Session 2P3
Physics Based and Statistical Methods in Subsurface Imaging

A Novel Modeling and Inversion Method to Image Weakly Scattering Sub-cellular Structure

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Non-invasive assessment of the health of an embryo or a single cell is an open issue of critical importance for the success of certain procedures like in vitro fertilization. To achieve this goal, we need a three dimensional understanding of the investigated structure, such as how mitochondria are distributed within the cell, or how many cells reside in the embryo. Advanced microscopy can provide both amplitude and phase information from multiple views, but obtaining detailed volumetric information is challenging. In particular, imaging mitochondria is usually quite difficult since there may be 100,000 of these tiny low-contrast scatterers overlapping each other within the cell.

Although the electromagnetic properties of cellular structures exhibit slight variations relative to the background, methods based on the Born approximation are not suitable to image these objects since their overall electrical sizes are quite large when they are probed in or near the visible spectrum, and the observed scattered light is in the farfield of the cell.

In this work, we present a novel method to image these objects in two dimensions, which is based on the expansion of the target object function in terms of Fourier-Bessel coefficients, and an alternative approximation for the total fields within the scatterer. This approximation satisfies the continuity of the total tangential fields at the object-background boundary for each circular mode using the known incident and observed scattered fields, and takes into account the fact that the refractive index distribution along structures being investigated varies slightly around a known mean value. The resulting linear system of equations is solved via Tikhonov regularization for the unknown expansion coefficients. This approach can be readily extended to more realistic 3D cases.

To illustrate the method, a number of Finite-Difference Time-Domain (FDTD) simulations involving cells models with miscellaneous organelle distributions, such as aggregated, perinuclear, cortical mitochondria distributions, have been performed. Basic ideas of the FDTD method, such as total-field scattered-field formulation, near to far field transform, PML absorbing boundary condition have been employed to obtain the far zone scattered fields due to the cell models under plane wave illumination. These far zone scattered fields have been utilized to form the image of the probed objects. Remarkably accurate reconstructions of the general density distribution of the subcellular structure have been obtained.

The Effective Permittivity of Inhomogeneous Objects Reconstructed by Inverse Scattering Methods

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The notion of effective permittivity originates from the effective medium theory (EMT), where a medium randomly inhomogeneous on a micro-scale is represented as a homogeneous bulk material. There exist many different formulas that give the effective permittivity in terms of the permittivities, sizes, and shapes of the microscopic constituents. Normally one tries to find an expression which would suit all possible illumination and measurement conditions. The problem is, in fact, an inverse scattering problem, and as such can be investigated using the standard inversion methodology. In particular, we have looked at it in the context of *effective inversion*, i. e. inversion with very limited scattered field data where it is impossible to reconstruct an inhomogeneous subsurface target, but may be possible to recover its effective permittivity having an approximate knowledge of the outer shape of the object. That latter shape is often the result of simple linearized imaging algorithms, such as the travel-time tomography and the sampling method. The difference with the EMT is that, strictly speaking, the reconstructed effective permittivity suits only some particular illumination and measurement configuration. Yet our results indicate that the reconstructed effective permittivities are closely related to the permittivities of the constituents. On the other hand, the inverse scattering approach is much more rigorous as far as the reconstruction of the effective permittivity is concerned, than the general but approximate techniques of the EMT. For example, no statistical assumptions are needed and the inhomogeneities do not have to be electrically small.

This time we shall talk about a very fast and efficient numerical method specifically designed for the effective inversion problem. As common in inverse scattering, the problem is nonlinear and therefore requires repetitive solution of the associated forward scattering problem. In its turn the forward problem has to be solved by one or another iterative algorithm. Hence, the solution of the inverse problem requires multiple runs of an iterative scheme. Most of the work in such a scheme is done at the stage of construction of the so-called Krylov subspace. In the effective inversion case, however, the once constructed Krylov subspace can be re-used, thereby significantly reducing the computational order of the inverse problem. With the help of this reduced-order algorithm various inhomogeneous targets can be analyzed with little computational effort. Special attention will be paid to the dispersion of the reconstructed effective permittivity.

Neural Networks as Statistical Indicator of Breast Cancer Using Scattered Electromagnetic Data

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In this work we will present the application of neural networks as a preprocessor in breast cancer imaging. In our previous work on imaging breast cancer using microwave modality, we observed that the reconstruction of shape and location of three-dimensional tumor required several CPU hours on a Hewlett-Packard Alpha Server DS25. We are proposing to avoid the high computational expenses of these algorithms by initially processing the data using neural networks, which have been used recently in predicting breast cancer based on mammography or magnetic resonance imaging data. In these applications, the neural network was used to replace radiologists or physicians interpretations. The major advantage of using neural networks lies in its real time results. We are proposing to train neural networks on data based on scattered electromagnetic fields from the breast with and without a tumor. The basic idea is to train the neural network on synthetic data and then test it on different data with added noise. The neural network will statistically indicate the presence or absence of a tumor. In case of a suspicious abnormality in the breast, our three-dimensional imaging algorithm will be used to reconstruct the tumor.

