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ТЕМАТИЧЕСКИЙ РЕФЕРАТИВНЫЙ СБОРНИК № 17-2

“UXO Detection”
(«Обнаружение невзорвавшихся боеприпасов»)

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"Development of a high temperature superconducting magnetic tensor gradiometer for underwater UXO detection"

We are developing a magnetic tensor gradiometer for underwater unexploded ordnance (UXO) detection using high-TcSQUID planar gradiometers. The system will use signals from six planar gradiometers, located on the faces of a hexagonal pyramid, to calculate the full gradient tensor. It will be towed underwater and will need to deal with noise caused by ocean waves, sensor motion and the measurement capsule itself. This paper presents our progress to date on this project including test results of gradiometer performance in laboratory conditions. [C1]

"Requirements for unexploded ordnance detection and discrimination in the marine environment using magnetic and electromagnetic sensors"

The topic of marine unexploded ordnance (UXO) mapping is becoming one of the most significant technology challenges of environmental characterization and remediation. For obscured object detection and characterization, magnetic and electromagnetic methods have been the primary sensor modalities used in terrestrial applications. However, while some marine systems have been developed and deployed, detection performance has been generally poor, particularly against small targets, and limited discrimination ability has been demonstrated. In this paper, we will review both the detection and discrimination requirements for magnetic and electromagnetic induction (EMI) sensor modalities and will discuss some systems either under development or at a conceptual stage. The paper focuses on data requirements and does not address the engineering required to effectively deploy the sensors. [C2]

"Benchmark targets for Computational Electromagnetics programs modeling structures with edges"

This paper considers several target structures containing edges which are useful to validate computer codes developed to the purpose of detecting hidden mines and Unexploded Ordnance (UXO). In particular, we investigate the capabilities of the singular basis functions' approach in Computational Electromagnetics for formulations based on surface integral equations. We compare the solutions obtained with several analytical/numerical methods and validate the simulations with anechoic chamber measurements performed on metallic targets. [C3]

"The precise INS/GPS geolocation of a vehicle-towed UXO detection system"

It is widely known fact that the precise position and orientation is necessary for the UXO detection and discrimination. The primary geolocation system is a dual-frequency GPS receiver integrated with a three dimensional inertial measurement unit (IMU). This study focused on the optimal data processing techniques (wavelet de-noising, nonlinear based filtering, post-processing smoothing) which have been developed and proposed for the high precise geolocation of IMU/GPS system. We mounted two IMUs (HG1700 and HG1900) and one GPS receiver on NRL's vehicle-towed system which already has three Trimble GPS and one IMU (Crossbow 400C). The positions from HG1700 and HG1900 are estimated between control points separated in time by 2 and 4 seconds and compared to 1 Hz GPS control. [C4]

"Feasibility study for IED detection using forward-looking ground penetrating radar integrated with target features classification"

In this paper, we examined the natural resonance frequency and polarization features of UXO-Like IED target in forward-looking GPR configuration. Based on the simulation results, we confirm that these feature not only exist but also measurable in the case of FLGPR. It is therefore, strongly suggested that these features be included in the target classification algorithms as they are expected to improve detection, increase stand off distance and minimize false alarm rate. [C5]

"Modeling water level's heaving and low-frequency Electromagnetic response from the highly conductive object submering in water environment"

In this paper we present simulation results, which illustrate how water level's heaving, can influence on low-frequency magnetic response of the electrically highly-conducting object placed in water environment. The time domain problem is solved using interpolation of partial solutions obtained in the frequency domain. In the frequency domain Electromagnetic problems are solved using the method of auxiliary sources. GEM sensor is modeled as excitant in the electromagnetic problem. Presented results estimate capabilities of the low frequency EMI in the detection and the discrimination of an unexploded ordinance (UXO) in water environment. [C6]

"Low noise actively controlled magnetometer array for underwater UXO survey"

Sky Research (SKY), through innovative use of advanced geophysical, marine, electronics, engineering, and remote sensing technologies has developed an underwater unexploded ordnance (UXO) detection system. Implementation of active depth control, terrain following, low noise magnetometers, and precise positioning measurements enables the system to rapidly execute precision surveys of large areas at depth of 10 meters (m) for detection, location and characterization of UXO. [C7]

"Multiple-aspect Fixed-Range Template Matching for the detection and classification of underwater unexploded ordnance in DIDSON sonar images"

This paper presents a sonar specific methodology to detect and classify underwater unexploded ordnance (UXO) in the low resolution sonar data captured by the DIDSON US300. This technique, known as the Multiple-Aspect Fixed-Range Template Matching (MAFR-TM) algorithm, is designed to detect and classify a target of high characteristic impedance in an environment that contains similar shaped objects of low characteristic impedance. The MAFR-TM is based on the proven concept of template matching, which is a two-dimensional correlation between a reference image (template) and an image collected during field operations (source image). In the MAFR-TM algorithm, the template matching method is efficiently implemented in the wave number domain using two-dimensional Fast Fourier Transforms (2D-FFT) and wave number leakage is reduced with an optimized separable two-dimensional Kaiser window. Experimental results are provided to demonstrate the performance of the proposed approach. [C8]

"Phenomenolgical model inversion with Fisher information metrics for unexploded ordnance detection"

Many of the ongoing efforts to develop strategies for detecting and locating subsurface unexploded ordnance (UXO) use features based on phenomenological models to discriminate between UXO and harmless clutter. The process of generating features requires model inversion to fit the phenomenological model to the measured sensor data. In commonly-used model inversion processes, the standard measures of model fit error do not incorporate the spatial distribution of the data used in the model inversion. This study incorporates the Fisher information in a joint metric optimization to assess the spatial distribution of data and how well the model parameters are supported by the data used in the model inversion. The outcomes of this study indicate that some outliers in the feature space can be mitigated by considering the Fisher information in the model inversion process, resulting in improved unexploded ordnance detection rates in a test using data collected at Camp Sibert, Alabama. [C9]

"Advanced classification of UXO using fully polarimetric GPR and frequency-polarization features"

The classification of buried UXO has been a difficult task due to the large amount of false alarms resulted from troublesome clutter objects. This paper closely examined scattering characteristics of such clutter objects by using numerical simulations. From the numerical study, we found that some clutter objects, which mainly causes the false alarms, produce multiple resonances at different frequencies and different polarizations. Based on these observations, we developed new classification algorithms which utilize the frequency-polarization dependent responses of complex targets in order to discriminate UXO-like objects form such trouble some clutters. The developed algorithms were tested by experiments in a test plot. In the test, the new classification algorithms clearly discriminated such clutters from UXO-like targets. In this paper, we present the simulation results for scattering characteristics of complex clutters and the new classification algorithm based on frequency-polarization dependent responses will be discussed. Finally, results from experimental verification will be presented. [C10]

"Magnetic tensor gradiometry in the marine environment"

We are developing a sensitive magnetic tensor gradiometer for detection of underwater unexploded ordnance (UXO) using high temperature superconducting quantum interference devices (SQUIDs). In parallel with the instrument development, we are looking at the challenges of making electromagnetic field and gradient measurements in electrically conductive seawater. We have been carrying out a theoretical analysis of how the measurements are distorted by the instrument package and developing methods to correct the measurements for this effect. We are also looking at the identification and removal of electromagnetic signals induced by motion of the seawater in the Earth's magnetic field. This paper will present the progress to date of the theoretical analysis and also look at dipole tracking methods using tensor gradient measurements. [C11]

"Investigation of EMI response for magnetically susceptible and conductive rough surfaces"

Electromagnetic induction (EMI) sensing has been identified as most promising technology for the detection and discrimination of subsurface metallic objects, particularly unexploded ordnances (UXO). In EMI, the sensors are detecting signals that are produced by induced and permanent magnetic polarizations. Soils, which contain small magnetic particles, called magnetically susceptible soils, can produce EMI responses and, therefore, mask or modify the object's EMI response. These soils are a major source of false positives when searching for UXO using magnetic or EMI sensors. Studies show that in adverse areas up to 30% of identified electromagnetic (EM) anomalies are attributed to geology. Therefore, to enhance UXO detection as well as discrimination in geological environments, the effects of the magnetic soils on the magnetic and EMI signal need to be studied in details. In this paper, the method of auxiliary sources (MAS) is applied to investigate the EMI response from magnetically susceptible rough surfaces. [C12]

"Subsurface object detection using UWB Ground Penetrating Radar"

Ultra wideband (UWB) ground penetrating radar (GPR) has been widely used in the detection of buried unexploded ordnance (UXO), particularly for small and/or shallow objects. Detecting subsurface objects from a weak reflection signal against strong clutter from GPR data is an important problem. A detection method which employs principal component analysis (PCA) and digital image processing techniques is proposed in this paper for clutter reduction in underground object location. The proposed method can robustly indicate not only the regular hyperbolas but also the perturbed slant lines as a result of buried objects. Experimental data collected using an UWB GPR system is used to demonstrate that the proposed methods are effective in reducing clutter and detecting subsurface targets. [C13]

"Inversion of soil's and immersed objects's electromagnetic parameters symultaneously"

