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Abstract
Land and water borne electromagnetic and magnetic surveys were performed near the old Lake Erie Ordnance depot in Ohio. The purpose of the study was to determine the presence and subsurface density of unexploded ordnance (UXO). Measurements were carried out within selected onshore and offshore areas using instruments adapted for underwater investigations. A test site with known buried ordnance was prepared in order to establish a base reference for conducting detailed land surveys and transects for the underwater investigation.

The interpretation of magnetic field data for man-made metallic ordnance is often difficult because of distortions to the observed field caused by permanent magnetization. The interpretation of the electromagnetic data is dependent on the condition of the metallic content of the object which will have an effect on the electromagnetic field. Advanced data processing and presentation software techniques were employed to determine the criteria for the plan and depth locations of the buried ordnance.

The goal of the tests is to help to establish a baseline against which to evaluate future changes in the rate of on-shore deposition of new ordnance. As the magnetic results were limited for the Lake Erie site (low sampling density), magnetic data from a Naval Research Laboratory (NRL) demonstration site at Fort Devens, MA was utilized as a further example for this paper. The purpose was to examine the relationship of higher sampling densities to the accuracy of the plan location and depth calculations of magnetic data.

Introduction
Shallow subsurface geophysics investigations are increasingly used in mapping distributions of buried metallic objects on land and underwater (Pawlowski, 1994). Geophysical investigations are vastly superior to traditional sampling programs as they minimize time, danger and cost factors, yet maximize the amount of information.

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The two most common geophysical methods used in ordnance detection are magnetics and electromagnetics. The magnetic method (typically based on a proton or cesium sensor configuration) is generally used for detecting the presence of ferromagnetic objects (barrels, pipes) and geological structures (dikes, faults). The electromagnetic method (using measurements by electromagnetic induction, without electrodes) is used in a wide variety of investigations ranging from buried hazardous wastes and landfill sites, to groundwater contamination studies (Glaccum et al., 1982; Greenhouse, et al., 1983; Valentine et al., 1985). Both methods offer a fast tool for mapping buried metallic objects in shallow (0 to 10 m) subsurface zones.

It should be noted that geophysical surveys are sensitive to instrument accuracy, survey methodology, cultural and geological noise and the physical characteristics of the model we are studying. It is important that the data is properly processed to enhance the components of the data that are of interest and to remove the effects of the noise. Equally important, the method of data presentation can significantly change the appreciation of the data.

**Geophysical Methods**

**The Transient Electromagnetic Method (TEM)**

In the transient electromagnetic method (TEM), two coils (antennas), which serve as a transmitter and a receiver, are situated on or near the earth surface (or sediment-water interface). A steady voltage is applied to the transmitter coil for a sufficiently long time to allow turn-on transients in the ground to dissipate. The current supplied to the transmitter (bipolar rectangular current) is sharply terminated at each cycle. A rapid reduction of the transmitter current, and thus of the associated transmitter primary magnetic field, induces an electromagnetic force in nearby conductors. This electromagnetic force causes electrical eddy currents to flow in conductors with a decay which is a function of the conductivity, size, and shape of the conductor. The decaying currents generate a secondary magnetic field which is detected and measured by a receiver coil. The measured quantity is usually the response of the instrument to metallic objects or the apparent conductivity of the material (Pawlowski, 1994).

An EM61 Transient Electromagnetic System was used on the Lake Erie test site. It consists of a transmitter with a peak power of 100 W that generates a pulsed primary magnetic field, which induces eddy currents in nearby metallic objects. The decay of these currents is measured by two receiver coils mounted one above the other on the coil assembly. The responses are recorded and displayed by an integrated digital data logger. By making the measurements at a relatively long time (0.45 ms) after termination of the primary pulse, the response is practically independent of the electrical conductivity of the ground. The instrument is equipped with an opto-counter which triggers the instrument every 19 cm or it can be set to a time increment mode of three readings per second (Geonics, 1993).

**Magnetics**

The theory and use of magnetics is well described in numerous papers (Breiner, 1973). Generally two types of field magnetometer systems (proton and cesium) are used to measure the total magnetic field for ordnance detection. As well, the vertical magnetic gradient is a useful parameter which can be measured by using two magnetic sensors, rigidly mounted one above the other. Alternatively, the vertical gradient can be calculated from the total magnetic field.

