Requirements for Unexploded Ordnance Detection and Discrimination in the Marine Environment Using Magnetic and Electromagnetic Sensors

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Abstract- **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.**

I. Introduction

The topic of marine UXO mapping is becoming one of the most significant technology challenges of environmental characterization and remediation. Magnetic and EMI methods represent the main sensor types used for detection of UXO in the terrestrial realm and are the most logical choice for detection of obscured munitions. Over the past 10 years, significant research effort has been focused on developing methods to discriminate between hazardous UXO and non-hazardous scrap metal, shrapnel and geology [1-6]. The most promising discrimination methods typically proceed by first recovering a set of parameters that specify a physics-based model of the object being interrogated. For example, in time-domain electromagnetic (TEM) data, the parameters comprise the object location and the polarization tensor (typically two or three collocated orthogonal dipoles along with their orientation and some parameterization of the time-decay curve). For magnetics, the physics based model is generally a static magnetic dipole. Once the parameters are recovered by inversion, a subset of the parameters is used as feature vectors to guide either a statistical or rule-based classifier.

Magnetic and EMI phenomenologies have different strengths and weaknesses. Magnetic data are simpler to collect, are mostly immune to sensor orientation and are better able to detect deeper targets. EMI data are sensitive to non-ferrous metals, are better at detecting smaller items and are able to be used in areas with magnetic geology. Therefore, there are significant advantages in collecting both types of data including increased detection, stabilization of the EM inversions by cooperative inversion of the magnetics [7] and added features that may improve classification performance [5]. However, these advantages need to be weighed against the extra costs of collecting both data types.

Within the marine environment, current deployment modes place sensors 1 to 2 m above the sea floor, restricting detection capabilities, equivalent to that of airborne platforms in terrestrial applications. This increased stand-off distance particularly militates against the use of EMI technologies due to the more rapid fall-off of signal with distance compared to magnetometry.

Magnetic sensors have long been deployed in the marine environment for mine-counter measures where they are usually used to confirm contacts identified by acoustic sensors [8]. Several magnetic detection systems have been deployed for marine UXO detection purposes including the Marine Towed Array with eight cesium-vapor magnetometers [9], and the Mobile Underwater Debris Survey System [10] with a low-temperature gradiometer. A high-temperature superconducting tensor gradiometer (HTSTG) that aims to improve stand-off detection performance of magnetic sensor systems is currently under development [11, 12]. EMI sensors that have been deployed underwater include modified versions of the Geophex GEM-3 [13] and the Geonics EM-61 and EM-68 sensors (e.g. [9]).

Geophysicists typically understand the data requirements for effective detection and discrimination of UXO in the marine environment but often struggle with the marine engineering required to effectively meet these data quality requirements in a wide variety of marine environments. For marine engineers the situation is reversed. In this paper we aim to educate marine engineers on the data quality requirements for effective marine UXO detection and discrimination. We do not provide an exhaustive list of data quality requirements but instead focus on the concepts and important factors that need to be kept in mind.

II. MAGNETOMETERS

A. *General Considerations*

The principle of magnetic UXO detection is that buried steel ordnance cause a distortion in the Earth's magnetic field

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that can be measured by a magnetometer. However, magnetic anomalies also arise from other ferrous munitions debris and cultural scrap in an area, as well as from geological variations in ferromagnetic minerals. The problem is to come up with a diagnostic feature of the magnetic anomaly of a UXO that will allow it to be distinguished from these clutter items. Ideally, we would like to be able to recover the shape and size of the anomaly's source and use that information for discrimination. However, there is a fundamental ambiguity in magnetics, whereby, for instance, any magnetic anomaly can be represented by an equivalent layer of susceptibility [14]. Consequently, target size and shape cannot be uniquely determined from magnetics data.

At distances of a couple of body lengths from an ordnance item the magnetic field **B** from the object is almost entirely dipolar and the only information that can be extracted about the object is a magnetic dipole moment **m** and an estimated location. The equation for a dipole is

$$\mathbf{B}(\mathbf{r}) = \frac{\mu_O}{4\pi r^3}\left(3(\mathbf{m}\cdot\hat{\mathbf{r}})\hat{\mathbf{r}} - \mathbf{m}\right) \qquad (1)$$

where **m** is the dipole moment, **r** is the vector between the dipole and observation location, $\hat{\mathbf{r}}$ the corresponding unit vector, r the distance and $\mu_0 = 4\pi \times 10^{-7}$ H/m is the permittivity of free space. The magnetic moment of a buried ordnance item arises from a combination of induced and remanent magnetization. The induced magnetization is caused by the Earth's magnetic field and the strength and orientation of the induced dipole is a function of the size, shape and orientation of the ordnance item. There is a fundamental ambiguity whereby the induced magnetization of an item of a given shape and size can be reproduced by an infinite number of different shaped items at different orientations relative to the Earth's field. Remanent magnetization, which is any magnetization remaining from the past magnetic history of the ordnance item, further complicates matters because it can change the dipole moment of a given ordnance in an unpredictable manner. During impact most remanent magnetization is erased via shock demagnetization [15] and at terrestrial sites methods that exploit this effect have been quite successful [6].