Our preliminary results show that when neural networks were trained with a reasonable amount of noise, they successfully predicted the cancer. In determining the utility of a neural network, the systematic approach espoused by Goodman was taken. First, a logistic regression model was constructed. After determining the linear weights for one set of synthetic data (fifty samples without a tumor, ten with), the model was tested on a second similar, but independent, set. Based upon the performance of the model on the new data, a non-linear model was indicated. The choice for a non-linear model was a single-hidden-layer neural network with full interconnections between layers. Experiments showed that the network's hidden layer could be composed of as few as two nodes and still achieve perfect prediction on the independent set. Moreover, training the network on the second set and testing on the original achieved the same result. Finally, an inferential analysis of a network trained on the combined data sets will be performed to yield the most important linear and non-linear aspects of the imaging data.

Some New Results for Shape Reconstruction in 3D Low-frequency Electromagnetic Induction Tomography Using Level Sets

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Recently the application of low-frequency electromagnetic fields has been discussed for probing geophysical test sites over distances of up to several hundred metres. This can be used for example in petroleum engineering for characterizing a reservoir, or in environmental imaging applications for tracking pollutant plumes above the ground-water table. The mathematical treatment of these problems is quite challenging since 2D approximations typically yield only very poor results, and the problems are furthermore severely ill-posed. Therefore, the problems need to be treated as fully 3Dinversion problems from relatively few data for the system of Maxwells equations. We will present and discuss some new developments for a shape reconstruction approach which is able to reconstruct in a stable way geophysical structures from few low-frequency electromagnetic data. The method is based on an artificial evolution of a level set function characterizing the unknown shapes. Numerical examples in 3D are presented for shape reconstructions from synthetically created data with different types of noise added.

Single Value Decomposition and Degree-of-ill-posedness Assessment in Microwave Imaging

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In all Gauss-Newton iterative microwave imaging scenarios, there are a number of parameters related to the overall configuration that can impact the resultant image quality. These include signal frequency, amount of measurement data, number of property parameters reconstructed, etc. Overall, the four most important constituents comprising the system and algorithms are the measurement data, accurate forward solution, parameter update and the sensitivity map in the form of the Jacobian matrix. The latter encodes rich information regarding system performance and algorithm efficiency.

In this presentation we explore the singular value decomposition (SVD) of the Jacobian matrix and adopt the notion of degree-of-ill-posedness, α [1], developed by Brander and DeFacio [2] for the inverse Born approximation. While these previous discussions were developed for analytical expressions of the Jacobian matrix, we have applied minor approximations to our standard imaging algorithms to generate the numerically-based nodal-adjoint expression for constructing the Jacobian matrix [3]. This has facilitated convenient computation of the degree-of-ill-posedness for multiple system parameter studies. We have also applied this only to the first iteration of the Jacobian matrix to simplify the overall discussion while being able to observe important trends with respect to parameter variation. We have also restricted this analysis to a circular antenna array geometry with the single point sources configured close to the target under investigation.

We have studied three important algorithm parameters in simulation which have important implications with respect to hardware implementation and overall system performance: signal frequency, amount of measurement data and number of property parameters reconstructed. In general, the results match previous intuitive notions; i.e., that increased frequency and increased measurement data improve α. However the results with respect to the number of inverse parameters are somewhat counter-intuitive in that α improves even well after the number of parameters has exceeded the amount of independent measurements ($\mathrm{N}_{\mathrm{sources}} \times \mathrm{N}_{\mathrm{receivers}}/2$). Historically, groups have worked to collect more independent data than parameters reconstructed at considerable system expense. This latter result confirms observations we have made with our microwave system in both phantom and clinical imaging sessions and also for the near infrared imaging system being developed at Dartmouth College [4, 5]. These analyses have provided important insights as we work toward robust clinical implementation.