This paper presents results of numerical simulation and algorithm of simultaneous inversion of soil's and immersed object's electromagnetic parameters. Inversion is performed from data of electromagnetic induction (EMI) sensing, when all other geometric parameters of the problem are known. Discrimination procedure of subsurface objects such as landmines and unexploded ordnances (UXO) accomplishes higher accuracy when mentioned parameters are determined a priori. A specially, when interaction effects between object its surrounding media is significant and there is no exact information about materials of UXO produced in different time. Combining Method of Auxiliary Sources (MAS) with Gauss-Newton minimization algorithm, we developed optimization methodology that simultaneously inverts for the EM parameters of both the object and the surrounding medium. [C14]

"UXO survey using vector magnetic gradiometer on autonomous underwater vehicle"

Vector magnetic gradiometer measures the gradient components of ferromagnetic objects and with appropriate processing, such as inversion, is possible to derive the range, bearing and magnetic moment of the target of interests. This paper presents the progress of the development of magnetic gradiometer using autonomous underwater vehicle (AUV) for UXO survey. A prototype magnetic gradiometer was developed for magnetic detection of underwater objects onboard an AUV. The prototype magnetic gradiometer is housed in a plastic nose cone of consisting of four fluxgate magnetometers. Rotation calibration is performed to correct offset, scaling and axis orientation errors of magnetometers with reference of a scalar magnetometer. The performance of magnetic noise compensation is evaluated with simulated magnetic noise sources, typically present in an AUV. Experimental tests have been conducted using a 3-axis rotation table to simulate motions to evaluate the performance of the magnetic gradiometer for mobile operation. This paper also discusses an iterative searching approach to determine the object detection range, bearing and magnetic moments by magnetic gradients matching with a volume magnetization model. [C15]

"High resolution subsurface imaging of deep targets based on distributed sensor networks"

A realistic forward model based on a near-ground distributed sensor grid for a target buried under soil is

devised. The soil medium is modeled as a planar stratified medium with a complex dielectric constant profile. The Dyadic Green's function for multilayer dielectric is used to compute the electric field at the target. A high resolution inversion algorithm based on phase-conjugation approach to detect deeply submerged targets is also presented. The sensor network is setup to enhance the lateral resolution by forming a synthetic aperture. The depth resolution is improved by using bandwidth. So as to improve the efficiency of the search algorithm a soil dielectric model to predict the real and imaginary parts of the dielectric constant from the volumetric soil moisture for a given soil textural composition is extended to the frequency of interest (VHF) resulting in less number of variables. [C16]

"Combining NSMS and High-Quality MPV-TD Data for UXO Discrimination"

In this paper, a new physics-based approach for estimating a buried object's location and orientation is combined with the normalized surface magnetic source (NSMS) model to analyze high-quality, high-density multiaxis data provided by the Man-Portable Vector (MPV) time domain (TD) sensor. The NSMS is a very simple and robust technique for predicting the EMI responses of various objects. It is applicable to any combination of magnetic or electromagnetic induction data for any arbitrary homogeneous or heterogeneous 3D object or set of objects. The physics-based approach to estimate location assumes that the target exhibits a dipolar response and uses only two global values, the magnetic field vector H and the scalar magnetic potential psi, reconstructed at a set of points in space. To demonstrate the applicability of the NSMS, we first compare its predictions with dynamic MPV-TD measurements and then present the results of a blind-test analysis using multiaxis static MPV-TD data sets. [C17]

"A radar target for calibration and for codes validation"

The electromagnetic scattering of a plane wave by a penetrable (e.g., dielectric) or impenetrable (e.g., metallic) sphere concentric with a thin metallic disk is considered, in the frequency domain. At low and intermediate frequencies, either separation of variables and mode matching with matrix truncation or a direct numerical approach such as the MoM is adopted, while at high frequencies a combination of GTD and physical optics is employed. The analytical and numerical results are compared to measurements made in an anechoic chamber. [C18]

"Novel geolocation technology for geophysical sensors for detection and discrimination of unexploded ordnance"

Reliable and precise navigation technology is essential for robust detection and discrimination of unexploded ordnance (UXO) in a wide range of field conditions. The detection and remediation of munitions and explosives-of-concern (MEC) on ranges, munitions burning and open detonation areas, and burial pits is one of the US department of defensepsilas (DoD) most pressing environmental problems. The MEC characterization and remediation activities using currently available technologies often yield unsatisfactory results, and are extremely expensive, due mainly to the inability of current technology to detect all MEC present at a site, and the inability to discriminate between MEC and non-hazardous items due mainly to insufficient accuracy of georeferencing of the geophysical images. As a result, most of the costs (90%) of MEC site remediation are currently spent on excavating targets that pose no threat. Thus, the goal of the research presented here, supported by a DoDpsilas strategic environmental research and development program (SERDP) grant, is to design and demonstrate a high-accuracy hybrid navigation and georeferencing device based on multi-sensor integration, which can meet the stringent requirements of a man-portable geophysical mapping system in open and impeded environments, and hence to lower the cost of remediation by improving the geolocation accuracy of MEC discrimination. This paper describes a hybrid system based on quadruple integration of GPS, inertial technology (IMU), pseudolites (PL) and terrestrial laser scanning (TLS) technology to improve the current geolocation capabilities at MEC sites. The concept design of the system, the algorithmic approach to sensor integration, with a special emphasis on TLS integration with GSP/IMU/PL, and the preliminary performance assessment based on simulations are presented. [C19]

"Modeling Highly Permeable and Conductive Ellipsoidal Clutter for the Detection of UXO in the Electromagnetic Induction Regime"

The modeling of unexploded ordnances in the electromagnetic induction regime (from tens of hertz to a few kilohertz) is carried out in the ellipsoidal coordinate system, thus presenting an important generalization of the existing dipole model or spheroidal approach. Ellipsoidal geometries are of interest because of their ability to more accurately model real 3D objects while retaining the appeal of an analytical solution. Computation speed is minimized here by assuming objects of high permeability and conductivity, allowing for the use of the small penetration approximation, and avoiding the necessity of solving the wave equation using ellipsoidal wave

functions inside the object. Simulations are compared with both existing numerical solutions and with measured data on fabricated ellipsoids, and prove the validity of our model. [C20]

"SAIC marine unexploded ordnance (UXO) survey system"

SAIC has developed a unique underwater UXO detection system for use in shallow water with typical depths up to 6 m (~20 ft) and a maximum depth of 10 m (~30 ft).This new system, known as the Marine Towed Array (MTA) has completed its first successful UXO survey on the Currituck Sound in Duck, NC in May 2005. A perspective view of the sensor platform is presented. [C21]

"Improved magnetic STAR methods for real-time, point-by-point localization of unexploded ordnance and buried mines"

There is a pressing need for a practical and effective magnetic sensing technology that can be deployed onboard highly maneuverable sensing platforms and used for real-time, point-by-point detection, localization and classification (DLC) of magnetic targets such as ferrous unexploded ordnance (UXO) e.g., bombs, buried mines and artillery shells. Therefore the Strategic Environmental Research and Development Program (SERDP) has supported research and development, by Naval Surface Warfare Center Panama City Division (NSWC PCD), of a novel man-portable Magnetic Scalar Triangulation and Ranging (i.e., "STAR" and/or "MagSTAR") technology for DLC of UXO. The STAR concept uses scalar magnitudes of magnetic gradient tensors to triangulate the locations of magnetic targets. The magnitudes are analogous to central potential-type functions and they can provide true point-by-point DLC capabilities for sensing platforms in general, unconstrained motion. A prototype man-portable STAR Gradiometer was designed and constructed at NSWC PCD to provide a completely portable and user-friendly technology for real-time DLC of magnetic UXO. The prototype STAR Sensor comprises: a) A cubic array of eight fluxgate magnetometers, b) A 24-channel data acquisition/signal processing system. In field tests the man-portable sensor has demonstrated very robust, motion-noise-resistant DLC performance against isolated dipole type targets . This paper describes work that is ongoing to enhance the performance of the MagSTAR Technology. In particular, two improved algorithms for solving the "STAR Equations" are described: 1) A directional derivative (DD) method based on the fact that the gradient of a central potential field is a vector that points toward the target/source of the locally strongest gradient. 2) A least-squares-fit (LSF) method that iteratively calculates a magnetic target's location and magnetic signature. The DD method is being developed for better discrimination between multiple target- s but for isolated targets it is more susceptible to sensor noise than the LSF method. The initial LSF method applies primarily to DLC of isolated dipole targets. Thus, the methods preferably should be used concurrently as complementary DLC modalities in environments that may be magnetically complex. These improved methods should help facilitate the transition of the STAR Technology from man-portable applications to applications using highly maneuverable autonomous sensing platforms for real-time "on the fly" DLC of magnetic targets such as UXO and buried mines. [C22]

"Humanitarian demining: Difficulties, needs and the prospect of technology"

Humanitarian demining is a critical first step for reconstruction of post-conflict countries and it requires that the entire land area to be free of mines and hence it is necessary to locates and removes reliably and safely every single mine, and UXO from targeted ground. The problem associated with humanitarian demining is characterized by an enormous variability in the nature of explosive ordnance to be removed, climate diversity, and in the type of terrain and vegetation. Current demining is a dangerous, time consuming, and costly process. To increase mine clearance daily performance by improving productivity and accuracy, and to increase safety of demining operations and personnel, there is a need for an efficient, reliable and cost effective humanitarian mine action equipment with flexible and modular mechanisms with adaptable mobility and equipped with some level of decision making capabilities. Technologies to be developed should take into account the facts that many of the demining operators will have had minimal formal education and that the countries where the equipment is to be used have poor technological infrastructure for equipment maintenance, operation, and deployment. In addition, it is necessary to overcome the constrain on the resources by developing innovative, cost effective and practical technology inspired by locality and real minefield needs to help in speeding up the demining process and enhance accuracy, productivity, operation and personnel safety, achieve a higher quality of the service, and contribute to local economy. [C23]