At marine sites the impact experienced by a projectile that does not explode will be quite different to that experienced at terrestrial sites. In addition, many items found in the marine environment were never fired and were simply dumped over the side of ships. Thus, there is no guarantee that remanent magnetization will be small. Discrimination approaches thus have to be restricted to methods that rank dig-sheet order based on the magnitude of the dipole moment. This procedure has been used quite successfully at a number of terrestrial sites (e.g. [16]), but its effectiveness diminishes as the size of the ordnance decreases.

Detection of individual UXO targets is a function of the signal-to-noise ratio (S/N) of the magnetic response. The signal amplitude is extrinsic to the sensors and is a function of UXO size, orientation and offset distance. The noise seen by

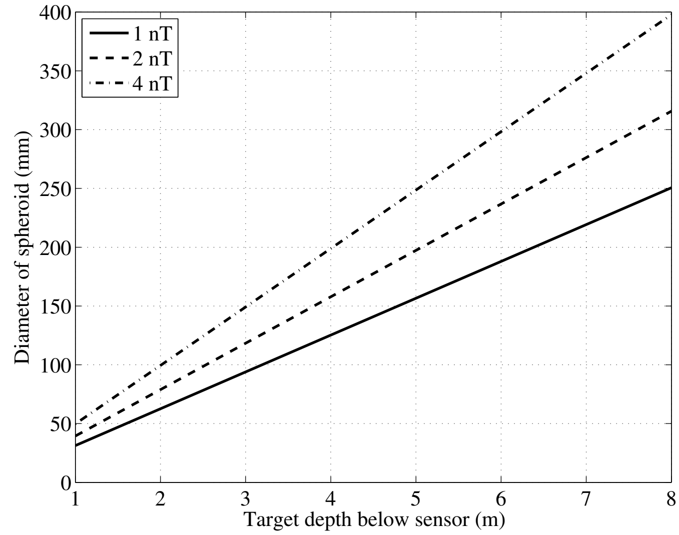

Figure 1. Marine survey planning tool showing minimum detected size as a function of sensor offset distance. The detection threshold is dictated by local magnetic conditions and survey altitude is dictated by site bathymetric and vegetation conditions. A prolate spheroid model with an aspect ratio of 3.5 was used to model the ordnance [17] and it was assumed to be in a "worst-case" orientation: long axis perpendicular to the ambient field.

a magnetic sensor is due to a combination of intrinsic noise sources (sensor noise floor, magnetic noise from platform etc) and extrinsic factors such as local geology and/or anthropogenic clutter. At terrestrial sites this extrinsic noise is highly variable and ranges from less than 1 nT at some sites to several tens of nT at other sites (or even parts of the same site). Given knowledge of local magnetic conditions and survey altitude limitations, we can predict the efficacy of the system for detection of various sized UXO targets. In Figure 1 we show a series of graphs plotting nominal UXO caliber versus survey altitude for given detection thresholds. The latter is defined as the magnitude of the difference between the positive and negative lobes of the dipolar anomaly at the specified stand-off distance. This graph applies to the "worst-case" orientation, which has the long axis of the UXO oriented perpendicular to the ambient magnetic field. In this orientation, there is a large self-demagnetizing field which causes a large decrease in the net magnetization of the item. When the UXO is oriented with its long axis along the ambient field direction ("best-case" orientation), the self-demagnetizing field is smaller and the resulting net magnetization is larger (typically by a factor of five).

From Fig 1. it is apparent that a primary requirements for good detection performance is maintaining a close stand-off distance from the sea-bottom, preferably within 50 cm. For passive magnetometers, signal strength falls off at $1/r^3$ for fields and $1/r^4$ for gradients. Most current deployment modes (except for bottom dragging systems) place sensors 1 to 2 m above the sea floor, restricting detection capabilities, equivalent to that of airborne platforms in terrestrial applications. Optically pumped cesium vapor magnetometers are the most commonly used magnetic sensor and provide a scalar measurement of the total-magnetic field. For detection and characterization purposes a magnetic field "map" needs to be produced and this is typically achieved by deploying arrays of sensors and collecting data along closely spaced transects (e.g. Fig. 2). Inaccuracies in the estimated position of the sensors distort the magnetic map and complicate interpretation and discrimination. As a rough rule of thumb magnetic sensor data needs to be positioned at better than 25% of the sensor offset distance (e.g. better than 25 cm accuracy at 1.0 m standoff): more accurate positioning is desirable but these larger errors can generally be tolerated. As the sensor to object distance increases so does the spatial extent of the magnetic anomaly. This can result in significant overlap of the anomalies from adjacent objects which further complicate the interpretation of the data. As the sensor standoff increases it becomes increasingly difficult to distinguish the anomalies caused by discrete metallic objects from variations in magnetite and other magnetic minerals in the rocks and sediments on the sea-bottom. Analysis in [18] indicates that a sensor spacing of half the stand-off distance ensures full-sampling of the magnetic field.

