.

Note that if $\alpha(f, r')$ is set to $\sigma(r') - \sigma_0$ and $\beta(f, r')$ is set to zero, equation 3-5 reduces to the Born approximation. Initially, we included only the electric field term, however a characteristic of any electric field scheme that does not explicitly include coupling between cells (including the extended Born approximation) always results in twin-peak profiles over confined conductors. This is because the maximum incident electric field is not directly below the Tx, and Born type schemes have response amplitudes that are directly proportional to the incident field. However, for compact (e.g., spheres, cubes, flat-lying plates), highly conductive targets, and small Tx-Rx separations, a single peak directly over the target in response to confined eddy current induction will result, easily verified using an analytic sphere algorithm. The full integral equation solution can predict the single profile peak, but it cannot predict the frequency response of a metal target. The addition of the magnetic field term allows the prediction of single-peak profiles because the incident magnetic field is a maximum directly under the Tx. The electric field term is required for void modeling and certain conductor geometry as well as low contrast situations.

The next step is to define a functional form for the frequency dependence of $\alpha(f, r')$ and $\beta(f, r')$ based on conductivity, permeability, and possibly other parameters that result in a frequency response characteristic of known targets. We emphasize that these functions are not derived via a rigorous solution to Maxwell's equations, but rather by finding a form that approximates the response of conductive and/or permeable anomalies. For the electric field term, we can choose a simple form that has asymptotic conductivity behavior for voids and current channeling saturation:

$$\alpha(f, r') = (\Delta\sigma) g_i \sigma_0 / [(g_i - 1)\sigma + \sigma_0] \quad (3-6)$$

where $g_i = 2 / [1 + l_i / (l_x + l_y + l_z)]$, is a geometric factor based on aspect ratio with l_x, l_y, l_z the target scale length in x,y,z directions and each component matched to the corresponding incident field direction. For an equal-dimensional target, we get the well-known quasi-dc response for a sphere, with the correct void and high-conductivity limits. For this particular model, there is no frequency dependence in the electric field response other than that inherent in the incident fields.

For the magnetic field term, we have defined a complex frequency dependent model designed to approximate the response of a permeable metallic sphere:

$$\begin{aligned} \text{Re} [\beta(f, r')] &= A[C_0 \Delta \mu_r - (C_1 \mu_r + \epsilon_0 f) \epsilon_0 f] / [C_0 \mu_r + (C_2 \mu_r + \epsilon_0 f) (\epsilon_0 f)] \\ \text{Im} [\beta(f, r')] &= A \epsilon_2 f / [1 + (C_3 + \epsilon_1 f) \epsilon_1 f] \end{aligned} \quad (3-7)$$

where:

μ_r = relative permeability, $\mu_r' = [(g_i - 1)\mu_r + 1]$ and g_i as above
 $\epsilon_0 = \Delta \sigma L$, $\epsilon_1 = \Delta \sigma L \sqrt{(\mu_r / [\mu_r' - .5])}$ $\epsilon_2 = 1.5 \Delta \sigma L \mu_r / \mu_r'$
 L = geomtric scale parameter, set to 4.0×10^{-8} for target scales of a few meters
 $C_0 = 5$, $C_1 = 3$, $C_2 = 0.8$, $A = 0.15$ are fitting parameters

As an example, we compare the free-space response of a .248 m sphere, conductivity of 1.0×10^6 S/m, with relative permeabilities of 1.0 and 5.0, to an equal volume cube (.4 m edge) buried 0.7 m to the center in a .001 S/m half-space, measured with a horizontal loop GEM-2 (note, the electric field term makes negligible contribution for this model) in Figure 2 below.

The parametric model does not include the weak response of the .001 S/m background. The essential features of the inductive and magnetic response of a compact metallic conductor are modeled with the parametric equations, in which the inphase response asymptotes to the same inductive limit at high frequency, has a negative quasi-dc response if permeable, and a quadrature peak that increases in amplitude with permeability. The peak frequency, a function of conductivity and radius for the sphere, is a function of conductivity contrast and the parameter L , which represents the geometry scale, for the parametric model. The adjustable parameter constants can be used to modify the shape somewhat, but the fundamental features are built into the second order frequency dependence. Similarly, the responses of metallic objects always have these fundamental features, but the exact shape depends on the geometry (sheet-like objects will have a sharper quadrature peak and more rapid inphase saturation).

The electric field term predominates for low-contrast (i.e., geologic) conductors and voids. Figure 3 below compares the profile response of a GEM-2 (horizontal loops) at 23970 Hz over an elongated void (perpendicular to profile direction) computed parametrically and with a rigorous integral equation algorithm.