"On the feasibility of using GPR technology for the UXO detection and discrimination in the volcanic soil of Hawaii"

In this paper we describe the recent results from an ongoing project at the University of Hawaii to use advanced GPR technology for the detection and discrimination of UXO in the high iron content volcanic soil of Hawaii. To help determine a suitable frequency range for detecting targets at two feet depth from the surface, a soil

characterization effort has been implemented. Both the dielectric and magnetic properties of the earth soil are being measured using a unique shunt capacitance terminating a transmission line method and a recently fabricated TEM cell. Both the reflection and transmission S-parameters are being measured to determine both the complex permittivity and permeability of the soil. Furthermore, a TLS-Prony method together with FDTD 3D simulations of typical detection environments are being used to extract the complex natural resonance frequencies (CNR) of targets from the late arrival signals associated with the scattering mechanisms from these targets. A UXO testbed has been development to help experimentally validate simulation results and provide data to check and improve the accuracy of the detection/discrimination algorithm. Results from this study including dielectric and magnetic characterization of the volcanic soils, and CNR of typical UXO targets encountered in Hawaii will be presented. [C24]

"An Analytical Expression for Estimating a Buried Object's Location, Orientation and Magnetic Polarization to Support UXO Discrimination"

A new physics based expression is presented for determining a buried object's location, orientation and magnetic polarizability. The approach assumes the target exhibits a dipolar response and uses only three global values: (1) a H magnetic field vector, (2) a vector potential A and (3) a scalar magnetic potential psi all at a single location in space. To illustrate the accuracy of the proposed algorithm, several numerical results are demonstrated using synthetic data for one and three dipoles. [C25]

"Fussy support vector machines for recongnition of airport unexploded ordnance"

Considering the risk and fuzzy characteristics of airport unexploded ordnances, the theory of fuzzy support vector machines (FSVMs) is applied to penetrate airport unexploded ordnances(UXO). The risk membership to each input points is confirmed on the base of processing input data, and then is leaded into the reasoning process of the decision function. At the end, the results of UXO detection show that the decision function has obvious improvement to the classification accuracy of important data. [C26]

"Demonstration of a Novel Man-Portable Magnetic STAR Technology for Real Time Localization of Unexploded Ordnance"

We report results of field tests of the first prototype of a novel man-portable Magnetic Scalar Triangulation and Ranging (STAR) technology. The new magnetic sensor system technology is being developed with support from the Strategic Environmental Research and Development Program (SERDP) to provide an easily deployable magnetic sensor system for real-time, point-by-point Detection, Localization and Classification (DLC) of magnetic targets such as Unexploded Ordnance (UXO) and buried mines. The STAR technology is based on a multi tensor gradiometer approach that uses magnetic gradient tensor magnitudes, i.e., "gradient- contraction-type" parameters to perform DLC of magnetic targets. The magnetic STAR sensor uses the scalar functions to triangulate a magnetic UXO-type target's position vector and to calculate the target's magnetic signature vector. The vector components of an object's magnetic signature provide a basis for real time classification of its type, i.e. UXO-like or not. In order to provide proof of principle of the STAR concept and demonstrate its advantages for high mobility magnetic sensing applications, we designed, constructed and field-tested a prototype man-portable STAR Gradiometer. The portable gradiometer's hardware and software are completely self- contained and provide a practical and user friendly capability for real time DLC of magnetic targets. Target DLC parameters: e.g., range, bearing, elevation and magnetic signature are correlated with Global Positioning System time and position data and displayed in near real time (total delay < 3 seconds) on a heads-up display that clips onto the operator's safety glasses. Interactive software controls data acquisition, performs signal processing to remove residual motion noise effects and runs the STAR Algorithm to generate and display the target's DLC parameters. Field tests have demonstrated proof-of-principle of the STAR concept and conclusively demonstrated that the technology has uniqu- e advantages for DLC by highly mobile sensing platforms. While being carried and operated by a single individual, the portable sensor has demonstrated very robust, motion noise resistant performance even while undergoing rotational motion of more than 40 degrees per second. The field test results very strongly indicate that the man-portable STAR technology can provide a wide variety of highly maneuverable sensing platforms (including Autonomous Underwater Vehicles) with uniquely effective, motion-noise-resistant magnetic sensing modalities for DLC of magnetic targets such as UXO and underwater mines. [C27]

"Particle swarm optimization as an inversion tool for a nonlinear UXO model"

The physics-based classification of unexploded ordnance (UXO) from electromagnetic induction (EMI) data is an exercise in nonlinear data inversion in which model parameters are extracted from a dataset by way of a physical model. Gradient-descent-based algorithms like Levenberg-Marquart (LM) suffer from local minima

entrapment, but deliver rapid, accurate estimates when initialized near the global minima. Global optimizers, like particle swarm optimization (PSO) are less susceptible to this limitation. Here we consider an approach for parameter estimation based on a hybridization of PSO and Levenberg-Marquart. For purposes of initializing the LM procedure, we demonstrate that PSO applied to a reduced form of the physical model reaches a reliable initialization in one tenth the time of a coarse search of parameter space. Monte Carlo testing of the approach shows PSO initialized Levenberg-Marquardt estimation converging to the best-fit solution every time, as opposed to a randomly but reasonably initialized estimation. PSO as a stand alone approach provides less fit solutions on average than the PSO/Levenberg-Marquardt hybrid within the same computation time. We demonstrate these observations using both the simple, dipole model for the UXO problem as well as an enhanced form of this model capable of better capturing signal structure for large UXO-type objects. [C28]

"Detection of Small Changes in a Hip Prosthesis using the E-Pulse Technique"

A subsurface target identification scheme based on the E-pulse technique is proposed and investigated. The target inside a homogenous medium is approximated using Baum's transform. An E-pulse is constructed with the transformed complex natural resonances (CNRs) and convolved with the target returns from subsurface targets. Numerical examples of a hip prosthesis implanted within a homogenous half space shows that the proposed technique is capable of differentiating small physical changes between two hip prosthesis models at least under a homogeneous half-space condition. The proposed method can also be applied to other subsurface target detection problems such as UXO recognition, and for a dielectric target, the problem of recognition of malignant lumps within human breast tissue [C29]

"Advanced EMI Modeling and Processing Approaches for UXO Discrimination"

This paper presents a new, advanced non-traditional physics based inverse-scattering approach for determining a buried object's location and orientation. The approach combines an advanced electromagnetic induction (EMI) forward model called the normalized surface magnetic charge model (NSMC) with the pole series expansions technique. First, the NSMC is used to generate bi-static EMI data from actual measured mono-static data, and then the pole series expansion approach is employed to localize scattered field singularities, i.e. to find object's location and orientation. Once the object's location and orientations are found, then the total NSMC, which is characteristic of the object, is calculated and used as a discriminant. The algorithm is tested against actual EM-63 time domain EMI data collected at the ERDC test-stand site for an actual UXO. Several numerical results are presented to demonstrate the applicability of the proposed method for UXO discrimination [C30]

"Portable Magnetic Gradiometer for Real-Time Localization and Classification of Unexploded Ordnance"

We report progress toward achievement of a new magnetic tensor gradiometer technology that is being developed with support from the Strategic Environmental Research and Development Program (SERDP). The objective of this R & D effort is to provide a man-portable magnetic tensor gradiometer for real-time, point-by-point detection, localization and classification (DLC) of unexploded ordnance (UXO). The portable gradiometer processes data from triaxial fluxgate magnetometers to develop sets of rotationally invariant, "gradient-contraction-type" scalar parameters. The scalar parameters provide the basis for a unique Scalar Triangulation and Ranging (STAR) method that determines the UXO's position and magnetic signature. In particular, our paper presents: (a) A review of the magnetic STAR concept, (b) Details of construction and operation of the portable STAR-type gradiometer, (c) Results of computer simulations of the effects of fluxgate noise on the gradiometer's target-tracking performance and (d) Results of experimental measurements of uncorrelated fluxgate noise and correlated gradient channel imbalance errors, (e) Preliminary results from a gradient imbalance noise compensation algorithm. The R & D results indicate that the magnetic STAR concept potentially will provide an exceptionally valuable, motion-noise-resistant magnetic sensing technology for real-time, DLC of UXO, and buried mines [C31]

"Magnetic Sensors for Navigation and Security Applications"