The HTSTG under development in [11, 12] may obviate the need for dense mapping, as each measurement provides a rich degree of information about any ferrous targets in the near vicinity of the sensor. Detection, localization and characterization can, in principle, be achieved with a few points along each profile [11]. The extremely low-noise floor of SQUIDs, combined with the coherent noise rejection abilities of gradiometers result in a system with minimal intrinsic noise and may allow good detection performance to be achieved at larger stand-off distances. It must be kept in mind that the gradient signal from an object falls off at one extra power of r compared to the magnetic field. In addition, significant spatial variations in the magnetic content of rocks and sediments can limit the effectiveness of the HTSTG system. Lastly, all previous comments regarding the paucity of information that can be obtained and used for discrimination still apply.

B. *Specific issues encountered in the marine environment*

Seawater has a nominal conductivity of 4 S/m, with the potential for significantly lower or higher values depending on the specific marine environment. The conductive seawater does not affect the magnitude and spatial variation of the magnetic field, but it does contribute an extra potential noise source and adds a couple of complicating factors during platform compensation interpretation of measurements.

Mobile magnetic survey data are affected by the fields and gradients produced by the sensor platform as it manoeuvres in the geomagnetic field. Removal of mobile platform effects is a procedure known as compensation. Compensation can be active or passive. Active compensation involves coil sets, controlled by feedback electronics that cancel platform effects at the sensor in real time. Passive compensation is accomplished by software that calculates the platform effects continuously and removes them from the measured data. For underwater surveys, there is the additional magnetic noise created by the passage of the sensor platform through the conductive saltwater.

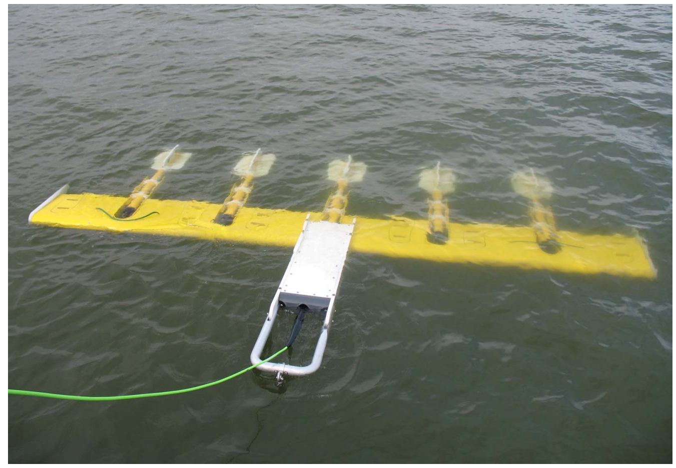

Figure 2. Marine magnetometer array with 5 total-field magnetometers spaced 1.0 m apart that has been deployed by Sky Research for underwater UXO detection.

In salt water environments, wave motion of the conductive medium in the geomagnetic field produces eddy currents that can be a significant source of magnetic field noise in the 0.1 – 1 Hz range for both total field and vector field component measurements [11, 19]. At 20 m depth, waves with a frequency of 0.25 Hz produce oscillating fields of amplitude up to a maximum of ~25 pT.

As explored by [11] uniform current flow around an ellipsoid cavity will leave the magnetic field at the centre of the cavity unchanged but can distort the magnetic gradient tensor.

C. *Summary of requirements*

The following summarize the considerations and requirements for detection and discrimination of ordnance using magnetic sensors:

1) Sensor height and detection: Detection performance drops off rapidly with increasing height. Specific height requirements will depend on the minimum size object of interest, intrinsic noise of the platform and sensor and any extrinsic noise sources. Given knowledge of these issues, for total-field sensors Fig 1. can be used to select the required stand-off distance.

2) Sensor height and interpretation: A sensor spacing of no greater than half the stand-off distance is required for full sampling. Anomalies increasingly overlap and interpretation becomes more difficult as stand-off increases.

3) Relative positioning accuracy: For creating a map using total-field sensors, relative positioning needs to be better than 25% of the stand-off distance. For the HTSTG sensors this position requirement is relaxed considerably.

4) Discrimination potential: Fundamental ambiguities in the interpretation of magnetic data, coupled with the unknown strength and orientation of any remanent magnetization mean that only a rough size estimate based on the magnitude of the dipole moment can typically be obtained.

5) Geological limits to performance: Variations in the magnetic mineral content of rocks and soils can limit detection ability and if sufficiently severe can render magnetics unusable.

6) Effects of sea-water: Can result in an increase in noise due to wave-motion, can complicate platform compensation and can distort magnetic gradient measurements.