The proton precession magnetometer sensor measures the precession of spinning protons of the hydrocarbon fluid to determine the magnetic field intensity. For the Lake Erie ordnance depot site, an OMNI IV was used to collect both total field and gradient measurements. The instrument requires the user to remain stationary for a two second measurement period and has a sensitivity of 0.01 nanoteslas (nT).

A cesium magnetometer sensor comprises a miniature atomic absorption unit from which a signal proportional to the intensity of the ambient magnetic field is derived. For the Fort Devens site, a SMARTMAG was used to collect the readings. The sensitivity of the instrument is 0.005 nT and can read as fast as 10 times per second. These rapid cycling rates provide for nearly continuous profiles, allowing for an improved resolution of possible anomalies.
Survey Design

Aside from the choice of instrumentation and survey procedures, one of the most important considerations is the locations at which to take the readings. Sample density is of utmost importance as we need to ensure that we properly define the features of interest. The “rule-of-thumb” is that there should be at least four readings on a geophysical anomaly that are greater than the detection limit of the instrumentation (Dobush et. al., 1990). This avoids aliasing problems and allows good definition of the anomaly shape.

For unexploded ordnance, this presents a challenge due to the characteristics of the objects. Aside from the safety factors, unexploded ordnance varies significantly in size, orientation, structure, density and the effects of surrounding surface and cultural noise. With the normally small size of ordnance, high sampling rates (small sample separations) are necessary. With today’s continuous profiling instruments, obtaining the necessary amount of data is within reasonable time and cost considerations.

Lake Erie

For this test site, the EM61 readings were taken along parallel lines separated by three feet. Readings were taken using the wheel-mounted counter which resulted in increments between stations of 0.66 feet. For the OMNI IV magnetometer, the sample readings were taken every three feet along parallel lines separated by three feet.

Fort Devens

For this test site, the SMARTMAG readings were taken approximately every 0.1 meter along parallel lines separated by two meters.

Data Processing

The Transient Electromagnetic Method (TEM)

The electromagnetic survey revealed numerous high amplitude responses originating from the surface or from shallow buried metallic objects. The distribution of the EM61 responses matches well with the locations of all buried metallic targets supplied by the Corps of Engineers. Additional responses are also present which indicate other unidentified anomalous materials present at or near the surface.

Due to its coil arrangement, the TEM response curve for a discrete anomaly such as UXO is a single well defined positive peak and the depth of the target can often be estimated from the width of the response or from relative response (“difference”) from each of the two receiver coils. For this project, apparent depth estimation of buried targets was calculated by utilizing the ratio of the responses from two EM61 receiver antennas (upper antenna placed 40 cm above the lower antenna).

The formula for calculating Apparent Depth is:

\[
R(z) = k \cdot \frac{f_1(z)}{f_2(z)}
\]

where:

\[
k = 2.8
\]

\[
z = \text{depth (cm)}
\]

\[
f_1(z) = \sqrt{((h + z + l1)^2 + 2a1)^2 \cdot ((h + z + l1)^2 + a1^2)}
\]

\[
f_2(z) = \sqrt{((h + z + l2)^2 + 2a1)^2 \cdot ((h + z + l2)^2 + a1^2)}
\]

\[
h = 42.2, \quad l1 = 3.3, \quad l2 = 43.3, \quad a1 = 47.15
\]
This can be simplified using the following formula:

\[
\begin{align*}
R &= \frac{\text{Channel1}}{\text{Channel2}} \\
\text{Apparent Depth} &= 2229.57 + (7288.13 \times R) - (9635.78 \times R^2) + (6458.69 \times R^3) \\
&\quad + (2158.63 \times R^4) - (292.118 \times R^5)
\end{align*}
\]

where if:

\[ R < 0.939 \text{ then } \text{App. Depth} = 0, \text{ and if } R > 2.269 \text{ then } \text{App. Depth} = 5.0 \text{ m} \]

The peak of the response is generally indicative of the center of the source. For calculating depth, it is very important that we obtain the exact peak values for the calculation. Each channel was gridded and the peak values were interactively extracted from the two gridded channel values. These values were inserted into the formula to obtain the Apparent Depth results.