Magnetic sensors are key elements in many security, military, and navigation systems. Fast development of new sensor types such as AMR (Anisotropic MagnetoResistors), GMR (Giant Magneto-Resistance), SDT (Spin-Dependent Tunelling) and GMI (Giant Magneto-Impedance) brings new opportunities; but not all new is better. The purpose of this tutorial is to critically review the principles and properties of modern magnetic sensors and show how they presently are employed in navigation and security applications and what is their future potential. The emphasis will be given for mine and UXO (Unexploded Ordnance) location. 1. Principles and techniques:- principles of DC magnetic sensors suitable for security applications (incl. AMR, GMR, SDT and miniaturized resonant and fluxgate sensors)-eddy-current methods-induction magnetometers-electromagnetic methods

including ELF and Ground Penetrating Radar-imaging techniques, signal processing, recognition-gradiometric techniques, sensor fusion-calibration and error corrections 2. Applications-Mine detection-UXO location-Detection and recognition of vehicles (incl. submersible)-Detection frames and other sensors for border security-Magnetic labels and anti-theft systems-Navigation systems-Magnetic tracking-Distance measurement-Distributed sensors and sensor areas [C32]

"Bomb Detection in Magnetic Soils: AC versus DC Methods"

We compare the performance of eddy-current metal detectors for finding small bombs and other items of unexploded ordnance (UXO) with the potencial of DC gradiometers of scalar and resonant type. Extensive database of results was collected during laboratory measurements and field trials performed by JRC. There are two main obstacles for bomb detection: false alarms caused by metal clutter and effect of magnetic soil and rocks. A number of soil samples were collected at mine fields and UXO affected areas. Magnetic properties of these soils were examined both in time and frequency domain. The results were compared with the detection depths measured both in soil and in air for various targets. In general, the most difficult soils show frequency dependent susceptibility, which creates signal similar to metal object. We show how to compensate such soils. [C33]

"A modified dipole model for target discrimination in EMI sensing"

As an inverse problem, UXO (unexploded ordnance) discrimination requires fast forward models to estimate the response of target to sensor sources. In EMI sensing, the most well developed models approximate an object using frequency (or time) dependent magnetic dipoles. If the dipole moments at each frequency are independent model parameters, the number of unknowns in the inverse problem will be very large, particularly when multiple dipoles are required. Here we introduce a modified dipole model, in which a small number of model parameters are needed to describe each element of magnetization tensor. The modified model simplifies the inversion process, which makes it more suitable for real field applications, especially for highly contaminated UXO sites. [C34]

"Special GPR antenna developments for landmine and UXO surveys"

Ground penetrating radar (GPR) is a promising technique for detecting and identifying buried landmines and UXOs. The antenna plays a critical role in determining the performance for tasks and requires to have a broad bandwidth, minimal ground dependency, fast or no antenna ring-down, desirable polarization and pattern characteristics. Three unique UWB dual-polarization GPR antenna designs are discussed. A dielectric rod antenna, covering from 1 GHz to 6 GHz, is suitable for shallow (less than 12 inches) targets, such as landmine detection/identification. The other two antennas, covering frequencies from 20 MHz to 800 MHz, are suitable for general GPR applications, such as the detections of pipes, utility lines, UXOs, AT mines, etc. [C35]

"Generalized magnetic gradient contraction based method for detection, localization and discrimination of underwater mines and unexploded ordnance"

We report significant progress toward full development of a unique magnetic-gradient-tensor-based "scalar triangulation and ranging (STAR)" method for detection, localization and classification (DLC) of magnetic targets. The STAR method converts magnetic tensors to rotationally invariant scalar parameters that are virtually unaffected by the effects of sensing platform motion. Thus, the STAR method is particularly appropriate for magnetic target DLC using highly mobile sensing platforms such as autonomous underwater vehicles (AUV). Prior work has resulted in development of a two-dimensional (2D) magnetic target-homing concept for fully autonomous localization of mines using crawler-type AUVs. However, the simple 2D STAR approach cannot effectively discriminate between magnetic clutter and mine-like target signatures. Improved, 3D simulations demonstrate that the STAR concept can be applied to measurements of the vector positions and dipole signatures of magnetic objects. The new results indicate that an improved STAR system will provide an enhanced capability for discrimination between magnetic clutter and real targets such as magnetic mines and Unexploded Ordnance (UXO). Consequently, further development of the advanced STAR concept will provide high-mobility autonomous sensing platforms (such as AUVs and man-portable systems) with a uniquely effective modality for DLC of magnetic mines and UXO [C36]

"Position detection of unexploded ordnance from airborne magnetic anomaly data using 3-D self organized feature map"

The detection of any buried object depends on the analysis of its emerged magnetic anomaly data. In this paper, the self-organized feature map (SOFM) neural network is used to detect the position of the unexploded

ordnance (UXO) from airborne magnetic anomaly data. The SOFM is an unsupervised-competitive neural network that can learn a topology-preserving mapping from a high dimensional input space to a lower dimensional map lattice. The SOFM was trained using two-dimensional theoretical magnetic signatures of an equivalent UXO dipole source in different X, Y, and Z coordinates. The feature map is designed as a three-dimensional SOFM, where each dimension in this feature map is used to detect one coordinate of the UXO position. The experimental results showed that the SOFM could accurately recognize the UXO position from both simulated magnetic anomaly data and actual airborne magnetic field data. The network could also recognize the UXO position correctly when tested with noisy magnetic anomaly data up to +/-15%. It is concluded that the SOFM is an efficient, fast, and accurate technique for position detection of the UXO buried objects [C37]

"Experimental data of a directional borehole radar system for UXO detection"

First Page of the Article [C38]

"Development of mechanical master-slave hand for demining operation"

A considerable number of landmines and unexploded ordnance (UXO) are buried in many disaster-affected countries. Although some methods to remove them have been proposed, there are still many problems. We propose new mechanical master slave hands to remove landmines and UXOs. At first, we have made a test model. We have conducted hearing about the first model with expert deminer of Afghanistan. Then we made improved model. Through several basic experiments, the second model is estimated to be practical. [C39]

"Section 15: UXO / Mine Detection"

First Page of the Article [C40]

"Unexploded ordnance detection by measuring object symmetry via linear prediction"

Humanitarian demining has become a serious international issue nowadays due to the post-war buried unexploded ordnance (UXO) and land mines. In this research, a new technique based on linear prediction is proposed to discriminate UXO from non-UXO targets. The proposed technique takes into account the symmetry of the ground penetrating radar (GPR) signal returning from a buried object. We use the GPR data set collected by Battelle company and the Ohio State University from the Jefferson Proving Ground (JPG), U.S.A. in the experiments The results evaluated in terms of receiver operating characteristic (ROC) curves show that our proposed technique has a better detection performance than a traditional detection technique based on energy. The false alarm reductions at 100% detection by the baseline technique and the proposed technique are about 11% and 23%, respectively, compared to a situation where no technique is applied. [C41]

"A concept for hip prosthesis identification using ultra wideband radar"

Ultra wideband (UWB) radar has been extensively investigated both theoretically and practically for the identification buried artifacts. Ground probe radar (GPR) concentrates on the identification of lightly buried land mines, unexploded ordnance (UXO) and archeological targets. The same technology is proposed in a similar context for the rapid identification of in vivo implanted metallic prostheses. The technique is based on resonance based target identification and the paper investigates UWB scattering from a metallic hip prosthesis in free space as a first step in the identification process. [C42]

"A standardized excitation approach for classification of buried UXO"

In this paper, a new discrimination procedure is presented to enhance classification of buried metallic object. This algorithm is based on a standardized source set (SSS) approximation, applicable for an arbitrary highly conducting and permeable metallic objects placed in a low frequency (from 10's of Hertz up to several 100's of kHz) time varying electromagnetic field. The method treats accurately all near field, heterogeneity, and internal interaction effects. In the SSS approach, any input primary magnetic field is represented as a sum of magnetic fields produced by a set of sources distributed over on an auxiliary surface outside the fictitious surface. The object's response corresponding to unit amplitudes of any of these input field sources is likewise quantified in terms of a set of (responding) sources, which can be derived from measured data. Thereafter, the object's response to any excitation can be expressed just by different superpositions of these standardized inputs. The spatial distribution and frequency dependence features of responding equivalent sources are analyzed and used for target discrimination. The numerical results are given for an actual unexploded ordinance (UXO) [C43]

"Application of Bayesian inversion for scatterer shape from EMI data"

Bayesian inversion approaches may be useful for inferring metallic scatterer shapes, and thereby assist in discriminating buried unexploded ordnance (UXO). The fundamental feature of Bayesian inversion is its attempt at rational incorporation of prior information in the inference algorithm. In UXO detection and classification, the model is a set of parameters corresponding to a particular object in a particular disposition. Prior information about the target sought and the randomness of noise and clutter from different sources warrant the application of a Bayesian approach. Broadband electromagnetic induction (EMI) responses at different locations, in terms of scattered magnetic field components in-phase and out-of-phase with the transmitted primary field, form the data vector. Here a fast forward model, in which we successfully represent a steel cylinder by a spheroid, is exploited for inversion computations. The validated model produces synthetic data, for which Bayesian inversion is compared to simple least squares (SLS), i.e. without weighting or damping. The Bayesian approach can provide more accurate results, if we can provide reasonable prior information. [C44]

"Semi-analytical calculation of Jacobian in the electromagnetic inverse scattering problem"