For both algorithms, the void was modeled with two cells in width (x), 8 cells in length (y), and 3 cells in depth extent (z), using cells with a 2/1 aspect ratio – 1 m x 2 m x 1 m. The profile shape and amplitude are consistent between the simple parametric approximation and the integral equation solution. The phase is determined by propagation effects of the incident and scattered fields, since the response parameter for the electric term is real (at lower frequency, the response is quadrature). The plotted response includes only the anomalous measurement (.01 S/m halfspace background response not included), which in data appears as reduction the positive background response.

Figure 2 a. Parametric model response of a 1.e+6 S/m cube compared to an equal volume analytical sphere response.

Figure 2 b. Parametric model response of a 1.e+6 S/m, relative permeability 5, cube compared to an equal volume analytical sphere response.

Figure 3. Parametric model response profile over a void in conductive earth compared to the response computed with a standard integral equation.

The objective is to image data in a way that delineates the spatial distribution of conductive and permeable anomalous zones as well as identifying what is metal, voids, and other man-made structures, and also what is geologic. The parametric model must be incorporated into some kind of data inversion algorithm, and this step has yet to be undertaken. The conjugate-gradient method is a candidate, although certain difficulties can be anticipated. For a response to metal objects that reaches the inductive limit at low frequency (note the sphere example above), the data sensitivities to the model parameters vanish – i.e the inphase response is saturated and the quadrature has vanished. Also, the parameter L would either be constrained, even though it does characterize the targets, or free to be inverted, which will further increase the degree to which the problem is underdetermined. A scheme that separates the spatial delineation from the target characterization (spatial variation in the measurements versus frequency response) may be a more viable method, though for spatially distributed targets, the frequency response may appear as a continuously variable with position.

3.2 Passive Data Software Development

The software development for the GEM-5P is focusing on enhancing visual displays of the data (i.e., the spectrographs) that aid in the user's ability to identify radiated electromagnetic fields that are likely to be from a source of interest. The program for converting raw data into spectrograph data has been updated with the following enhancements: a fast Fourier transform subroutine that does not require a power-of-2 data set, and that sets up a sine table for reuse, has replaced the DFT, greatly reducing the computer time required; the option to process 2 channels

of data has been added, so that the reference coil as well as the gradient signal can be analyzed; an option to remove the average amplitude along the profile for each frequency has been added, to suppress ambient power-line noise and enhance local sources; and spectral averaging incorporated into the spectral sampling code. The structure of the program was modified (for the average removing feature) to facilitate any spatial filtering along the profile desired. The output file of this program can be used by the commercial program "Surfer" to produce spectrographs, as in the experiment described below. When the average amplitude is removed, it is done prior to conversion to dB, thus all values below average in amplitude are set to negative dB saturation (background).

We have also derived some simple equations for comparing the response of a single loop sensor (GEM-2H in passive mode) and gradient sensor (GEM-5P) for various types of current sources.

3.2.1 GEM-5P Response over Current Carrying Romex Pair

The geometric behavior for either the vertical (z) or horizontal (x) gradients as a function of position over an infinitely long, flat, straight pair of wires carrying current in opposite directions is governed by the expression:

$$G_{x,z} \cong \pm [6x^2z - 2z^3]/[x^2 + z^2]^3 \quad (3-8)$$

Where x is the horizontal offset as measured from the point directly over the wire, and z is the height above the wire, and the plane of the wire pair is horizontal. The strength of the signal is also proportional to the current and the separation of the wire pair (about .25 inches for Romex). Similarly, for a pair oriented in a vertical plane, the expression is an interchange of x and z of the above, with a zero crossing directly above the wire pair.

The expressions for the vertical (z) and horizontal (x) magnetic field behavior for a profile over the center of a finite length of pair of wires of length 2a (i.e., extending +/- a in the y direction), carrying current in opposite directions, are:

$$B_z \cong a/[(x^2+z^2)(x^2+z^2+a^2)^{1/2}] \{1 - x^2[2/(x^2+z^2)+1/(x^2+z^2+a^2)]\} \quad (3-9)$$

$$B_x \cong -axz/[(x^2+z^2)(x^2+z^2+a^2)^{1/2}] \{2/(x^2+z^2)+1/(x^2+z^2+a^2)\} \quad (3-10)$$

Figure 4 compares the computed response for the exact gradient amplitude measured along a profile 10 feet above an infinitely long wire (equation (3-8), horizontal and vertical are equal), with the computed vertical and horizontal differences as measured by the GEM-5P for a profile centered over a 30 foot long wire (differencing equations (3-9) and (3-10) over the 1.5m coil separation). The instrument does not provide sign information, and the values are normalized to one at the peak. The gradient and the measured field difference are approximately the same, and the effect of a finite length wire not significant for lengths comparable to the wire-GEM distances.