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REFERENCES

1. Hansen, P. C., "Rank-deficient and discrete ill-posed problems: numerical aspects of linear inversion," SIAM, Philadelphia, 1997.
2. Brander, O. and B. DeFacio, "The role of filters and the singular value decomposition for the inverse Born approximation," *Inverse Problems*, Vol. 2, 375–393, 1986.
3. Fang, Q, P. M. Meaney, and K. D. Paulsen, "Singular value analysis of the Jacobian matrix in microwave image reconstructions," *IEEE Trans. Ant. Propag.*, 2005 (submitted).
4. Meaney, P. M., Q. Fang, et al., "Microwave breast imaging with an under-determined reconstruction parameter mesh," *IEEE Int. Symp. Biomedical Imaging*, Arlington, VA, 1369–1372, 2004.
5. Poplack, S. P., K. D. Paulsen, et al., "Electromagnetic breast imaging C average tissue property values in women with negative clinical findings," *Radiology*, Vol. 231, 571–580, 2004.

Radar Detection of Subsurface Objects Using Correlation Imaging

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The radar detection of objects below a rough surface is an active area of research motivated by the problem of detecting shallowly buried land mines. The primary challenge for this approach is the extremely low signal-to-noise ratio between the return from the buried object and the reflected return from the rough surface. The weakness of the former is due to the low dielectric contrast between the buried object and the enclosing soil, as well as the lossiness of the soil medium. The strength of the latter is due to the random roughness of the surface. In this work, correlation imaging is employed to separate the return from the rough surface from that originating from the object by correlating radar measurements made at multiple angles. We incorporate a probabilistic weighting function (filter) to further enhance the effectiveness of correlation imaging, taking into account the random phase variation of the buried object return due to the rough surface.

The electromagnetic scattering is computed using a dyadic Greens function which describes the scattering from a half-space medium with planar boundary, and spherical objects embedded below this boundary. An approximate solution is obtained using a perturbation technique to yield expressions for the scattered field as a function of the viewing geometry (incident and scattering angles), object placement, and soil dielectric properties. The rough surface height variation is assumed to have a Gaussian distribution.

To evaluate the effectiveness of the correlation processing, we simulate the response of a monostatic Synthetic Aperture Radar with a linear viewing geometry that illuminates each ground patch from different angles. The samples from each patch are then used to measure the correlation:

$$C(\vec{r}_p) = \sum_{m=1}^{N} \sum_{n=1}^{N} E_p(\vec{k}_m) E_p^*(\vec{k}_n) e^{2i(\vec{k}_n - \vec{k}_m)} W(\vec{k}_m, \vec{k}_n)$$

where $\vec{r}_p$ is the patch location, N is the number of radar positions, $E_p(\vec{k}_m)$ is the electrical field received from the pth patch due to excitation from the mth source position, and $W(\vec{k}_m, \vec{k}_n)$ is the weighting function.

Our previous results showed that this approach was effective at reducing the clutter to allow detection of buried objects when the modeled scattering response is computed to first order. In this work, we extend the scattering model to consider second order scattering terms so that the return from the buried object after scattering from the random surface is taken into account. This term contains small variations in both the magnitude and the phase of the buried object return, and reduces the correlation between independent measurements. To compensate for this, a new weighting function is applied based on the assumed statistical properties of the rough surface. For a Gaussian surface, the weighting function has a normally distributed phase term that is centered at the assumed object depth, z_0. Results are presented that show the robustness of this approach to inaccuracies in the assumed depth and the width (σ) of the probability distribution.

Statistical and Adaptive Signal Processing for UXO Discrimination for Next-generation Sensor Data

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Abstract—Until recently, detection algorithms could not reliably distinguish between buried UXO and clutter, leading to many false alarms. Over the last several years modern geophysical techniques have been developed that merge more sophisticated sensors, underlying physical models, statistical signal processing algorithms, and adaptive training techniques. These new approaches have dramatically reduced false alarm rates, although for the most part they have been applied to data collected at sites with relatively benign topology and anomaly densities. On more challenging sites, performance of even these more modern discrimination approaches is still quite poor. As a result, efforts are underway to develop a new generation of UXO sensors that will produce data streams of multi-axis vector or gradiometric measurements, for which optimal processing has not yet been carefully considered or developed. We describe a research program to address this processing gap, employing a synergistic use of advanced phenomenologicalmodeling and signal-processing algorithms. The key foci of the program are (1) development of new physics-based signal processing approaches applicable to the problem in which vector data is available from such sensors; and (2) development of the theory of optimal experiments to guide the optimal design and deployment of the new sensor modalities. Here, we present initial results using simulated data obtained with our phenomenological models that indicate that optimal processing of features extracted from multi-axis EMI data can provide substantial improvements in discrimination performance over processing of features extracted from single-axis data.