Discrimination of unexploded ordinance (UXO) from widespread metallic clutter remains a very urgent environmental remote sensing problem. One of the most promising technologies for such discrimination is ultra-wideband low frequency electromagnetic induction (EMI), operating from a few Hz up to a few hundred kHz. The numerical hybrid of the full method of auxiliary sources (MAS) and the MAS-thin skin approximation (MAS-TSA) (Shubitidze, F. et al., Proc, ACES, 2003; IEEE Trans. Geosc. & Remote Sens., vol.40, no.4, p.928-42, 2002) solves the forward governing equations very efficiently. Solving the inverse problem numerically requires calculation of the gradient of the system Jacobian. In the hybrid full MAS/MAS-TSA method, one obtains an analytical form of this gradient, producing an overall semi-analytical system for inferring a metallic object's electromagnetic parameters. We illustrate our main ideas with a simple body of revolution problem, and results are compared with measured data. The method can readily be extended to general inverse electromagnetic scattering problems at higher frequencies. [C45]

"Studies of ground penetrating radar antennas"

Virtually all systems that have been developed in recent years to detect landmines and buried unexploded ordinance (UXO), have included the ground-penetrating radar (GPR) as one of the principal subsystems. Much of the effort reported to date in evaluating these GPRs has focused on obtaining overall end-to-end detection performance metrics (Pd, Pfa). These studies have been useful but they provide little insight into the functioning of individual GPR components and the limitations they may impose on system performance. By contrast, this project concentrates on investigating performance characteristics of the GPR antenna, which is perhaps the most critical component in determining GPR system performance. Some of the antenna issues that remain unresolved are: determination of the most useful bandwidths, defining the role of polarization and polarization diversity, minimizing the effects of self-clutter (also known as "ringdown" or "reverberation"). Over the course of this ongoing program, we plan to investigate a variety of GPR antenna subsystems, including the spiral, the sinuous log-periodic, various dipoles, the TEM horn, the TEM rhombus, tapered slots and forms of the impulse radiating antenna (IRA). In this paper, we report some initial experiments carried out on a transmit-receive pair of Archimedean spiral antennas. To characterize these antennas, we carried out measurements in a conventional radio frequency (RF) laboratory using a vector network analyzer to synthesize waveforms covering the frequency range from 500 MHz to 5.5 GHz. Transformation of these data to the time domain allows us to gate out extraneous laboratory clutter beyond a 1.5-m (10 nsec) range. The principal measurements reported here are: the gain and phase properties, noise and clutter levels, and the antenna system spatial response footprint. The spatial patterns were measured by raster-scanning a stainless steel sphere through a two dimensional grid located 17 cm (a range typical of GPR applications) from the aperture of the transmit/receive antenna pair. [C46]

"Investigation of side looking EM field scattering from a buried metallic object to support UXO discrimination"

Detection and identification of buried unexploded ordinance (UXO) remains a challenging problem. Despite limitations due to clutter and ground coupling, ground penetrating radar has shown considerable virtues for UXO discrimination. Recent UWB field tests between 10's of MHz and 100's of MHz have demonstrated that certain of the target's dimensions can be estimated from analysis of complex natural resonances in the signal. The problem becomes much more complicated when objects are placed in layered ground and oriented vertical to the antenna, so the incident field cannot excite currents along the major axes and the scattered field from the object cannot easily be separated from the layer interface response. To investigate this, we pursue simulations here designed to test side looking EM field scattering from a buried object placed in layered ground. The numerical calculation is done using the finite difference time domain (FDTD) method in conjunction with the generalized perfectly matched layer GPML. The results are analyzed for a cylinder placed in a uniform and layered earth.

[C47]

"Fast direct and inverse EMI algorithms for enhanced identification of buried UXO with real EMI data"

Discrimination of buried unexploded ordinance (UXO) from innocuous buried items remains a challenging, top priority problem for the electromagnetic induction (EMI) sensing community. In general, classification is an inverse problem, requiring very fast and accurate representation of the target response. To address this critical issue, this paper presents a very fast, rigorous way to compute EMI scattering from a realistically complex, composite target. Full interaction between all parts of the object are included in the calculations. The method is based on a hybrid of the full method of auxiliary source (MAS) and the MAS-thin skin depth approximation formulation (MAS-TSA), together with new modal decomposition and reduced source set techniques. For general excitation, a primary field is decomposed into the fundamental spheroidal modes on a fictitious spheroid surrounding a real target. Finally the total response from the target is reproduced using only a few auxiliary magnetic charges. A least square minimization is used for discrimination an unseen object's orientation and position. Numerical results are given and compared with experimental data. [C48]

"Analysis of GPR scattering by multiple subsurface metallic objects to improve UXO discrimination"

Detection and identification of buried unexploded ordinance (UXO) is an emerging problem worldwide. Recent ultra wideband (UWB) field tests between 10s of MHz and 100s of MHz have demonstrated that certain of the target's dimensions can be estimated from analysis of complex natural resonances in the scattered signal. However, the problem becomes much more complicated at highly contaminated UXO sites where clutter items, from which subsurface UXO must be distinguished, appear simultaneously within the field of view of the sensor. This often occurs in realistic field conditions, where GPR discrimination capabilities are typically limited by ground clutter, coupling between antenna and ground, and limited view of the target due to innocuous items. Under extreme shielding by clutter, the incident field cannot excite strong currents on the target and in turn the scattered field from the object cannot easily be separated from the responses of the clutter. To investigate this, we pursue simulations here designed to test subsurface side-looking EM field scattering from multiple buried objects placed in a uniform ground. The numerical calculation is performed using the finite difference time domain (FDTD) method in conjunction with generalized perfectly matched layer GPML. The results are analyzed for a cylinder and plate placed in a uniform ground. [C49]

"Application of TSA formulation for inversion of a metallic object's electromagnetic properties from EMI data"

Estimating electric conductivity σ (S/m) and magnetic permeability μ (F/m) is of great interest both for industry, mineral exploration, and for geophysical discrimination of buried objects such as unexploded ordnance (UXO). We present here a technique for inferring physical parameters of a metallic object in the EMI frequency range (from tens of Hz to several hundred kHz). Electric conductivity and magnetic permeability are inferred by an inversion algorithm operating on inphase and quadrature received components. The forward model is based on the BIE-TSA formulation, which works well over the majority of the EMI frequency range, especially for magnetic material. The formulation is organized so that most matrices related to object geometry need only be calculated once and the Jacobian matrix can be constructed easily from these matrices. Therefore, both forward solution and Jacobian matrix can be calculated quickly. For material with high magnetic permeability, forward solutions indicate that the scattered field is mostly only sensitive to the ratio of σ and μ. In this case the inversion algorithm becomes ill conditioned and some kind of regularization is needed. The performance of the inversion algorithm was studied under different kinds of regularization, via both theoretical analysis and numerical experiments. An optimized method for choosing regularization is suggested which may also benefit more general inverse problems. [C50]

"Combining GPR and EMI data for discrimination of multiple subsurface metallic objects"

Cleanup of subsurface metallic objects such as unexploded ordnance (UXO) constitutes an urgent problem worldwide. The heart of the problem is discrimination, as opposed to detection. Ultra-wideband electromagnetic induction sensors (UWB EMI), operating from a few Hz up to 100s of kHz, have shown considerable promise in subsurface discrimination of metallic objects. Unfortunately, a great many objects, including widespread clutter items, produce very broad, smooth EMI signal patterns, over a number of decades of frequency. Shape identification is complicated by the sensitivity of EMI fields to metal type. UWB ground penetrating radar (GPR) has also shown definite discrimination capability for characterizing subsurface metallic targets. Uninfluenced by metal type, GPR is capable of registering complex natural resonances from which target length can be estimated. Further, examination of the spatial patterns of GPR signals can indicate the (X,Y,Z) locations of

targets, even of multiple targets present simultaneously in the incident beam. In this paper we consider potential collaborative roles of UWB GPR and UWB EMI for discrimination of multiple subsurface metallic objects. Rigorous 3-D FDTD models demonstrate GPR's ability to estimate target positions, orientations, and length even when reflections overlap. These data can then be used to constrain inversion of UWB EMI patterns. Processing of EMI measurements based on prior estimates of object location and orientation successfully extracts distinct frequency response signatures for two very closely spaced objects. [C51]

"Evaluation of approximate analytical solutions for EMI scattering from finite objects of different shapes and properties"

UWB electromagnetic induction (EMI) sensing, from 10s of Hz up to 100s of kHz, is emerging as one of the most promising remote sensing technologies for discrimination of subsurface metallic objects. Progress is urgently needed to distinguish dangerous objects, such as unexploded ordnance, from innocuous clutter. Development of EMI signal calibration, interpretation, processing, and inversion have all been impeded by the lack of rigorous, reliable analytical solutions for any scatterer shape other than the sphere. Here we test a number of new approximate solutions and determine that most canonical geometries and common, homogeneous material compositions can be treated adequately by the simple formulations proposed. [C52]

"Treatment of broadband and multi-object electromagnetic induction scattering using high frequency approximations"