The difference curves are plotted again but with +/- positions, and actual test data are compared in Figure 5, all of which are normalized to unity directly over the wire. The theory predicts a

larger relative response with distance from the peak over the wire than the test data shows. The reason is not understood, but the environment is a noisy, light industrial area, and also, the wire extended beyond the ± 15 feet but not constrained to lay flat so that some canceling fields could have been generated that have a greater impact at larger distances.

Figure 9. Theoretical gradiometer response 10 feet above Romex paired wire.

Figure 4. Theoretical gradiometer response 10 feet above Romex paired wire.

Figure 5. Normalized GEM-5P response 10 feet over 30 foot length Romex.

3.2.2 GEM-5P Response over a Current Carrying Loop of Single Wire

The expressions for the vertical (z) and horizontal (x) components over the center of a side of a horizontal rectangular loop (coordinate origin at the center of the loop) 2a long (x dimension) by 2b wide (y dimension) are:

$$B_z \cong 2b\{(x+a)/[r_2(r_2^2-b^2)] - (x-a)/[r_1(r_1^2-b^2)] + 1/[r_2(r_2-(x+a))] - 1/[r_1(r_1-(x-a))]\} \quad (3-11)$$

$$B_x \cong 2bz\{1/[r_2(r_2^2-b^2)] + 1/[r_1(r_1^2-b^2)]\} \quad (3-12)$$

Where:

$$r_1^2 = (x-a)^2 + b^2 + z^2$$

$$r_2^2 = (x+a)^2 + b^2 + z^2$$

Equation (3-11) was differenced over the 4.6 foot GEM-5P coil separation to obtain the vertical gradient, and similarly equation (3-12) for the horizontal gradient. Plots of these theoretical results for profiles 10 feet over the center of one side of a 100 foot x 100 foot square loop are compared with test data in Figure 6. The calculated data are absolute values normalized by the maximum, and the test data normalized to obtain the best fit except at the peaks, where the instrument "clipped" from signal peaks exceeding the A/D dynamic range.

Figure 6. Simulated GEM-5P profiles 10 feet over side of square loop (100 feet x 100 feet) and actual data.

3.2.3 Signal/Noise Comparison of Single Loop Versus Co-axial Gradient Passive Sensors

The electromagnetic characterization of an underground facility is complicated by the presence of interfering EM signals arising from nearby cultural sources, particularly power lines. In this regard, the gradiometer should be superior to a total-field sensor, since the gradiometer tends to cancel slowly-varying fields arising from distance sources, even when accounting for the gradiometer's more limited range of sensitivity. One way to quantify the gradiometer's ability to suppress interfering signals is to plot its response (or sensitivity pattern) to a current source as a function of source position and then compare this to a similar plot for a total-field sensor. Figure 7a shows the response of a single horizontal coil (vertical component total-field sensor) to a line current source (simulating an unbalanced power line) perpendicular to the plane of the figure; the plot shows the magnitude of the sensor output as a function of the position of the line source. Figure 7b shows a similar plot for the gradiometer, which has vertical and horizontal nulls. Plots for a dipole source will, however, differ from the above plots for a line source. For a dipole source on the axis of the sensors, both the total-field and gradiometer sensors will exhibit maximum responses, with the single loop falling off as $1/r^3$ and the gradiometer as $1/r^4$.

Below, we give a simple analysis of this trade-off to determine the gradiometer provides a superior signal-to-noise ratio for a power line noise source. Here, for simplicity, the power line is modeled as a line current source shown coming out of the page in Figure 8. This could represent a crude model of an unbalanced three-phase power line, where one phase is dominant. The case of a balanced three-phase line is described briefly in the next section, for which a similar analysis can be performed.

Figure 8 shows a power line at height h above ground at a distance r from the sensor (total field or gradiometer).

Figure 7a. Vertical component of the magnetic field about a single power line.

Figure 7b. Vertical gradient of the vertical magnetic field component about a single power line.

Figure 8. The power line is modeled as a line current perpendicular to the figure. The subsurface dipole source is assumed coaxial with the sensor.

Directly below the sensor is a dipole source of EM emissions originating from within a UGF. We compute the signal-to-noise ratio, defined as the ratio of the output of the sensor due to the dipole source to the output of the sensor due to the power line. We then compare the SNR's for both a single loop sensor and a gradiometer.