III. ELECTROMAGNETICS

A. General Considerations

In the terrestrial realm, EMI sensors have proven to be better able to detect and discriminate hazardous UXO from non-hazardous shrapnel, range and cultural debris. For active EMI sensors, the fall-off varies from about $1/r^4$ at distances comparable to the loop size and approaches $1/r^6$ in the far-field: thus stand-off distance requirements are more stringent for EMI sensors compared to magnetometry. For discrimination, terrestrial tests of EMI systems have demonstrated that discrimination works best when sensors are deployed in a static cued interrogation mode and when the underlying object is interrogated from multiple different incident field directions. When data are collected from moving platforms, positioning errors on the order of several centimetres can significantly degrade discrimination performance. Positioning in the marine environment is more difficult than on land, and without the development of new positioning techniques it is unlikely that the sensors can be positioned at better than 10 cm accuracy. Thus for effective deployment in the marine environment a sensor system must attempt to excite the object from multiple directions when passing over it, so that data from adjacent traverses do not need to be combined.

We now expand on each of these points in turn, starting with detection as a function of sensor height. Due to the wide-range of possible configurations of transmitters and receivers it's not possible to produce a generic detectability graph as was done for magnetics in Fig 1. Instead in Fig 3. we provide some examples of signal level versus standoff distance for the second time-channel of the Geonics EM61 metal detector. The EM61-MK2 is a pulse-based time domain electromagnetic instrument that records data in four time-windows centered at 0.216, 0.366, 0.660 and 1.266 milliseconds after pulse turn-off (e.g. Bosnar, M., 2001, Geonics Ltd. Tech. Note, TN-33). The response for a vertical projectile (most favorable orientation) is considerably stronger than the response for a horizontal projectile (least favorable orientation). The signal response dies off rapidly with distance from the sensor. Once the distance is larger than the longest dimension of the transmitter, both the transmit and received secondary field are dipolar. The signal thus falls of a $1/r^6$. This means that a 64 fold increase in SNR is required to double the detection depth: this compares to magnetometry where an 8 fold increase is required for fields and 16 fold increase for gradients. The key consideration is that EM sensors cannot tolerate significant stand-off distances.

For UXO discrimination a polarization tensor model is usually fit to the observed EMI data with

$$B(\mathbf{r},t) = \frac{\mu_o}{4\pi r^3}\left(3(\mathbf{m}(t)\cdot\hat{\mathbf{r}})\hat{\mathbf{r}} - \mathbf{m}(t)\right) \quad (2)$$

where all terms were defined in (1) but now the dipole moment has a time-dependence:

$$\mathbf{m}(t) = \frac{1}{\mu_o}\mathbf{M}(t)\cdot\mathbf{B}_p \quad (3)$$

is the induced dipole moment, $\mathbf{B}_p$ is the primary magnetic field at the object location and $\mathbf{M}(t)$ is the target's polarization tensor [3, 21, 22]. The polarization tensor governs the decay characteristics of the buried target and is a function of the shape, size, and material properties of the target (and in this formulation includes the convolution effect of the transmitter waveform). The polarization tensor is written as

$$\mathbf{M}(t) = \mathbf{A}^T \begin{bmatrix} L_1(t) & 0 & 0 \\ 0 & L_2(t) & 0 \\ 0 & 0 & L_3(t) \end{bmatrix} \mathbf{A} \quad (4)$$