Wideband electromagnetic induction (EMI) sensing shows increasing capability and promise for characterizing subsurface metallic objects, such as UXO. While EMI has some advantages over radar, such as superior penetration of moist soil, the field problem is still difficult due to the frequent occurrence of multiple targets in close proximity. The numerical modeling problem, even for a single object, is complicated by the fact that transmitted ("primary") fields typically penetrate the target, but will often only do so slightly. In most of the established numerical treatments, the scale of discretization is dominated either by the dimensions of the thin subsurface layer of electrical activity, or, more or less equivalently, by the range over which a Green's function decays, based on the characteristics of the metal. Resolution at this scale is often computationally prohibitive, particularly for magnetic materials, even though external fields of interest have only mild gradients. We approach the problem using the Thin Skin Depth Approximation (TSA). The TSA assumes an exponential form for the internal normal magnetic field component, as a function of distance inwards from the object surface. Despite the fact that it is designed to treat a state of affairs characteristic of relatively high EMI frequencies, results based on the TSA turn out to be accurate across the entire EMI band when the relative permeability of the scatterer material is high (e.g. as for steel). [C53]

"Application of broadband EMI responses to infer buried object's aspect ratio"

A new broadband electromagnetic (EMI) sensor, operating as lows as 10s of Hz and as high as 100s of kHz, has shown significant improvement for classification of buried metallic objects. EMI responses ("secondary" or scattered magnetic field) are characterized by two components, one inphase and another in phase quadrature with the primary field. Numerical and experimental investigations show that the frequency location of the quadrature peak in EMI scattered fields from metallic objects depends strongly on the major axis length ratio and on the object's orientation relative to the transmitted field. To illustrate potentially useful processing of EMI sensor data, this paper presents results of high fidelity numerical simulations to verify a theory for simple estimation of an object's aspect ratio based on the frequency location of the quadrature peak (permeable case). Results are shown for a permeable cylinder and spheroid. [C54]

"Model-based statistical sensor fusion for unexploded ordnance detection"

Detection and remediation of unexploded ordnance (UXO) represents a major challenge on closed, closing, and transferred military ranges as well as on active installations. The detection problem is exacerbated by the fact that on sites contaminated with UXO, extensive surface and sub-surface clutter and shrapnel is also present. Traditional methods used for UXO remediation have difficulty distinguishing buried UXO from these anthropic clutter items as well as from naturally occurring magnetic geologic noise, and thus incur prohibitively high false alarm rates. The reduction of the false alarm rate has proven to be the greatest challenge for UXO remediation. In this paper, sensor fusion techniques are applied to field data from magnetometer and electromagnetic induction (EMI) sensors in order to determine to what degree such an approach results in false alarm mitigation. The adoption of a model consisting of multiple non-colocated dipoles is shown to improve our ability to predict measured signatures. The results indicate that performance can be improved by limiting the processing bandwidth to those frequencies that are the most robust to naturally occurring geological noise. [C55]

"A numerical study of the effects of realistic GPR antennas on the scattering characteristics from unexploded ordnances"

The detection and classification of unexploded ordnances (UXOs) is a difficult task, and it is even further complicated by the fact that the ground penetrating radar (GPR) antenna can significantly distort the scattering signal from the UXO. We consider the model of the real antenna which will be used in the numerical study of scattering from UXOs. We consider a rigorous finite difference time domain (FDTD) model of a fully polarimetric horn-fed bowtie (HFB) antenna and study how various modifications of the parameters of the antenna can affect it performance. [C56]

"Wavelet based UXO detection"

The detection and classification of unexploded ordnance (UXO) is considered a multidimensional pattern recognition problem. Standard techniques in solving multidimensional detection and classification problems involve using large sets of templates or libraries. This paper shows that by using wavelet transformation a single library will allow a particular class of ordnance to be classified over a range of depths. [C57]

"Testing of an EM induction platform for UXO discrimination on a seeded site with real exploded shell fragment clutter"

We present the analysis results of EM induction sensor data collected on a live ordnance site. The site was a practice firing range for 105-mm, 155-mm, and 8-inch projectiles. Because of the low density of unexploded rounds, a test area was set up where inert rounds were seeded in an area of exploded clutter. Individual anomaly signatures are fitted to a simple induced dipole response model based on each compact metallic object being characterized by three orthogonal magnetic polarization coefficients along the object's axes of symmetry. We find that a high degree of discrimination between the intact rounds and clusters of exploded fragments is possible based on these model parameters. However, the fit results quickly degrade for anomalies with low signal to noise. [C58]

"Advanced classification of buried UXO using a broadband, fully polarimetric ground penetrating radar"

A broadband, fully polarimetric ground penetrating radar (GPR) system has been applied for classification of buried unexploded ordnance (UXO) for the past few years. It utilizes both late-time and early-time signatures extracted from GPR data collected with multiple antenna positions and multiple scan orientations. Various field measurements were conducted from 1999 to 2001 at UXO sites that have quite different environmental conditions. Lessons learned from these tests have led to significant system improvements. [C59]

"A cluster-based geophysical template matching system"

There has been increased interest in the use of sensing devices in the detection and classification of subsurface objects, particularly for the purpose of eradicating Unexploded Ordnance (UXO) from military sites. The Geophysical Template Matching System (GTMS) is a cluster-based framework for the storage and analysis of spatial data sets derived from scanning subsurface objects using geophysical sensing devices. Current approaches to the UXO detection and classification problem have met with limited success. The template matching approach employs libraries of templates extracted from known objects. Coarse grain parallel processing techniques are used to speed up the matching algorithms with fine grain parallelism also planned. The user interface is via the World Wide Web providing interaction, a graphical user interface and convenient access from remote locations [C60]

"Magnetoquasistatic response of a distribution of small conducting and permeable objects"

The authors study the magnetoquasistatic response of a collection of small conducting and permeable objects. In the formulation each individual object is characterized by its complex magnetic polarizability tensor which gives the dipolar response to a locally uniform exciting magnetic field including diffusion effects. Taking mutual interactions into account, a linear system of equations is solved for the vector dipole moments induced in the objects. Thus the total electromagnetic induction (EMI) response of the collection of objects is obtained, and the significance of mutual interaction and the influence of spatial distribution and varying parameters of the objects can be studied [C61]

"Electromagnetic scattering characteristics of UXO and non-UXO objects in the presence of a water table"

An investigation of the scattering characteristics of a typical UXO target versus similar non-UXO targets is done. This investigation will be done with a computer code based on the finite difference time domain (FDTD) method. Initially, comparisons are made based on targets in free space excited by a plane wave. Then more realistic features are systematically incorporated into the model to determine their effects on the scattering characteristics of the UXO. First, the plane wave excitation is replaced by a dipole. Next, the UXO is embedded in a lossy half space with realistic ground conductivity and permittivity parameters. Finally, a water table is placed underneath the UXO [C62]

"Impact of interfacial dipole radiation on UXO target detection using 3-D Kirchhoff imaging"

Ground penetrating radar radiation patterns are shown to effect array results on locating, and characterizing buried targets similar to those found in many unexploded ordnance scenarios. This is accomplished by comparing results obtained from physical experiments with theoretical dipole radiation patterns. Their experimental data uses 1.2 GHz mono-static resistively tapered dipole antennas precisely positioned in course rectangular grid over a 2- by 2by 1-m dirt filled box. The dirt fill is a silty river bank sand with a relative dielectric of 8.1. It contains a large number rocky inclusions. Buried at various depths are spherical and cylindrical bodies representing UXO and antipersonnel mines. These targers are a combination penetrable dielectric bodies and foil covered perfect reflectors. Their diameters range from 3 cm to roughly 7 cm. They apply mono-static 3D Kirchhoff migration to the data. Their results show that low contrast near surface targets including air filled, plastic, and metal targets can be resolved both vertically and horizontally when array coverage considers the dipole radiation pattern. Deeper cylindrical targets are also observed just above a bottom layer interface. Results from the deeper targets are less affected by individual antenna orientations [C63]

"Numerical modeling of scattering from targets with small but non-negligible skin depths"

In the urgent quest for adequate discrimination of metallic targets such as unexploded ordnance (UXO), considerable progress is being made by resorting to the electromagnetic induction (EMI) frequency range, between about 100 Hz and 300 kHz. In this frequency range, the fields may penetrate the metal target to some significant degree. Thus the authors must model electromagnetic activity within the target as well, complicated by the fact that penetration of the target will be very slight, though non-negligible, over much of the relevant parameter range. It is often grossly impractical to discretize the entire surface or volume of a target in space increments corresponding to this scale of electromagnetic activity. To deal with this problem they retain a simple integral equation formulation in scalar potential for the region outside the target, applying ·H=0 within the target and bringing to bear an approximation reflecting the particular nature of the fields within the shallow layer below the target surface. Examination of analytical solutions for simple geometrical shapes shows the utility of the method. They also show scaling or similarity relations that apply in the limiting case of negligible penetration of the target [C64]

"Discriminating capabilities of multifrequency EMI data"

An object, made partly or wholly of metals, has a distinct combination of electrical conductivity, magnetic permeability, and geometrical shape and size. When the object is exposed to a low-frequency electromagnetic field, it produces a secondary magnetic field. By measuring the broadband spectrum of the secondary field, the authors obtain a distinct spectral signature that may uniquely identify the object. Based on the response spectrum, they attempt to “fingerprint” the object. This is the basic concept of electromagnetic induction spectroscopy (EMIS). From numerous surveys that they have conducted using our multifrequency electromagnetic sensors (GEM-2 and GEM-3), they have accumulated significant evidence that a metallic object undergoes continuous changes in response as the transmitter frequency changes. These observations made over many UXO targets suggest strongly that the EMI anomaly measured in a broad band offers an ability to both detect and identify a target. The frequency-dependent structure of the difference was also reproducible and consistent over a range of depths. These experiments have established that the GEM-3 is capable of delivering broadband EMT data with ample target-specific information content for the purpose of target classification and identification [C65]

"Performance bounds for target identification using decay rates estimates from EMI measurements"

Decay rate estimation has been proposed as an effective method for landmine and unexploded ordnance (UXO) detection. The physical basis for this strategy is that every object in the target library possesses a unique set of decay rates. In theory, the characteristic decay rates can be estimated from the measured electromagnetic induction (EMI) response, and then utilized for target detection and subsequent identification. Unfortunately, decay rate estimation is notoriously difficult and this difficulty adversely impacts target identification performance.