We emphasize that this simple analysis neglects the conductivity of the earth. If the conductivity of the earth is included, a diffuse image of the power line is induced in the earth below it; this

will tend to suppress its field at large distances. Also, the conducting earth tends to refract the fields downward so that they appear more horizontally polarized than they would be in free space. This effect tends to change the dominant polarization of the power line field at large distances. Below, we give a simple analysis neglecting the effect of the earth's finite conductivity and assuming a one-phase power line and a vertical orientation of the gradiometer.

The magnetic field due to the power line at the location of the sensor is:

$$H_{line} = \frac{I}{2\pi r} \hat{\theta}, \quad (3-13)$$

where I is the current in the line and $\hat{\theta}$ is the azimuthal unit vector relative to the axis of the power line. Let A denote the area of the single-loop sensor; then the emf induced in this loop by the power line is:

$$emf_{line}(total\ field) = \frac{i\omega\mu_0 I A}{2\pi r} \cos\theta, \quad (3-14)$$

where the angle θ is shown in Figure 13, ω is frequency and μ_0 is the free-space permeability. Let the dipole source within the UGF have moment M and depth d . Then the field on the axis of the sensor at the surface is $\mu_0 M / 2\pi d^3$. The emf induced in the single loop sensor by this field is given by:

$$emf_{ugf}(total\ field) = \frac{i\omega\mu_0 M A}{2\pi d^3}. \quad (3-15)$$

The total-field SNR is the ratio:

$$SNR(total\ field) = \frac{emf_{ugf}(total\ field)}{emf_{line}(total\ field)} = \frac{M r}{d^3 I \cos\theta} \quad (3-16)$$

The gradiometer response to the power line can be shown to be:

$$emf_{line}(gradiometer) = \frac{i\omega\mu_0 I A \Delta z}{\pi r^2} \sin\theta \cos\theta, \quad (3-17)$$

where Δz is the gradiometer coil separation, with each coil assumed to have area A . The gradiometer response to the UGF source is:

$$emf_{ugf}(gradiometer) = \frac{3i\omega\mu_0 M A \Delta z}{2\pi d^4} \quad (3-18)$$

and the gradiometer SNR is:

$$SNR(gradiometer) = \frac{emf_{ugf}(gradiometer)}{emf_{line}(gradiometer)} = \frac{3Mr^2}{2Id^4 \sin\theta \cos\theta}. \quad (3-19)$$

We can compare the performance of the gradiometer to that of the total-field sensor by taking the ratio of the SNR's for both cases:

$$\frac{SNR(\text{gradiometer})}{SNR(\text{total field})} = \frac{3r^2}{2d h} \quad (3-20)$$

where the relation $\sin\theta = h/r$ was used. Note that when the power line height is reduced to zero ($h = 0$), the gradiometer SNR becomes infinite since the power line response vanishes for the gradiometer, but remains finite for the total-field sensor. The above result shows that, whenever $r > \sqrt{2dh/3}$, the gradiometer's performance is superior to that of the total-field sensor.

Consider a balanced three-phase power line with vertically-aligned conductors, as shown in Figure 9.

Fig. 9. Three-phase line with vertically-spaced conductors.

The z-component of the resultant magnetic field can be shown to vary spatially according to the relation:

$$H_z = \frac{c}{r^2} \sin\theta \cos\theta$$

where c is a constant depending on the line current and the conductor spacing. This pattern is plotted in Figure 10. An SNR analysis similar to that of the last section can also be carried out for this case. One finds that a vertical orientation of the gradiometer does not in general provide the best SNR in this scenario, but the optimal orientation depends on the relative position of the UGF source and the height and distance of the power line.

4.0 Passive EM Experiment

In the Phase I program, the GEM-2H was used in a passive mode to collect data in various "real world" settings, including along Maywood Road in Raleigh, near the Geophex office. We have subsequently taken data along Maywood Road with the GEM-5P in two orientations – coil axes vertical, and coil axes along the profile direction. We also repeated the GEM-2H experiment with the horizontal loop (vertical coil axis), and added the orientation with coil axis along the profile direction (in Phase I, the vertical loop orientation was done with the coil axis perpendicular to the profile direction). One of the objectives is to enhance the spatial resolution of various local sources in the presence of a strong ambient power line EM field. Since power lines run parallel to the road, both the vertical axis and the side axis orientations are not optimal for suppressing the ambient, whereas the profile axis orientation is. The GEM-5P, which measures the (approximate) field gradient using two matched coils wired differentially, intrinsically suppress the ambient, so more local sources (i.e., power lines that cross the street) should be best resolved with the GEM-5P in the profile axes orientation. The spectrographs can be generated with further enhancement of local sources with the processing option to subtract the average amplitude, as described above.