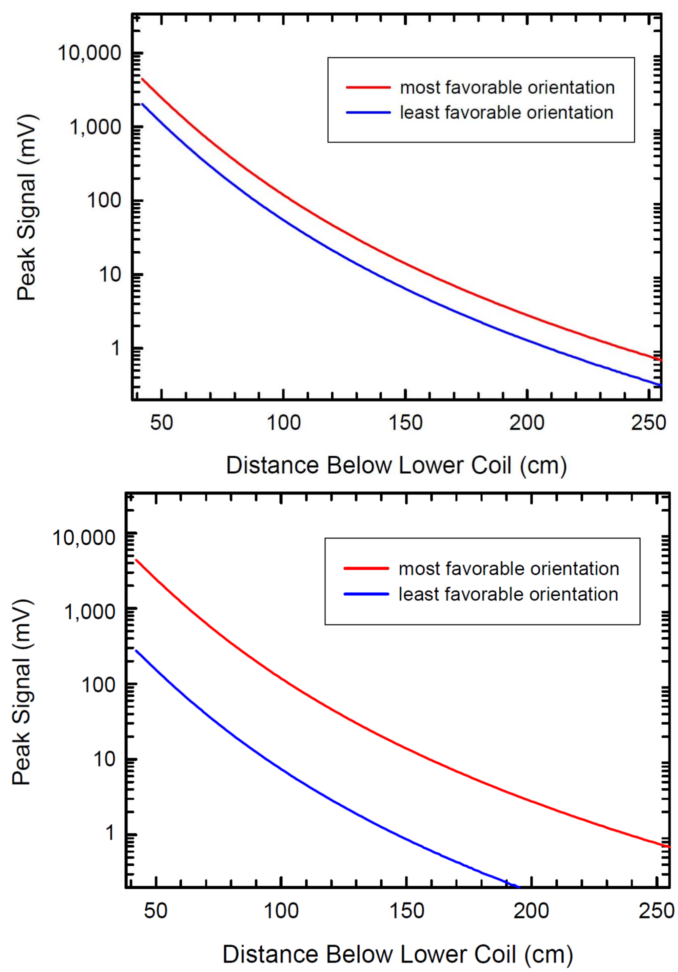

Figure 3. Maximum amplitude in time-channel 2 of a Geonics EM61 metal detector as a function of distance below the coil for two ordnance types: 105 mm projectile (top) and 2.36" rocket. Figures reproduced from [20].

where **A** is the Euler rotation matrix that rotates earth-centered coordinates to object centered coordinates and we use the convention that $L_1(t_1) \geq L_2(t_1) \geq L_3(t_1)$.

Once model parameters are estimated from sensor data, they are used to define features to be input into statistical classification algorithms. Examples of such features include the magnitude of the polarizabilities and the rate of time decay. The features form the basis vectors of a model or feature space and each target in a data set is a point in an N-dimensional space. Rule-based classifiers use relationships derived from the underlying physics to partition the feature space (e.g the ratio of TEM decay parameters [3]). For statistical classification, the goal is to partition the feature space using prior knowledge of class distributions obtained from a training data set for which ground truth is available. There are two common (and sometimes equivalent) approaches to partitioning the feature space. The *generative approach* models the underlying probability distributions which are assumed to have produced the observed feature data. Examples of generative approaches include Generalized Maximum Likelihood and Probabilistic Neural Networks [1, 2, 4]. The *discriminative approach* is not concerned with underlying distributions but rather seeks to identify decision boundaries which provide an optimal separation of classes. Here optimality can be defined by minimizing the probability of misclassifying a new feature vector. Support Vector Machines [4, 5].are a commonly-used generative algorithm.

An example [23] of applying the statistical classification approach to some EMI data is shown in Fig 4. The data were collected at San Luis Obispo, CA, in a cued-interrogation mode (where the sensor revisits anomalies flagged in a previous survey) by the MetalMapper sensor. This sensor has three orthogonal transmitters and multiple three component receivers and is able to stimulate and measure all components of a buried object's polarizability. Items expected to be found at the site included 60 mm, 81 mm and 4.2" mortars along with 2.36 rockets. A feature space comprising a size and a time-decay feature was found to provide good separation between the ordnance and clutter on about 200 items used for training (Fig 4a.). Predictions of UXO likelihood were made on 1409 items in the test-data (items where we didn't know the ground-truth) and resulted in a recommendation to excavate 368 anomalies. These comprised 202 of 203 UXO found at the site (the one missed item was an unexpected 37 mm projectile) and 166 clutter items. By using discrimination methods all but one UXO item were found after digging just 13.8% of the 1205 clutter items at the site.

The relatively clear separation between UXO and non-UXO classes evident in Fig. 4 is a consequence of the quality of the data collected by MetalMapper. As mentioned in the previous paragraph the three orthogonal transmitters ensure that all components of the polarizability are excited. Collecting data while stationary allows SNR to be maximized by stacking and ensures that there is no error in the relative positions of the transmitters and receivers. Whether this is a feasible