1. Introduction

Until recently, detection algorithms have not reliably distinguished between buried UXO and clutter, leading to many false alarms. Over the last several years modern geophysical techniques have been developed that merge more sophisticated sensors, underlying physical models, statistical signal processing algorithms, and adaptive training techniques. These new approaches have significantly reduced false alarm rates, although for the most part they have been applied to data collected at sites with relatively benign topology and anomaly densities [1–5]. Most recently, blind source separation techniques have been applied to data collected on *highly cluttered* sites with commensurate reductions in the false alarm rates [6]. However, UXO clearance activities are ongoing or are planned at a wide variety of sites, and many of these activities involve complex terrain, vegetation and difficult geology, in addition to complex ordnance and clutter distributions. Moreover, most existing processing algorithms have been developed based on data associated with traditional sensors, such as CS-vapor magnetometers and coil-based electromagnetic induction sensors. Although these sensors are quite sensitive, they provide only limited information at any given survey point, as they do not illuminate the object under scrutiny along all three major axes. These limitations necessitate the use of highdensity spatial maps of anomalies, sometimes requiring multiple surveys, in order to collect data that support target localization and identification. Several investigators have noted that survey techniques that provide multi-angle illumination, while slower, improve discrimination performance [7, 8]. Others have shown theoretically or in limited field studies that sensors capable of multi-axis transmission provide data that result in improved object discrimination, as the parameters associated with the subsurface object are estimated more precisely [9].

In our previous efforts, we have successfully applied statistically-based signal processing algorithms using spatially-collected scalar EMI and magnetometer data for UXO discrimination. In one approach, probability density functions are developed that describe the statistical behavior of the data, x, obtained from a given sensor suite under the target and non-target hypotheses, denoted H_1 and H_0, respectively. Given these probability density functions, $f(x|H_1)$ and $f(x|H_0)$, and a vector of sensor data, x, the optimal decision statistic, or likelihood ratio test (LRT), is utilized to make a decision regarding the appropriate hypothesis, this represented as $\Lambda(x) = f(x|H_1)/f(x|H_0)$. For EMI and/or magnetometer data, the vector x typically contains the parameters estimated from the data using a phenomenological model. (We discuss automatic feature selection algorithms below.) Features are estimated using a constrained search methodology. We have demonstrated that the multiple-local-minima problem associated with this search is largely mitigated using multi-axis sensor data, thus resulting in better parameter estimates and better discrimination performance [9, 10]. The probability density functions associated with the data under each hypothesis are estimated from training data.

Both the LRT and other approaches have been applied to several data sets, with outstanding results [2, 10]. Performance on several data sets indicated that these approaches performed very well when relevant training data were available. In particular, in one demonstration, these algorithms were scored in a blind test. Our goal in this current effort is to develop robust statistical signal processing techniques for data obtained from multi-axis sensors. Such processing has not previously been developed. We are considering simulated modeled on data from sensors already in development (e. g., Zonge nanoTEM system, the LBL/Morrison time-domain sensor, the USGS TMGS system, the QM MTG system, and the Oak Ridge SQUID-based system).

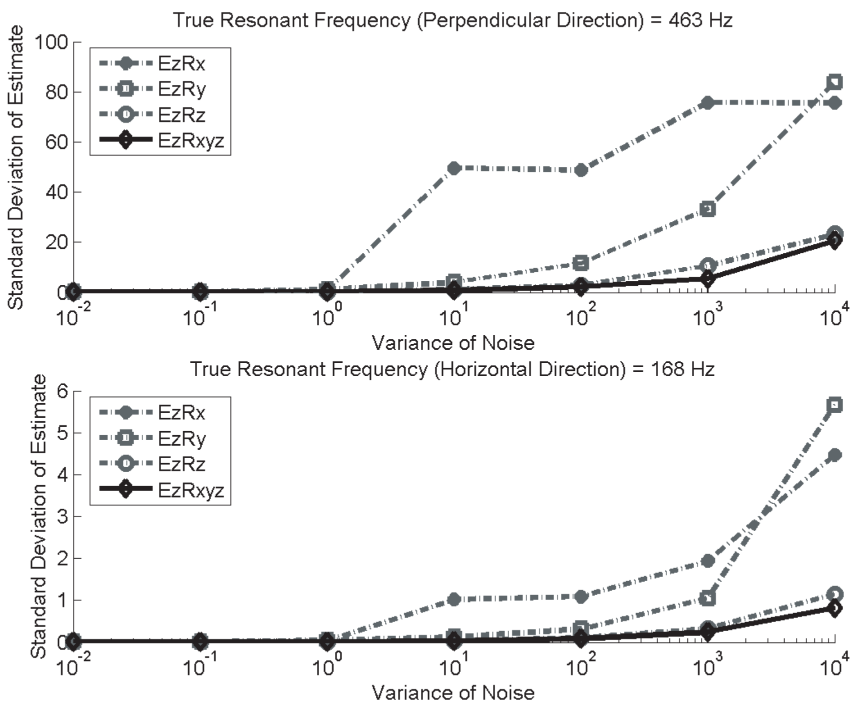

Figure 1: Standard deviation as a function noise variance for four different system configurations as noted in the legend. Ez indicates an excitation coil whose axis is perpendicular to the ground (z dimension), Rx, Ry, Rz denote receive coils in the x, y, and z dimension, and $Rxyz$ denotes three receive coils, one in each of the dimensions.