4.1 GEM-2H passive with vertical coil axis

The full 24kHz band of the GEM-2H (averaged over 30Hz intervals) with the coil axis vertical (horizontal loop) is shown as a spectrograph in Figure 11. The strong 60Hz and associated odd harmonics shows along the entire profile, as expected since there were power lines along the road, and it is difficult to discern additional local sources. Also evident is the localized power in the 15-16kHz range at 200 feet, which is the railroad communication carrier that controls the crossing signal present at this location. The same data with the average amplitude subtracted is shown in Figure 12 – bright zones appear, but a lot of signal still pervades much of the profile, particularly at the lower harmonics.

4.2 GEM-2H passive with coil axis in the direction of the profile

Orienting the coil axis parallel to the power lines that follow the road reduces the EM coupling to those power lines, while remaining well coupled to lines that cross the road (or other localized EM radiators). The spectrograph for data collected in this way is shown in Figure 13, and indeed the higher harmonics are strongly localized around 900 feet, near an AM radio station transmitter. The first few harmonics remain strong along the entire profile, however. In Figure 14, the 0-6kHz band with 10Hz-averaged intervals shows this better. We have reprocessed this data with the average amplitude removed (Figure 15), and the brighter intervals along the profile at the low 60Hz harmonics have become evident.

Figure 11. Spectrogram of passive GEM-2H data taken along Maywood Rd. Coil axis vertical, 30Hz spectral resolution.

Figure 12. Spectrogram of passive GEM-2H data taken along Maywood Rd. Coil axis vertical, 30Hz spectral resolution, average amplitude subtracted.

Figure 13. Spectrograph of passive GEM-2H data taken along Maywood Rd. Coil axis horizontal (along profile direction), 30Hz spectral resolution.

Figure 14. Spectrograph of GEM-2H data taken along Maywood Rd.
Coil Axis along profile direction, 10Hz spectral resolution.

Figure 15. Spectrogram of GEM-2H passive data taken along Maywood Rd. Coil axis along profile direction. 10Hz spectral resolution, average subtracted.

4.3 GEM-5P with vertical coil axes

Since the GEM-5P effectively measures the gradient of the field component along the sensor axis (balanced co-axial coils wired in a differential configuration), the ambient field from sources at greater distances than local sources will be suppressed. The power lines parallel to Maywood Road, however, are close, and thus with the coil axes vertical, still produce a strong signal, as is evident in Figure 16. What is interesting is the pronounced power around the harmonics just below 4kHz. We do not know what the source is, nor why it is picked up by the GEM-5P so much more than the GEM-2H. In order to highlight the zones with the strongest power in this frequency interval, these data are shown in the 0-6kHz band with the average amplitude subtracted in Figure 17. Note that the average is computed for each frequency, and thus a greater amount subtracted for frequencies having greater average power, so that some spectral sharpness is lost. The spectral peaks are at the 59th and 66th harmonics (35.4kHz and 36.6kHz) and the spatial pattern of this power appears rather diffuse. Also, the relative amplitudes at these frequencies vary with position, and single localized source seems unlikely, other than power line ripple from the lines that run along the road. The GEM-2H shows greater power in the harmonics between 2-3kHz – perhaps the ripple frequency changes during the day.

4.4 GEM-5P with coil axes in the direction of the profile

With the sensor rotated to minimize coupling from the lines parallel to the profile direction, a very different response is observed (Figures 18 and 19). The power is clearly strongest at 36.6kHz and is confined to a narrow zone at the beginning of the line (it may extend beyond the starting point), which is the weakest zone in the vertical axis orientation. It is likely that we are observing power line ripple in cables along Lake Wheeler Road, which intersects Maywood just before the start of the profile. Subtracting the average (Figure 20) suppresses the faint background power at these (and other 60Hz) harmonics, but does not change the picture much. We also recorded the reference coil data (i.e., single loop data), shown in Figures 21 and 22. This should be similar to the GEM-2H profile axis data; the loop moment is much lower, however, reducing the sensitivity but eliminating the A/D clipping that often occurred with the GEM-2H. The reduced overall response is evident in Figure 11, and the radio station does not dominate the picture – again, this could be a time variation of the radio station power usage. The 36.6kHz is strong at the beginning of the profile as in the gradient data. Subtracting the average does highlight the radio station as well as the 36.6kHz peak.