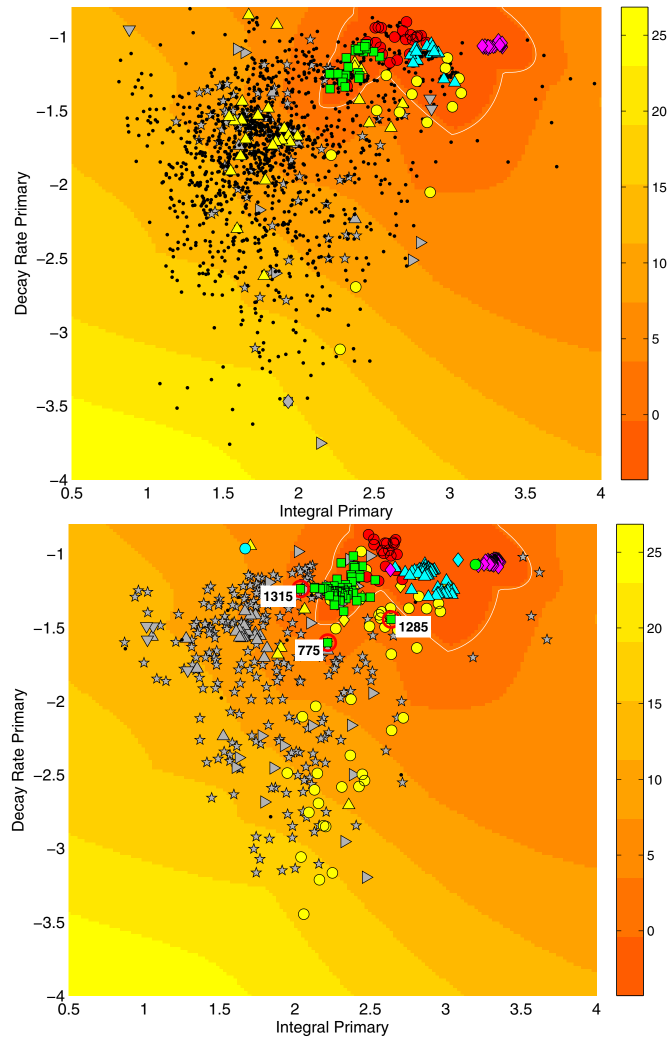

Figure 4. Example application of discrimination at a Terrestrial site (San Luis Obispo, CA) using the MetalMapper sensor. Top: Training data feature vectors (unlabelled test data are shown as black dots). Bottom: Test data feature vectors. Both plots have the decision surface overlain with higher values indicating decreasing UXO likelihood.

alternative for the marine environment remains to be seen. Survey efficiency considerations lead us to prefer to deploy a sensor in a constantly moving mode so that productivity could be maximized. Terrestrial tests of EMI systems have demonstrated the need for accurate sensor positioning (on the order of a centimetre) and orientation (on the order of a degree) for discrimination to be successful using similar methods to those used in Fig. 4. Positioning in the marine environment is more difficult than on land, and without the development of new positioning techniques it's unlikely that the sensors can be consistently positioned at better than 10 cm accuracy. There are two alternatives for achieving discrimination success underwater. The first is to use discrimination methods that do not rely on fitting polarization tensor models to the data. An example would be the use of decay curve information to reject thin-walled scrap and small items from consideration. The second option is to attempt to excite the object from multiple directions when passing over it, so that data from adjacent traverses don't need to be combined. These adjacent passes would, most likely, have a large positional error relative to the first pass. In contrast, a one or two second sequence of measurements in an array would be accurately positioned relative to each other.

B. Specific issues encountered in the marine environment

From the perspective of EMI data, the most significant difference between the underwater and land based environments is the presence of a conductive host as a result of submersing the EMI sensor in water. Water conductivity can range from resistive (in the nearly pure water case) to conductivities greater than 5 S/m for salt water environments. The conductivity of seawater is governed mainly by salinity and temperature. Due to the presence of the conductive host, there will be: (1) distortions to the target signal due to the coupling of the target to the conductive host body; and (2) non-target related signals as a result of conductivity variations in the ocean setting.

The underlying phenomenology of multi-frequency EMI measurements of UXO-like targets made in a conductive host medium was established by [13]. In [13], the EMI response of a metallic target in a conductive host was defined as having two components: (1) the eddy current response (ECR) and the current channeling response (CCR). The ECR is the response that would be measured in free space, and is the response that we model using the point dipole model of (2). The CCR is the response measured as currents induced in the surrounding conductive medium flows are perturbed by the presence of a target. The concept of "current channeling" is important in the application of electromagnetic methods to mineral exploration, but has generally been ignored in terrestrial UXO detection due to low conductivity of soils. When a highly conductive target is present, currents tend to "channel" through the target. When the target is insulated (through corrosion or paint, for example), currents will flow around the target.

In [13] the CCR - and its magnitude relative to the ECR - was extensively studied through theoretical simulations with spheres and spheroids, and through analysis of experimental data acquired in seawater using a frequency domain EMI Geophex GEM3 sensor. It was shown that the CCR is highly dependent on the distance and orientation of the target relative to the transmitter and occurs at higher frequencies (e.g. Fig 5). In [24], modeling showed that the CCR effect occurs at early times, with a maximum amplitude when the target is in the plane of the transmitter coil, and a minimum when the target is directly beneath the transmitter coil (e.g. Fig 6.).

Due to conductivity variations in the underwater environment, variations in the EMI signal occur even in the absence of a metallic target. Seafloor sediments are usually saturated and, in the case of ocean environments, are be more resistive than the ocean water (i.e. conductivities of 0.1 S/m to 1.0 S/m). There is some variation of conductivity with sediment type, with the most significant controls being porosity and conductivity of the fluids (i.e. sea water, fresh