2. Results

Typical electromagnetic induction (EMI) systems used for UXO detection had discrimination have two co-located coils—one used for transmitting the electromagnetic field, one used for receiving the field induced in the subsurface object. Historically, these coils have been located so that the axis of the coil is perpendicular to the ground. As noted above, recent studies have suggested that adding additional transmitter and/or receiver coils in different orientations can improve sensitivity and discrimination performance. The goal of this preliminary study was to assess the level of performance gain using simulated data, but realistic field scenarios and uncertainties.

It has been established that UXO can be adequately modeled using a dipole model [2, 4, 5, 8–10]. The imaginary resonant frequencies of the EMI resonant modes are a function of target material parameters. Thus, these features can be used after the data is inverted using the model for signal processing and classification. Imagine a cylinder coordinate system with the target's symmetry axis as z, the frequency-dependent moment can be expressed as

$$M(w) = \hat{z}\hat{z}[m_z(0) + \sum_k \frac{wm_{zk}}{w - jw_{zk}}] + (\hat{x}\hat{x} + \hat{y}\hat{y})[m_p(0) + \sum_i \frac{wm_{pi}}{w - jw_{pi}}]$$

The six target moment parameters are $m_z(0)$, $m_p(0)$, m_{zk}, m_{pi}, w_{zk}, and w_{pi}, where $m_z(0)$ and $m_p(0)$ account for the dipole moments contributed by ferrous targets. Parameters w_{zk} and w_{pi} are resonant frequencies, which are determined by the target geometry and material properties. Generally the first term in the sum, which is the principle dipole moment along each coordinate axis, is all that is needed to provide an accurate representation of the measured data from UXO and clutter.

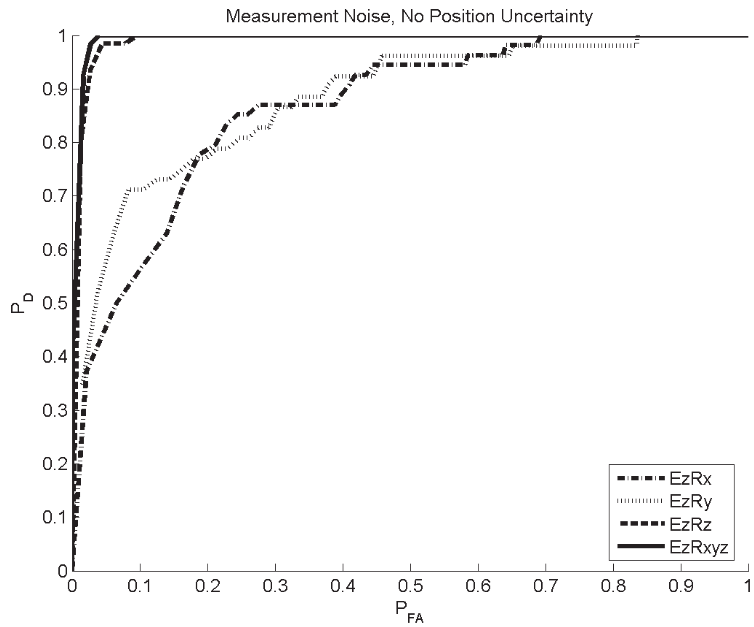

Figure 2: ROC curves plotting probability of detection versus probability of false alarm for the case where measurement noise is included, but it is assumed that measurement position is known perfectly. Single axis and multi-axis results are shown.