Figure 16. Spectrogram of GEM-5P data taken along Maywood Rd.
Coil axis vertical, 30Hz spectral resolution.

Figure 17. Spectrogram of GEM-5P data taken along Maywood Rd.
Coil axes vertical, 10Hz spectral resolution, average amplitude subtracted.

Figure 18. Spectrograph of GEM - 5P data taken along Maywood Rd.
Coil axes horizontal (along profile direction), 30Hz spectral resolution.

Figure 19. Spectrograph of GEM -5P data taken along Maywood Rd.
Coil axes along profile, 10Hz spectral resolution.

Figure 20. Spectrogram of GEM-5P data taken along Maywood Rd.
Coil axes along profile direction. 10Hz spectral resolution,
average amplitude subtracted.

Figure 21. Spectrograph of GEM-5P Bx data taken along Maywood Rd.
Coil axes along profile direction, 10Hz spectral resolution.

Figure 22. Spectrogram of GEM-5P Bx data taken along Maywood Rd. Coil axes along profile direction, 10Hz spectral resolution, average amplitude subtracted.

5.0 Project Summary

Research performed during this project extended the science related to the use of EM geophysical techniques applied to the detection and characterization of UGF. The problem of UGF characterization is not easy, and there will be continued research in developing sensor technology as well as data analysis and interpretation software. We have completed an effort to evolve EM sensor technology for both active and passive EM measurements, and to advance the science of EM data interpretation software. Accomplishments under this project include:

Hardware development:

- Refining the coil design in the GEM sensors to improve stability, with new materials and more optimum windings.

The new materials were chosen to reduce the temperature dependence of the dielectric properties of the coil inter-winding insulation in order to stabilize the loop capacitance and thus the loop resonance. The stability of the loop resonance is directly correlated to the stability of the system response. The reduced windings increases the coil resonance peak (but with a trade-off reduction in signal moment) well above the operational bandwidth so that the system response is as flat (and thereby stable) as possible over the operational frequency band.

- Replacing the transmitter H-bridge components with new, high-speed low-dissipation components.

This reduces the heat generated in the transmitter electronics and extends the battery cycle time and increases the potential maximum current. The increased speed allows a higher fidelity waveform to be transmitted so that the output power is concentrated in the desired frequencies and reduced in the transmitter switching frequency. An extra benefit is the elimination of receiver coil "de-spiking" circuitry required to filter these high frequency transmitter noise signals.

- Design next generation sensors with preamplifiers integrated into the coils, and upgraded A/D with 24 bits and higher bandwidth.

By putting the preamplifiers at the coil, noise picked up in the cables will have a lower impact on the signal/noise. The increased bits in the A/D provide increased dynamic range and/or resolution so that strong signals will not saturate the system and the resolution can be as fine grain as the internal noise level. The increased speed will increase the maximum operational frequency of the instrument.

- Develop a GEM-2 calibration technique that is more systematic than the current procedure and combines into a single procedure the free-air offset and transfer function measurements.

Also, an improved compensation algorithm in the GEM console has been defined, in which the transfer function is incorporated into the channel gain ratio, and the frequency variation is fit with a quadratic interpolation function instead of a global polynomial fit.

Software development:

- Development of “extended Born”, Neumann series, and full matrix integral equation algorithms for modeling the EM response to conductive anomalies in a conductive halfspace.

We examined the performance of these algorithms, determined that voids and low-contrast targets can be modeled efficiently with the iterative Neumann series or with an iterative version of the “extended Born” algorithm and they converge to consistent results with the full matrix integral equation. The shortcomings of the approximate algorithms were illuminated with an example of a simple prismatic conductor buried in a conductive halfspace.

- Incorporating the “extended Born” and full integral equation models into a conjugate-gradient inversion algorithm in an attempt to expand the suit of imaging techniques available.

The non-linear forward model dependence on conductivity requires an iterative inversion algorithm which, unfortunately, has poor convergence behavior when inverting a general model that is underdetermined (many extra grid cells), particularly for the “extended Born” forward model. Even though a perfect data fit is possible, the conjugate-gradient algorithm failed to obtain a model with a good data fit, nor was the inverted model a good approximation of the model used to generate the data. Attempts to improve convergence and model recovery with a “focusing” regularization function incorporated into the chi-squared objective did not significantly improve the inversion performance. Computational demands rapidly become excessive with the number of cells when the full matrix integral equation is used as the forward algorithm.

- Introduction of a parametric response modeling approach with the objective of treating metal targets as well as voids and weak scattering targets.