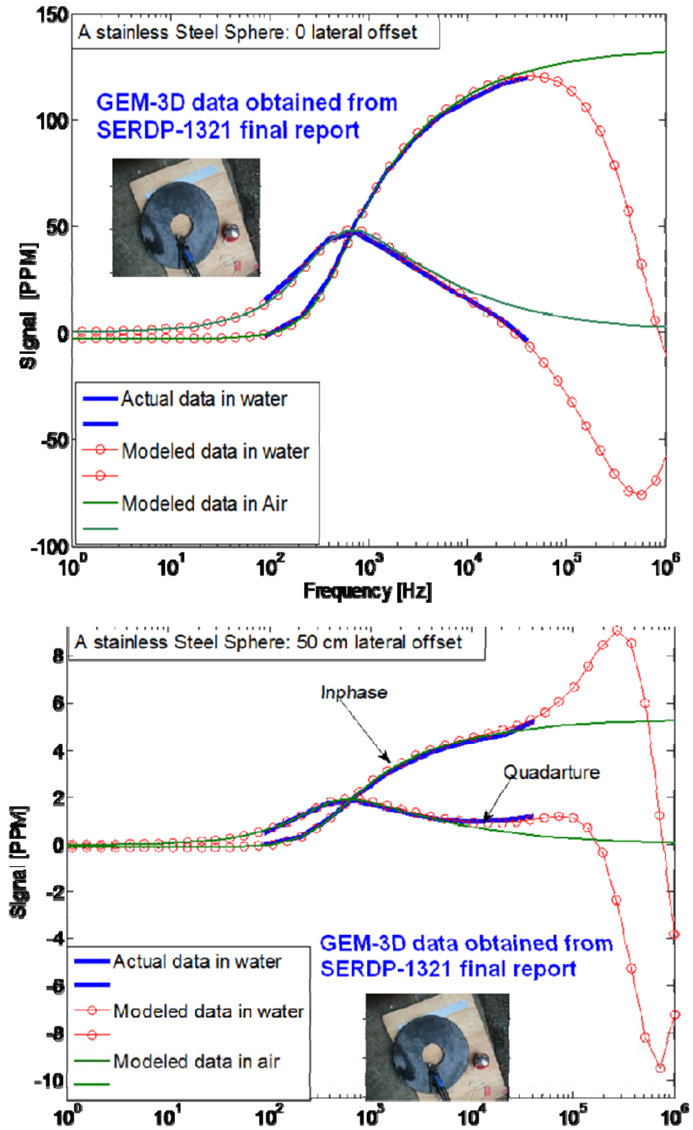

Figure 5. Modeled and measured (GEM-3) data over two spheres at different offsets. Figures reproduced from [24].

water, or brackish water). Boulders range from basalts to granites, which are both resistive when dry. Conductivity increases with fractures, porosity, and fluid time. For example, [25] quotes a conductivity of 0.005 S/m for a basalt rock at 25 degrees with 8 percent porosity. Granite rocks, which generally have a lower porosity, generally have a lower conductivity. Boulders are essentially localized voids in the underwater environment.

Fig 7. shows an example of a EMI signal caused by a 20 cm deep depression in the sea-floor. This response was obtained with a 3D finite volume solution to Maxwell's equations in the frequency-domain [26]. The units are in parts-per-million of the primary field. While somewhat subtle the example illustrates that topography of the sea-floor could contribute to false-alarms and could distort the spatial response measured over metallic objects. Fig. 8 shows the effect of varying

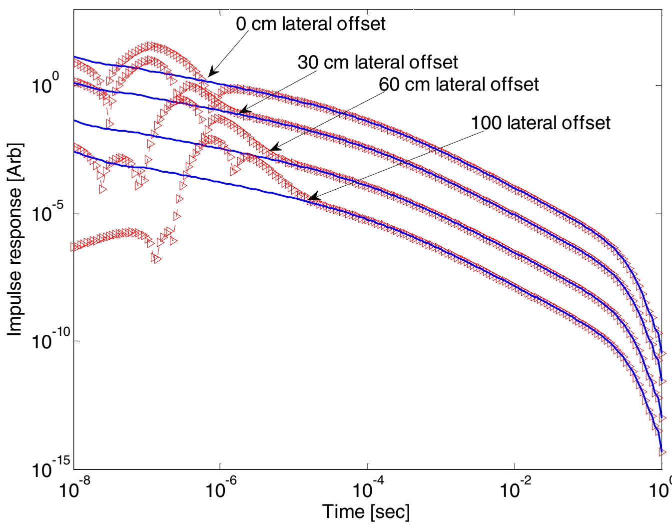

Figure 6. Impulse EMI response of a sphere with conductivity 4×10^6 [S/m] and relative permeability 100, illuminated with the EM-63 time-domain sensor placed at different locations. Figure reproduced from [24]

transmitter altitude on background response, with the calculations also made using the code described in [26]. Within a 0.5 m height there is an approximately 40% variation in the magnitude of the quadrature response of the background at 200 Hz.

The roughness of the air/water interface and the motion of that interface also contribute to the noise of the survey [24]. In [13] the investigators observed that, as sea surface roughness increased, there was a significant increase in noise levels within the GEM-3 sensor. One of the conclusions from the work presented in [13] was that the sensitivity to the air interface and resistive bodies is likely a more significant concern than target/conductive medium coupling.