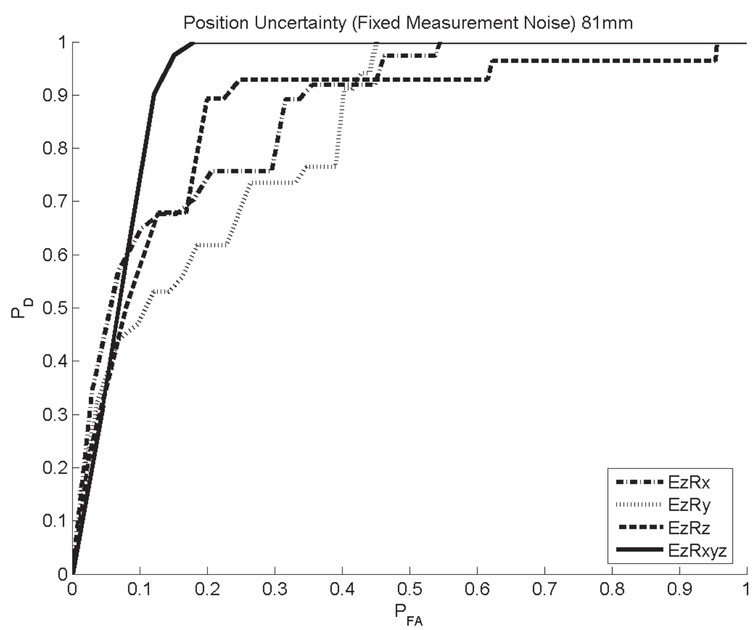

Figure 3: ROC curves plotting probability of detection versus probability of false alarm for the case where measurement noise is included and fixed, but it is assumed that measurement position is uncertain. Single axis and multi-axis results are shown.

In our initial simulations, we consider a system with one transmitter at a fixed orientation and three receiver coils along three perpendicular axes: x, y, and z. We consider a simulated target whose resonant frequencies along horizontal and perpendicular directions are 463 Hz and 168 Hz. These parameters were estimated from 81 mm projectile field data. The target is located 0.5 meters from the sensor. To minimize the effect of the target orientation on conclusions based on this simulation, we use a uniform distribution for the target orientation. Using the dipole model, we calculate the electromagnetic field measured from the target when the receiver coil is located in the three different orientations and add Gaussian noise, as is normally observed from the instrument, to the simulated field. Using our standard inversion algorithms [2, 9, 10], we obtain the estimated moments, the position and the orientation of the buried target from the simulated noisy field.

One mechanism by which to compare the performance of various system configurations is to consider the mean and standard deviations of the estimated moments/resonant frequencies as a function of the level of the Gaussian noise. Fig. 1 shows the standard deviation data for the simulated 81 mm target. Clearly, the three-axis receive coil provides better performance with increasing noise variance than any of the single axis systems.

In order to further quantify performance gain, the simulated 81 mm projectile was classified against a simulated clutter field where the clutter moments were distributed uniformly. A Bayesian classifier was used to discriminate the UXO object from the clutter using the estimated moments. Testing and training of the classifier were performed separately. Fig. 2 illustrates the classification performance achieved from three single axis and one multi-axis system. Some performance gain is obtained for the three axis system. Fig. 3 illustrates similar results, however in this case we simulated uncertainty in the position of the measurements. In this more realistic case, substantially more performance gain is observed in the case of the multi-axis system.

3. Conclusions

The results presented here indicate that a multi-axis system may potentially provide performance gain for discriminating UXO from clutter. We considered a case of discriminating an 81 mm projectile from a uniform field of clutter in the presence of additive Gaussian sensor noise. When no location uncertainty was included in the problem formulation, performance gains were small for the multi-axis sensor. However, when uncertainty in the exact location of the sensor was incorporated into the simulations, performance gain was enhanced substantially when the multiaxis sensor was utilized. This performance gain is a direct result of more accurate inversions possible with the multi-axis system.

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REFERENCES

1. Billings, S. D. and F. Herrmann, "Automatic detection of position and depth of potential UXO using a continuous wavelet transform: SPIE conference on detection and remediation technologies for mines and minelike targets," Orlando, April 21–25, 2003.
2. Collins, L. M., Y. Zhang, J. Li, H. Wang, L. Carin, S. Hart, S. Rose-Pehrsson, H. Nelson, and J. McDonald, "A comparison of the performance of statistical and fuzzy algorithms for unexploded ordnance detection," special issue on Recognition Technology, *IEEE Trans. Fuzzy Systems*, Vol. 9, No. 1, 17–30, 2001.
3. Tantum, S. and L. Collins, "A comparison of algorithms for subsurface object detection and identification using time domain electromagnetic induction data," *IEEE Transactions of Geoscience and Remote Sensing*, Vol. 39, No. 6, 1299–1306, June 2001.
4. Barrow, B. and H. H. Nelson, "Model-based characterization of electromagnetic induction signatures obtained with the MTADS electromagnetic array," *IEEE Transactions of Geoscience and Remote Sensing*, Vol. 39, No. 6, 1279–1285, June 2001.
5. Bell, T. H., B. J. Barrow, and J. T. Miller, "Subsurface discrimination using electromagnetic induction sensors," *IEEE Transactions of Geoscience and Remote Sensing*, Vol. 39, No. 6, 1286–1293, June 2001.
6. Hu, W. and L. M. Collins, "Classification of multiple closely-spaced subsurface objects: application of Iindependent component analysis," submitted to *IEEE Trans. Geosc. Remote Sensing*.
7. Barrow, B. J. and H. H. Nelson, "Model-based characterization of EM induction signatures for UXO/Clutter discrimination using the MTADS platform," UXO Forum, 1999.
8. Carin, L., H.-T. Yu, Y. Dalichaouch, A. R. Perry, P. V. Czipott, and C. E. Baum, "On the wideband EMI response of a rotationally symmetric permeable and conducting target," *IEEE Transactions of Geoscience and Remote Sensing*, Vol. 39, No. 6, 1206–1213, June 2001.
9. Zhang, Y., L. M. Collins, H. Yu, C. Baum, and L. Carin, "Sensing of unexploded ordnance with magnetometer and induction data: theory and signal processing," *IEEE Trans. Geosc. Remote Sensing*, Vol. 41, No. 5, 1005–1015, May, 2003.
10. Y. Zhang, L. M. Collins, and L. Carin, "Model-based statistical signal processing for UXO discrimination: performance results from the JPG-V demonstration," *Detection and Remediation Technologies for Mines and Minelike Targets VII Conference*, International Symposium on Aerospace/Defense Sensing and Controls, Orlando, Florida, April, 2003.