The results of the EM61 survey over the Lake Erie test are presented in Figure 1. Channel 2 is plotted on Figure 1a, and the difference is plotted on Figure 1b.

The results of this estimation are presented in Table 1. This table compares the known depths of buried test ordnance with the calculated depths. The comparison of the given (known) and calculated depths reveals a good correspondence. The error of the calculated depth for 17 targets varies between 7% and 47% with an average value of 26%. However, it should be noted that the “known” depths of inert ordnance were only measured to the nearest 0.5 ft.

**TABLE 1**

<table>
<thead>
<tr>
<th>Description of Inert Ordnance</th>
<th>Given Depth [feet]</th>
<th>Calculated Depth [feet]</th>
<th>Error [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. 60 mm</td>
<td>1.0 0.7</td>
<td>30</td>
<td></td>
</tr>
<tr>
<td>2. 75 mm</td>
<td>1.5</td>
<td>1.7</td>
<td>13</td>
</tr>
<tr>
<td>3. 75 mm</td>
<td>1.5</td>
<td>1.4</td>
<td>7</td>
</tr>
<tr>
<td>4. 90 mm</td>
<td>1.5</td>
<td>0.8</td>
<td>47</td>
</tr>
<tr>
<td>5. 4.2 in</td>
<td>1.5</td>
<td>1.4</td>
<td>7</td>
</tr>
<tr>
<td>6. 81 mm</td>
<td>2.0</td>
<td>1.2</td>
<td>40</td>
</tr>
<tr>
<td>7. 4.2 in</td>
<td>1.5</td>
<td>1.3</td>
<td>13</td>
</tr>
<tr>
<td>8. 4.2 in</td>
<td>1.5</td>
<td>1.0</td>
<td>33</td>
</tr>
<tr>
<td>9. 120 mm</td>
<td>1.5</td>
<td>1.3</td>
<td>13</td>
</tr>
<tr>
<td>10. 81 mm</td>
<td>2.0</td>
<td>1.7</td>
<td>15</td>
</tr>
<tr>
<td>11. 90 mm</td>
<td>2.0</td>
<td>1.5</td>
<td>25</td>
</tr>
<tr>
<td>12. 90 mm</td>
<td>2.0</td>
<td>1.8</td>
<td>10</td>
</tr>
<tr>
<td>13. 4.2 in</td>
<td>2.0</td>
<td>1.3</td>
<td>35</td>
</tr>
<tr>
<td>14. 81 mm</td>
<td>2.0</td>
<td>1.6</td>
<td>20</td>
</tr>
<tr>
<td>15. 4.2 in</td>
<td>2.0</td>
<td>1.7</td>
<td>15</td>
</tr>
<tr>
<td>16. 106 mm</td>
<td>1.5</td>
<td>1.0</td>
<td>33</td>
</tr>
<tr>
<td>17. 155 mm</td>
<td>1.5</td>
<td>1.1</td>
<td>27</td>
</tr>
</tbody>
</table>
The Magnetic Method

The problem with interpreting total field magnetic data is the complexity of the anomaly. The shape, orientation, susceptibility, permanent magnetization and distance and direction to the magnetic body all are factors to consider in interpreting the magnetic data. Also, the direction of the magnetic field of the earth must be taken into account.

Of all of these considerations, the permanent magnetization is a very significant factor as the production of man-made ferro-magnetic objects generally produces a vector that differs from that produced by the Earth’s magnetic field. Figure 2 shows the effect on the magnetic response when you vary the vector direction of the permanent magnetization.

When dealing with magnetic field data, the goal is to simplify the complex information contained in the original data. This paper uses 3D analytic signal (Nabighian, 1984; Roest et al., 1992; MacLeod et al., 1993) and Euler’s homogeneity relationship (Reid et al., 1990) to determine the plan location and depth of the magnetic sources.