Since the basis for this approach to target detection and identification is that targets are uniquely characterized by their decay rates, discrimination performance is dependent upon decay rate estimation performance. The Cramer-Rao lower bound (CRLB) for decay rate and amplitude coefficient estimates is utilized to investigate the fundamental limitations on target identification via decay rate estimation. It is shown how both the temporal sampling strategy and the number of poles being estimated affects pole estimation and target identification performance [C66]

"Results of synthetic aperture sonar experiments"

Results are presented from synthetic aperture sonar (SAS) experiments with three different test systems: one oriented toward mine detection; one toward buried UXO detection; and one toward buried cable detection. The first two systems share hydrophone arrays of 32-10-cm long elements. Results are presented that demonstrate key features of SAS images: azimuth resolution independent of range, grating lobe suppression by spatial sampling, synthetic filling of sparse array, and seafloor elevation from interferometric SAS. Results demonstrate resolutions of 10 to 20 cm at ranges up to 1000 m. Interferometric results compare SAS bathymetry and multi-beam echo sounder bathymetry [C67]

"Improving detection of low-metallic content landmines using EMI data"

EMI, or metal detector, sensors are used extensively to detect landmines. There is often a significant amount of metallic clutter present in the environment, thus EMI sensors that utilize traditional detection algorithms based solely on metal content suffer from large false alarm rates. The focus of this paper is on performance improvements that have been obtained using Bayesian-based statistical algorithms designed to detect low-metallic content landmines in highly cluttered environments. The Joint UXO Coordination Office (JUXOCO) is sponsoring a series of experiments designed to establish a performance baseline for a variety of sensors for the problem of detecting low-metallic content mines. Algorithm developers are blind to the ground truth. This paper describes the results of several experiments performed in conjunction with this effort. Statistical algorithms have been applied specifically to the problem of detection of low-metal mines, and dramatic performance improvements have been observed with respect of the baseline performance. The tradeoffs associated with the amount of spatial information used as well as the incorporation of prior information are explored, along with the performance of alternative approaches. Approaches to classification of the mine-type are also discussed and the performance of such classifiers is presented [C68]

"UWB full-polarimetric horn-fed bow-tie GPR antenna for buried unexploded ordnance (UXO) discrimination"

A novel broad bandwidth dual-polarization GPR antenna was also developed for collecting fully polarimetric data over a wide frequency range (20 MHz-800 MHz). This new design was improved from its single-polarization version, dielectric-loaded horn-fed bow-tie (HFB) antenna, introduced by Chen (1997). The new design features improved stability and directivity over conventional surface-based GPR antennas. Such antenna is currently applied to discriminate buried UXOs from other false alarm reduction [C69]

"Ramp response signatures for UXOs"

Previously, the ramp response has been used to provide images of missile targets for plane wave incidence in free space, which requires multiple incidence angles. Obviously, this is not feasible for buried targets such as unexploded ordnance (UXO); however, a recent development that extends the ramp response into the shadow region of the target has resulted in the generation of scattered fields through the Rayleigh region and beyond, very accurately, S.K. Nag et al. (1999). This same process can be used to generate the length and diameter of UXOs, which has been verified for selected targets in free space. It is observed that this is a unique signature, completely different from those developed from complex natural resonances and consequently supplements them as a signature [C70]

"Matched neural filters for EMI based mine detection"

Remedial mine detection and the detection of unexploded ordnance (UXO) have become very important for humanitarian reasons. This paper addresses mine detection using commonly used electromagnetic induction sensors. We propose and evaluate two neural network approaches to mine detection which provide a robust nonparametric technique, based on training the networks using data from a previously calibrated portion of the minefield, or from a similar minefield. In the first approach, we combine a novel statistic, the S-statistic (which is a real valued variable related to the relative energy difference measured around a point in the minefield) with the δ-technique in a random neural network (RNN) design. In the second approach, a RNN is trained using a 3Ч3 block measurement window, and then applied as a postprocessor for the δ-technique. This RNN has an

unconventional feedforward structure which realizes a matched filter to discriminate between nonmine patterns and mines. Experimental results for both approaches show that the RNN reduces false alarms substantially over the δ-technique and the energy detector [C71]

"Ultra-wideband source research"

Ultra-wideband (UWB) microwave sources and antennas are of interest for a variety of applications such as transient radar, mine detection and unexploded ordnance (UXO) location and identification. Much of the current research is being performed at the Air Force Research Laboratory (AFRL) at Kirtland AFB, NM, USA. The approach to high power source development has included high pressure gas switching, oil switching and solid-state switched arrays. Recent advances in triggered gas switch technology and solid-state-switched shockline technology have opened up new possibilities for the development of much higher power systems and have thus opened the door to many new applications. The research into UWB transient antennas has also made significant contributions to the development and improvement of wideband continuous wave (CW) antenna designs and has brought new knowledge about the complex behavior of ferrites, dielectrics and resistive materials in short pulse, very high voltage environments. This has in turn led to advances in the technology of transformers, transmission lines, insulators and UWB optics. This paper reviews the progress to date along these lines and discusses new areas of research into UWB technology development [C72]

"Fast multipole method for targets above or buried in lossy soil"

We demonstrate the accuracy of the half-space fast multipole method (FMM) by considering two targets: a model unexploded ordnance (UXO) buried under soil and a rectangular box situated above the ground. In both examples, the bistatic radar cross sections (RCS) is computed via the FMM developed here, as well as with a rigorous method of moments (MoM), wherein the half-space Green's function is evaluated rigorously via the method of complex images. The results show an excellent agreement between the FMM and MoM, for co- and cross-polarized RCS. The RAM and CPU requirements of the half-space FMM are about twice to three times compared to the free-space FMM (caused by the extra set of real images and the additional Fourier transforms), but the complexity of N 3/2is unchanged [C73]

"Classification of buried metal objects using wideband frequency-domain electromagnetic induction responses: a comparison of optimal and sub-optimal processors"

Classification of buried metal objects can be important for metal landmine and unexploded ordnance (UXO) detection. Previously, the authors have investigated classification of landmine-like metal objects using wideband frequency-domain electromagnetic induction (EMI). The classification performance of a Bayesian detector that incorporates modeled wideband EMI signatures as well as sensor/target orientation uncertainties was compared to that of a processor reminiscent of a matched filter bank. In this suboptimal, but fairly standard approach, each of the filters is essentially `matched' to the response obtained at the mean position of one of the targets. Both simulated and measured data were considered. The measurements were taken using a prototype wideband frequency-domain EMI sensor, the GEM-3. Dramatic performance improvement was obtained by implementing the optimal classifier. However, the optimal processor is not usable for real-time applications, as it is computationally expensive to perform the integration over the uncertainties associated with the target/sensor orientation. The authors examine the performance of alternative processors whose computational complexity is similar to that of the matched-filter bank, but which take advantage of the physical nature of the wideband EMI response. The wideband frequency-domain response of targets with substantial metal content changes substantially in overall level as the target/sensor orientation changes, but the overall structure of the response as a function of frequency changes only slightly. To exploit this structure in a suboptimal processor, the output of the sensor is normalized prior to processing. Using the normalized and unnormalized data, the optimal classifier performs better than the matched filter classifier. However, the discrepancy between the two is much smaller for the normalized data, indicating that normalization can mitigate the uncertainty associated with the target/sensor orientation. Interestingly, the optimal classifier operating on the normalized data outperforms the optimal classifier operating on the unnormalized data [C74]

"Statistical signal processing techniques for the detection of low-metal landmines using EMI and GPR sensors (Topic area: E.1)"

The Joint UXO Coordination Office (JUXOCO) at Ft. Belvoir, VA is sponsoring a series of experiments designed to establish a performance baseline for a variety of sensors. The purpose of these experiments is to determine if advanced algorithms are useful for detecting low-metallic content mines and if ground penetrating radar (GPR) sensors can help mitigate the high false alarm rates associated with electromagnetic induction (EMI) sensors. In this paper, the authors describe the results of two data collection and algorithm development efforts. One

involves a prototype frequency-domain EMI system; the other involves a prototype wide-band GPR system. In both cases, substantial performance improvements over baseline are achieved using statistically-based signal processing algorithms [C75]

"Mobile Underwater Debris Survey System (MUDSS)"