C. *Summary of requirements*

The following summarize the considerations and requirements for detection and discrimination of ordnance using electromagnetic sensors:

1) Sensor height and detection: Detection performance drops off rapidly with increasing height and approaches r^6 at distances exceeding the longest dimension of a transmitter. Ideally the sensor should be kept within 1.0 m of the bottom and preferably lower (30 cm would be ideal).

2) Relative positioning accuracy: Requirements depend on the type of discrimination technique deployed. For recovery of polarization tensor models positions of better than 10 cm are required (closer to cm level is preferred). If data based attributes are used the position requirements are more relaxed, and errors of 50 cm or more could probably be tolerated.

3) Discrimination potential: Significant discrimination potential exists depending on the quality and positional accuracy of the data. Discrimination works best when all principal axes of an object are stimulated and the response measured.

4) Geological limits to performance: More tolerant than magnetic data to variations in magnetic mineral content

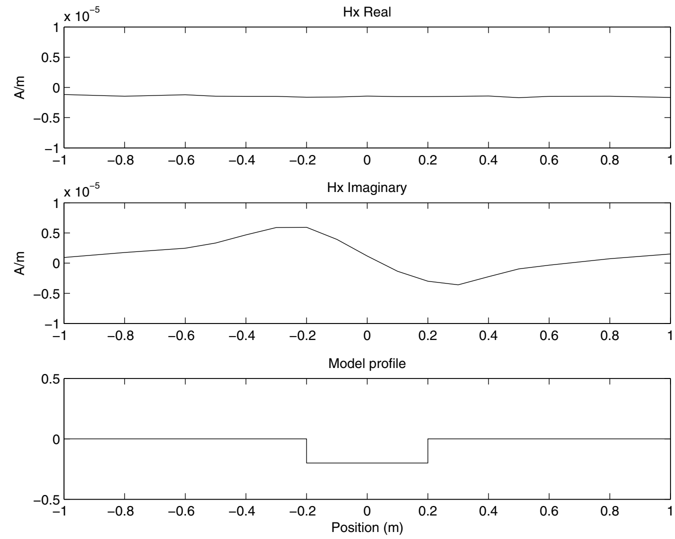

Figure 7. Anomalous horizontal magnetic field at 200 Hz over a depression in the sea-bottom (geometry is the same as Fig. 7 with the exception of the 20 cm deep depression). Sensor is at 30 cm from the sea-floor

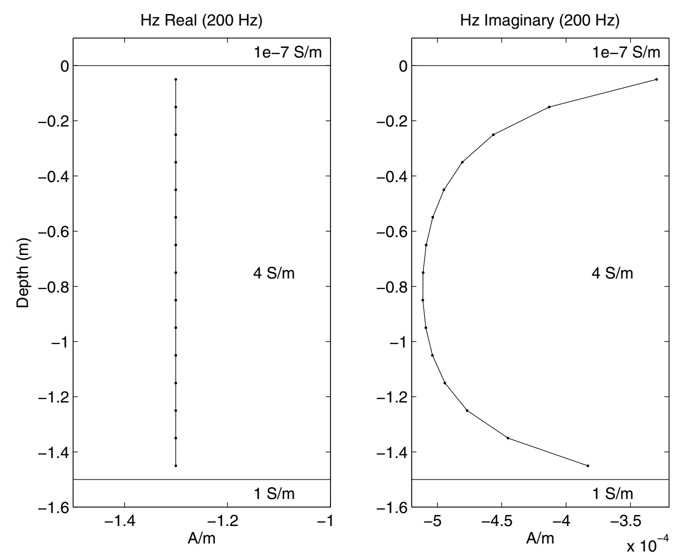

Figure 8. Variation in the vertical magnetic field for an 0.7 m by 0.7 m transmitter within a 1.5 m deep layer of sea-water of conductivity 4 S/m that lies between layers with conductivity 10^{-7} S/m (air) and 1 S/m (seafloor).

although problems can arise if the grain size distribution is conducive to viscous remanent magnetization. False alarms may be caused by sea-floor topography

5) Effects of sea-water: The conductivity causes a current channeling response (mostly significant at high frequencies or early times). The air-water interface can generate noise and the variations in height and orientation relative to the resistive seafloor can cause variations in the background response.

IV. CONCLUSIONS

In terrestrial applications magnetometers and low-frequency EMI sensors are the sensors of choice for obscured object detection. Deployment of these sensor modalities in the marine environment presents a number of phenomenological and logistical challenges. The increased stand-off distances often required in marine deployments can limit detection performance. Magnetometer signals decay less precipitously with height but detection performance can be severely hampered by geological noise, and the data contain only limited information that can be used for discrimination. EMI sensors signals degrade rapidly with height, but detection performance is less affected by geology, and the data often contain significant information that can be used for discrimination. Conductive sea-water mostly affects magnetometers through noise generated by waves. For EMI, the conductivity causes a number of measureable effects, including a current channeling response, noise from waves, variations in background signal with variations in stand-off distance and potential false alarms due to sea-floor topography.

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