A Lossy Half-space Green's Function Forward Model and Inversion Method for Geophysics Problem

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Sensing and detection of dense non-aqueous phase liquids (DNAPLs) in soil is very significant and beneficiary for geo-environmental engineering, but challenging due to uncertain and hard to determine wave characteristics through soil media. The detection task may be possible by discriminating dielectric property contrast between DNAPL pools and saturated soil background. Despite least invasiveness of ground penetration radar (GPR), but due to its depth limitations, other alternatives should be implemented to detect DNAPLs. Sensing the subsurface volume between boreholes using cross-well radar (CWR) is an innovative and non-invasive technique, which is effective for deep investigations.

In this work, an analytical model is developed to approximate CWR sensing in infinite half-space lossy media in the frequency domain. Half-space dyadic Green's function in integral form for a vertical polarized dipole source is derived. Integration for angles goes far into evanescent range. To analyze the reflection behavior of a spherical wave onto a planar interface at oblique angle, plane wave decomposition technique is used to replace the spherical wave with a collection of all modes of plane waves. Fresnel reflection theory is utilized to investigate each plane wave reflection due to the planer inter- face. The Born approximation is employed as a linear model for a shape-based inversion, developed to localize the object. This localization is possible assuming the contrast between the clutter and lossy background as a priori information.

The forward model is validated via CWR experiment. Soil parameters (relative dielectric constant, and loss tangent) variance with frequency is approximated with a quadratic polynomial. Calibration of soil parameters is conducted comparing the results with experimental CWR data, using an iterative low-order parameterized optimization technique that involves both magnitude and phase information. Forward model and CWR experimentation results agree well over broad frequency range. Localization and reconstruction of the object is implemented using non-linear least square optimization by minimizing a cost function that calculates the misfit between the predicted numerical simulation and experimental observation. The proposed inversion method generates satisfying preliminary results, which are validated by numerical experiments.

Optimal Ultrasonic Surface Displacement and Velocity Estimation in the Presence of Surface Roughness

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An analytic model is developed for the ultrasound field reflected off a moving surface in the presence of random surface roughness for an ultrasonic displacement sensing system in bistatic configuration. The model incorporates the beampattern of both the source and receiver ultrasound transducers as well as spectrum of the rough surface. Conventional approaches for estimating surface displacement and velocity amplitudes based on the laser vibrometer, such as coherent interferometry and incoherent doppler shift spectra, are applied to the ultrasound system. Simulation with the model indicates that surface displacement and velocity estimation is highly dependent upon measurement geometry such as the area of surface insonified and angle of incidence of the system, height and correlation length scales of the rough surface, and frequency and duration of the ultrasound pulse. The model is then applied to determine an optimal measurement scheme for the ultrasound displacement sensor in land-mine confirmation.

One-dimensional Inverse Scattering: Localization of Planar Interface

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The problem of localization of a planar interface in a layered medium from the knowledge of the scattered electromagnetic field is set as an inverse problem within the frequency domain.

This problem has practical interest in many disciplines, as civil engineering and geophysics, because in many applications the subsurface can be considered as a planarly layered medium and the unknown position of interfaces are to be determined. In particular, in civil engineering, an important application is the localization and the determination of the depth of voids embedded in masonries of ancient buildings. Other promising applications concern the assessment of the widths of asphalts or the evaluation of the position of metal inclusions, e.g., sheets or fine meshes reinforcement. In geophysics, the determination of underground stratification is very important.