The Mobile Underwater Debris Survey System (MUDSS) is a technology demonstration program funded by the Strategic Environmental Research and Development Program (SERDP) in the Cleanup thrust area. Its purpose is to demonstrate technologies necessary to successfully survey underwater formerly used defense sites (FUDS) for unexploded ordnance (UXO). The MUDSS concept uses (1) acoustic, magnetic, and electro-optic (EO) minehunting sensor and signal and image processing technologies under development at the Coastal Systems Station (CSS), and (2) sensor fusion, visualization, and trace chemical detection technologies under development at the Jet Propulsion Laboratory (JPL). The MUDSS program includes both a feasibility demonstration in St. Andrew Bay, Panama City, FL, and a technology demonstration in Choctawhatchee Bay, FL, in an area that was expected to contain WW-II UXO. Potential users include the Department of Defense, commercial industries involved in UXO remediation and environmental cleanup, and even archeological site survey activities. MUDSS sensors and technology are presented along with test results from the recent technology demonstration survey conducted in Choctawhatchee Bay, near Eglin Air Force Base, FL [C76]

"Recent advances in unexploded ordnance (UXO) detection using airborne ground penetrating SAR"

A combined team is currently in the process of planning and conducting the largest ever survey at the Former Buckley Field (60,000 acres), in Colorado, by using SRI airborne, ground penetrating, Synthetic Aperture Radar (SAR). The purpose of this survey is the detection of surface and subsurface Unexploded Ordnance (UXO) and in a broader sense the site characterization for identification of contaminated as well as clear areas. In preparation for such a large-scale survey, JPL has been developing advanced algorithms and a high-performance testbed for processing of massive amount of expected SAR data from this site. Two key requirements of this project are the accuracy (in terms of UXO detection) and speed of SAR data processing. The first key feature of this testbed is a large degree of automation and a minimum degree of the need for human perception in the processing to achieve an acceptable processing rate of several hundred acres per day. For accurate UXO detection, novel algorithms have been developed and implemented. These algorithms analyze dual polarized (HH and VV) SAR data They are based on the correlation of HH and VV SAR data and involve a rather large set of parameters for accurate detection of UXO. For each specific site, this set of parameters can be optimized by using ground truth data (i.e., known surface and subsurface UXOs). In this paper, we discuss these algorithms and their successful application for detection of surface and subsurface anti-tank mines by using a data set from Yuma proving Ground [C77]

"Detection and discrimination of landmines and UXO"

We consider the use of electromagnetic sensor measurements for discriminating unexploded ordnance and landmine responses from those due to background noise or clutter. The data stream is potentially very large depending on the time or frequency channels used, the number of receiver elements, and the spatial sampling density. Sensor classification performance will typically improve if the raw input data is reduced to its intrinsic dimensionality. Compression may be achieved in a number of ways but we concentrate on (1) model-based and (2) data-based approaches. In the model-based approach we estimate the model parameters of a physical model that represents the target. Key to this approach is the availability of an accurate and rapid method to compute the electromagnetic scattering from a high contrast and possibly complex-shaped object. We have developed a mean field theory to address this precise need. In the data-based approach we seek the coefficients of an efficient basis set (spanning the dataspace) to represent the original data. We use the so-called best-basis paradigm to discover the optimal wavelet basis. Approach (1) explains the data since it uses a physics-based model to fit the recorded measurements. Approach (2), on the other hand, represents the data in terms of a basis that may or may not have physical significance. The parameters estimated from either approach may then be used to compose a feature vector for input into a conventional classifier that has embedded in it a data bank of parameters for known targets. Each approach has complementary advantages, and it is likely that their joint use is optimal. Finally, an understanding of the discrimination methodology to be used can be coupled into the sensor design process for improved performance [C78]

"Analysis of magnetometer and EMI data for the MTADS program"

The multisensor towed array detection system (MTADS) provides the capability for rapid, efficient detection of buried unexploded ordnance (UXO). The system consists of two arrays of sensors, total-field magnetometers

and time-domain, pulsed-induction sensors, coupled to an extremely precise GPS location system Data collected in the field are transferred to a workstation-based data analysis system for analysis. Anomalies are selected interactively by an operator and fit to a physics-based model. The MTADS has been demonstrated at several prepared rest ranges and two live sites. In all cases, probabilities of detection of greater than 95% have been achieved. The outstanding research issues in this program involve discrimination between UXO and fragments and scrap. Up to two thirds of the costs of a remediation effort result from digging holes that do not contain UXO. Even small improvements in classification ability will lead to large savings in real world operations [C79]

"Summary of the DARPA background clutter data collection experiment"

Most technologies in use or proposed for use to detect landmines and unexploded ordnance (UXO) suffer from unacceptably high false-alarm rates, even at modest probabilities of detection. High false-alarm rates are a consequence of the inability to discriminate real UXO and landmines from man-made and naturally occurring clutter. Experimental data on expected signatures of UXO and landmines have been collected by various sensor developers and research agencies. However, an equivalent characterization of clutter returns has been lacking. As a result, background signatures have not been considered in sensor or algorithm design. The goal of the two-phase, DARPA-sponsored Background Clutter Data Collection Experiment is to begin to fill this void. The first phase, completed during the fall of 1996, consisted of high aerial density site surveys using the following sensor types: magnetometer, infrared electromagnetic induction, and ground-penetrating radar. The second phase, which is currently underway, consists of analysis of the collected sensor data to include excavation of clutter objects. This paper describes the clutter data collection program and provides a cursory summary of the analysis done to date [C80]

"Electromagnetic induction spectroscopy [Cfor landmine & UXO detection]"

An object, made partly or wholly of metals, has a distinct combination of electrical conductivity, magnetic permeability, and geometrical shape and size. When the object is exposed to a low-frequency electromagnetic field, it produces a secondary magnetic field. By measuring the secondary field in a broadband spectrum, we obtain a distinct spectral signature that may uniquely identify the object. Based on the response spectrum, we attempt to “fingerprint” the object. This is the basic concept of Electromagnetic Induction Spectroscopy (EMIS). EMIS technology may be particularly useful for detecting buried landmines and unexploded ordnance. By fully characterizing and identifying an object without excavation, we should be able to reduce significantly the number of false targets. EMIS should be fully applicable to many other problems where target identification and recognition (without intrusive search) are important. For instance, an advanced EMIS device at an airport security gate may be able to recognize a particular weapon by its maker and type [C81]

"Summary of the DARPA background clutter data collection experiment"

Most technologies in use or proposed for use to detect landmines and unexploded ordnance (UXO) suffer from unacceptably high false-alarm rates, even at modest probabilities of detection. High false-alarm rates are a consequence of the inability to discriminate real UXO and landmines from man-made and naturally occurring clutter. Experimental data on expected signatures of UXO and landmines have been collected by various sensor developers and research agencies. However, an equivalent characterization of clutter returns has been lacking. As a result, background signatures have not been considered in sensor or algorithm design. The goal of the two-phase, DARPA-sponsored background clutter data collection experiment is to begin to fill this void. The first phase, completed during the fall of 1996, consisted of high aerial density site surveys using the following sensor types: magnetometer, infrared, electromagnetic induction, and ground-penetrating radar. The second phase, which is currently underway, consists of analysis of the collected sensor data to include excavation of clutter objects. This paper describes the clutter data collection program and provides a cursory summary of the analysis done to date [C82]

"Super-sensitive, real time and wide coverage, all terrain ground robotic and hand held systems for mine and UXO detection and mapping"

This paper describes a demonstration prototype (Dempro) of super sensitive magnetic and GPR all-terrain ground robotic system and its outgrowth designed and developed, for real-time and wide coverage mine & UXO detection and mapping. The Dempro has been tested at various sites containing buried UXO and mines. On March 1997, a limited survey for recovery of AP plastic mines, was carried out near Eilat, the southern Israeli city on the Gulf of Aqaba. The performance of the magnetic array and real time processing algorithm, revealed detection capability of buried objects from plastic low metal antipersonnel mines, specified by its metallic striker of less than 5 gr, buried to a depth of 1 meter, up to 100-1000 kg, air bombs buried to a depth of 7-13 meter, respectively. The real time processing algorithm has discrimination capabilities that reduce the high false positive

alarm rate, induced by mine-like clutter of real ferrous fragments or man-made targets. The most promising derivative of the real time, wide coverage and standoff detection capability is a man-portable gradiometric system for enhanced automatic detection, location and discrimination of buried ferrous objects that does not required professional or special training. Incorporation of the portable standoff gradiometric system and the remotely driven vehicle, offers a cost effective solution for humanitarian demining [C83]

"Prodding to detect mines: a technique with a future"

The advantage of `close-in' detection, requiring transducers to be actually introduced into the soil covering a landmine, has been argued. Experiments with mechanically assisted rotating prodders shows that they can penetrate even very hard dry soils at low force and high speed, provided the soils are homogeneous. The speed of penetration is roughly proportional to the speed of rotation of the prodder up to very high values around 20000 rpm. Less homogeneous soils, e.g. those containing gravel, can also be penetrated at speed provided a more brush-like tool is used. Simple smart prodders, with low power consumption and a well-designed user interface, can offer a significant improvement in the quantity of information available to a deminer who is attempting to discriminate between a mine and other objects [C84]

"Applying system identification and neural networks to the efficient discrimination of unexploded ordnance"

This paper describes system identification and neural network methods which, when applied to simulated noisy radar returns from unexploded ordnance (UXO), result in significantly better performance than more traditional methods. The methods are applicable to wideband ground penetrating radar (GPR) waveforms. The target set consists of a conducting cone and cylinder of similar dimensions. The classification is based on features derived by the singularity expansion method [C85]

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