We treated the total response of a target as the combined electric polarization and magnetic polarization response to incident fields in a conductive halfspace generated by a magnetic dipole source at the earth surface. The electric polarization response uses a parameterized function that behaves consistently with voids and weak (current channeling) scattering, whereas the magnetic polarization response uses a parameterized function that bears the essential features of both eddy-current and permeability response characteristics. This model can potentially be incorporated into an inversion scheme that determines model parameter values and spatial distributions of scatterers.

- Analysis of passive sensor coil configuration signal/noise.

A comparison of the relative signal/noise between a single loop and co-axial gradiometer passive sensor was made assuming that the target signal was generated by a nearby dipole source below the sensor and the noise was generated by distant power lines. Single current power lines indicative of far-field unbalanced power lines as well as balanced three-phase power lines were considered. The analysis shows that the best signal/noise configuration depends on the specific geometry considered, so that a sensor that measures both, such as the GEM-5P, is the best overall choice.

Experiments:

- Comparison of a new, coaxial gradient sensor with the single loop sensor, each in two orientations, for passive spectral EM measurements.

We collected time-series data using the GEM-2H in passive mode with the loop in both the horizontal orientation (vertical loop axis), and the vertical orientation with axis along the profile direction. Similarly, we collected data in the same orientations with the GEM-5P.

Spectrographs show the different sensitivities and spatial resolution of the different sensors and orientations. The data was obtained along a semi-industrial urban street, and contained several strong spectral signatures, including 60 Hz harmonics, broadband emissions from an AM radio station, and control signals transmitted along railroad tracks.

Much of the technology developed under this project has applications beyond UGF characterization – mineral exploration, engineering and environmental geophysics, etc. General inversion and imaging techniques, particularly when metal as well as voids are encountered, remains to be solved.

6.0 References

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Appendix A

Sensor Calibration

Appendix A—Sensor Calibration

The objective is to measure in a single, systematic procedure, the instrument transfer function and free-air offset as a function of frequency. The underlying principle used to accomplish this is to include data collected at two different heights above the ground (in a relatively “clean” setting) over the entire operational frequency spectrum, with and without Q-coil targets of known frequency responses. The influence of the conductive earth can be resolved by the change in response with height, whereas the system free-space error does not change with height, and the transfer function can be ascertained with Q-coil net response. The system free-space errors and transfer function, once known as a function of frequency, are currently compensated for in the GEM firmware in real-time with the following equation:

$$ppm = [(1.e+6) Q(f)] \frac{S - S_0(f)}{K(f)[1-Z] + S_0(f) - Z S} \quad (A-1)$$

where: *ppm* is the compensated complex output in parts-per-million relative to the primary field induced *emf* at the receiver coil (Rx) {but measured by the reference “bucking” coil Bx, which by design is equal}.

Q(f) is the frequency dependent system transfer function that accounts for the Rx and Bx coil resonance responses.

S is the measured (complex) ratio of the “bucked” signal *emf* (Rx – Bx) to the reference *emf* (Bx) after digital sine/cosine convolution processing.

S₀(f) is the frequency dependent free-space error resulting from non-ideal primary field bucking cancellation.

K(f) is the frequency dependent Rx/Bx electronics channel gain ratio, nominally equal to the pre-amp gain ratio required to keep the signal and reference voltages at the A/D within appropriate range (for resolution and dynamic range considerations).

Z is the bucking ratio, defined as the Bx/Rx moment ratio, also equal to the primary field ratio between the Rx and Bx coils (bucking criteria), nominally equal to the cubed ratio of their distances to the transmitter coil (Tx).

Upon review of the above compensation formulation, we recognized that it was more appropriate to incorporate the system transfer function into the gain ratio, so *Q(f)* has been eliminated, and *K(f)* is now determined via the calibration procedure. The objective of the calibration is to determine *S₀(f)* and *K(f)* so that they can be loaded into the GEM firmware for operational compensation. In the current design (prior to changes as a result of this effort), these parameters are modeled with a third order polynomial in frequency, and *K(f)* is pre-calibrated by the GEM electronics using a precision test signal built into the hardware and activated during a special factory calibration mode. Global polynomial models were decided to be subject to ring, that noisy data in a small frequency interval effected the results over a large frequency band, and that fitting the curves over the entire frequency range required a high (fifth or greater) degree

polynomial. For these reasons, we are using a quadratic interpolation scheme between ten discrete frequencies spaced approximately uniform in log space.