The problem is often considered in time domain by the search for successive reflections within received reflected field; however sometimes, because of the finite available bandwidth, later reflections due to deeper interfaces are 'buried' by oscillations of earlier responses. We choose to deal with the problem in the frequency domain and found that multiple reflections allow to improve the resolution in the localization. In the formulation we assumed that the dielectric properties of the layered medium are known.

Consider first the localization of a single interface within a layered medium. Since the relation between the scattered field and the position of the unknown interface is non linear; we reformulate the problem by introducing a Dirac distribution [1] centred on the unknown position and derive a linear operator linking such an unknown distribution to the scattered electric field. Next, we invert this operator by the Singular Value Decomposition (SVD) and use the truncated SVD (TSVD) as regularizing algorithm.

In the case of two-layered media, the operator to be inverted is a finite Fourier transform with limited data whose SVD has been well studied and is known in closed form. The resolution [1] is independent of the threshold of truncation of the SVD, that is of the uncertainties on data, due to the typical step-like behaviour of the singular values.

In the case of a three-layered losseless medium, in the search for the second interface, the operator can be recast as the summation of an infinite number of Fourier transforms in correspondence of successive bouncing of the waves inside the layer and a numerical investigation of the SVD of the relevant operator shows the curve of the singular values as successive steps corresponding to each reflection. When only the first two contributions are taken into account [2], an analytical estimate can be performed in some circumstances. The main results is that the achievable resolution can be improved with respect to the single interface case, according to the available uncertainty level on data.

Numerical experiments confirm the main conclusions. In addition the approach has been successfully employed to experimental data, in order to find the position and the width of a void layer inside a masonry of tuff. A procedure amounting to iteratively locating successive interfaces has been established. Calibration data collected in reference geometries make it available the scattered field at each step needed for the inversion.

REFERENCES

1. Pierri, R., A. Liseno, and F. Soldovieri, "Shape reconstruction from PO multi-frequency scattered fields via the singular value decomposition approach," *IEEE Trans. on Antennas and Propagat.*, Vol. AP-49, No. 9, 1333–1343, Sept. 2001.
2. Solimene, R. and R. Pierri, "Localization of a planar perfect-electric-conducting interface embedded in a half-space," in print on *Journal of Optics A: Pure and Applied Optics.*

A Unified Surface Source Model for Discrimination of Subsurface Metallic Objects by Magnetometry and UWB Electromagnetic Induction

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Clean up of land and water from subsurface metallic objects, particularly unexploded ordnance, still remains the number one military environmental problem. This process requires two steps: first a signal from a metallic object has to be detected and second, from the detected signal the object of interest must be distinguished from widespread pieces of metallic clutter. Recent studies have shown that magnetic and time or frequency domain electromagnetic induction (EMI) sensing technologies are the most promising approaches for UXO detection. In EMI the practical depth of penetration of the target by EMI signals is determined by the input frequency and target's conductivity and permeability. Signal clutter due to the dielectric heterogeneity of the surrounding environments or other non-metal material is negligible. Since, most if not all UXOs are metal, or contain substantial amounts of metals, they can easily be detected, but it is extremely difficult to discriminate them reliable from non-hazardous items. In order to overcome the discrimination problem, joint and cooperative (typically magnetic and EMI) approaches have been proposed. In these approaches magnetic and EM forward models have different parameterizations. Therefore when attempting joint or cooperative inversions, constraints imposed by one data set (for example magnetic) on the other (EM) is partially active — because of forward models.

In order to use all information obtained from each data set, this paper presents a unified source model applicable for any combination of magnetic and frequency or time domain EM data, for any sensor configuration and for any input waveform. In this approach, the EMI field from a given object is generated by a reduced set of surface sources: magnetic charges for a dry soil (free space approximation) or magnetic dipoles for relatively high conductivity host media such as seawater. These sources are distributed on a fictitious spheroid, which surrounds the object. First an input primary magnetic field is decomposed into fundamental spheroidal modes. Then, for each input spheroidal mode, a full low frequency EMI problem is solved via the method of auxiliary sources. Finally, for efficiency the EMI responses are reproduced by the reduced (few) set of sources, which is stored inside a library. Once all these processes are completed the full EMI problem for any transmitter/receiver can be easily solved by carrying out a spheroidal decomposition of the primary field and simply superposing the stored modal solutions. In time domain cases the EMI responses from the reduced set of sources are generated from frequency data for different waveforms using the inverse Fourier transform. In this paper, the first comparisons between the proposed model and real data in time and frequency domains will be presented and demonstrated for different waveforms. Finally, the method will be applied to the UXO discrimination problem.