An off-line algorithm has been developed to simultaneously invert single or multiple Q-coil (having different resonance frequencies) and background data acquired at two heights (nominally 0.5m and 2.0m) for the compensation parameters and the earth conductivity. The Q-coil response algorithm accounted for reference coil bucking, finite loop (Tx, Rx, Bx, and Q-coil) size, and Q-coil inductive coupling perturbation by the conductive half-space as recommended by Fitterman (1999). The algorithm output parameters were the best fit (in a least squared error criteria) third-order polynomial coefficients for the real and imaginary parts of $S_0(f)$ and $K(f)$ and the half-space conductivity. The appearance of $S_0(f)$ and ZS in the denominator of the equation above, as well as the effect of the conductive earth, results in a non-linear inverse problem, and observation redundancy in the data results in an over-determined problem; the algorithm is thus iterative and driven by residual squared error sum (chi-squared) minimization. Analytic derivatives were used for the compensation parameter sensitivities, and finite-difference derivatives for the earth conductivity sensitivities. Comparison of conjugate-gradient and modified Marquardt-Levenberg algorithms were done, and the latter shown to be far superior for this problem, with very little damping required.

The algorithm was first tested with synthetic data, including 1) ideal, 2) with random noise added, and 3) with 2-layered earth models. The ideal case converges quickly to an arbitrarily small chi-squared residual; the random noise case tolerates 25ppm rms noise levels, but degrades at 200ppm levels (most of the actual noise is not random gaussian, so this is of minor concern). The miss-modeling when the earth is not a half-space was shown to cause insignificant degradation on the compensation parameter estimates for either a resistive or conductive overburden, and was accounted for by the algorithm with an intermediate value for the estimated half-space conductivity.

Calibration Experiments

Data collected at 0.48m and 1.86m heights (using a wooden frame support) with a Q-coil having three series resistance settings was used for trial calibration of a GEM-2H. Frequency sampling was taken at 120Hz intervals from 30Hz to 23970Hz, however the lowest frequencies (below 270Hz) were somewhat noisy and not used, and the spectrum for each Q-coil was individually windowed in order to select the strongest signals. There appeared to be a problem with the third (high frequency) Q-coil, so the inversion was performed using two Q-coils. The model data fit at the 0.48 m height is shown in Figure A-1, and the calibration parameters are shown in Figure A-2.

A second calibration trial was performed using a different sensor mode of operation in which only the ten discrete frequencies are used, but multiple samples are recorded for each allowing signal/noise enhancement via averaging data. This was done to extend the calibration to lower frequencies, and also to streamline the procedure (this mode operates much faster). Two full sets of data were collected to test repeatability. A modified version of the inversion algorithm was used in which multiple *ppm* sample sets for the ten frequencies are pre-averaged before inverting for the compensation parameters. Because only the ten discrete frequencies are used, the

interpolation scheme is not needed (however, the interpolation will be used operationally if a user selects an intermediate frequency).

Figure A-1. Compensated measurement fit to predicted model response for the initial trial calibration of a GEM-2H sensor using the enhanced interpolation algorithm.

The compensation parameters derived from data set "a" and data set "b" are compared in Figure A-3, showing excellent repeatability above 500 Hz (30Hz was noisy and is not shown). For frequencies above 150Hz, agreement with the initial 200-frequency experiment is also good. The compensated data are compared to the predicted model in Figure A-4.

Data in the operational survey mode using horizontal loop orientation were collected over a test site at Geophex, where a 55 gallon drum, a 255 gallon tank, and two iron-capped drill-holes comprise the test target. Color image maps are shown in Figure A-5 in which uncalibrated and calibrated data (same data post processed) are compared. The background level is clearly much closer to zero, as would be expected, for the calibrated data. If quantitative interpretation is to be performed so that absolute values are required, the calibration is important.

GEM-121 free air $S(f)$ CIVITAN Park Inversion results using 8 point frequency grid from 150Hz-23970Hz

GEM-121 gain ratio $K(f)$ CIVITAN Park Inversion results using 8 point frequency grid from 150Hz-23970Hz

Figure A-2. Compensation parameters, free-space (top) and gain ratio (bottom), showing discrete frequency and interpolated (quadratic) values.

Figure A-3. Compensation parameters from 90Hz to 23970Hz for the 10 stepped frequency mode data sets "a" and "b".

GEM-121 CIVITAN Park step frequency mode calibration "a" data fit

Figure A-4. Compensated measurement fit to predicted model response for the step frequency mode trial calibration of a GEM-2H sensor.

Figure A-5: Comparison of uncalibrated and calibrated images at 1230 Hz over buried 55 gallon drum (upper left), 255 gallon tank (center), and two iron capped well-heads.