The amplitude of the 3D analytic signal of the total magnetic field produces maxima over magnetic sources regardless of the direction of the magnetization (MacLeod et al., 1993) [see Figure 2]. The amplitude of the 3D analytic signal at any location can be derived from the three orthogonal gradients of the total magnetic field using the expression:

$$|A(x,y)| = \sqrt{\left(\frac{dT}{dx}\right)^2 + \left(\frac{dT}{dy}\right)^2 + \left(\frac{dT}{dz}\right)^2}$$

where:
- $A(x,y)$ is the amplitude of the analytic signal at $(x, y)$
- $T$ is the observed magnetic field at $(x, y)$

The advantage of 3D analytic signal is that it can be easily calculated utilizing a simple 3x3 filter for the $(x,y)$ horizontal gradients and a Fast Fourier Transform (FFT) for the $(z)$ vertical gradient.

Alternatively, the vertical gradient can be measured in the field using a gradient magnetometer.

The depth to the magnetic source can be derived from the analytic signal by using the distance between the inflection points of the analytic signal anomaly. To calculate depth, we apply a 3x3 Laplacian convolution filter:

```
0, 1, 0
-1, 4, -1
0, -1, 0
```

to the 3D analytic grid and measure the distance between the inflection points. This distance is directly proportional to the depth to the top of the source. The depth calculated in this way will depend on the assumed source model being depth=0.68 with for ordnance (MacLeod et al., 1993), assuming that there is only a single source in the vicinity of the anomalous field.

Euler’s homogeneity equation (Euler deconvolution) relates the magnetic field and its gradient components to the location of the source of an anomaly, with the degree of homogeneity expressed as a structural index (Yaghoobian et al., 1992). The structural index is a measure of the fall-off rate of the field with distance from the source. Euler’s homogeneity relationship can be written (Reid et al., 1990) for magnetic data in the form:

$$\left|\mathbf{X}_0 \cdot \mathbf{j}_s \cdot \mathbf{z} \right| \frac{\delta T}{\delta x} \left|\mathbf{y} - \mathbf{y}_s \right| \frac{\delta T}{\delta y} \left|\mathbf{z} - \mathbf{z}_s \right| \frac{\delta T}{\delta z} = \mathbf{N}(\mathbf{B} - \mathbf{T})$$

where:
- $\left|\mathbf{X}_0 \cdot \mathbf{j}_s \cdot \mathbf{z} \right|$ is the position of the magnetic source whose total field ($T$) is detected at $(x, y, z)$
- $\mathbf{B}$ is the regional magnetic field
- $\mathbf{N}$ is the measure of the fall-off rate of the magnetic field and may be interpreted as the structural index (SI).
The method involves setting an appropriate SI value and solving the equation by least squares inversion for an optimum $x_0, y_0, z_0$ and $B$. This inversion process yields an uncertainty (standard deviation) for each of the fitted parameters which may be used as a criteria for accepting or rejecting certain solutions. As with 3D analytic signal, the magnetic gradients can be obtained utilizing a simple 3x3 filter for the $(x,y)$ horizontal gradients and a Fast Fourier Transform (FFT) filter or measured gradient for the vertical gradient. Table 2 summarizes the structural indices for simple models in a magnetic field:

**TABLE 2**

<table>
<thead>
<tr>
<th>SI</th>
<th>Cultural Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0</td>
<td>Sheet</td>
</tr>
<tr>
<td>2.0</td>
<td>Long Pipe</td>
</tr>
<tr>
<td>3.0</td>
<td>Sphere (Ordnance)</td>
</tr>
</tbody>
</table>

The advantages of this technique over conventional depth interpretation methods (i.e., characteristic curves, inverse curve matching, etc.) are that no particular geological or cultural model is assumed, it is objective, and the process can be directly applied to large gridded data sets.

From the total field magnetics, we calculate the three gradients, apply the 3D analytic equation and determine the Euler deconvolution results. The $(x,y)$ locations of the Euler solutions were plotted as circles proportional in size to depth of the anomaly source. Euler deconvolution produces a solution for each square window (typically 10 by 10 grid cells in size). A correct SI for a given feature is that which gives the tightest clustering of solutions.

Lake Erie

The Lake Erie results of the magnetic survey carried out by USAE Waterways Experiment Station are presented in Figure 3. The Total Magnetic Field is plotted on Figure 3a; Vertical Gradient of Magnetic Field on Figure 3b, the Analytic Signal on Figure 3c and the Euler deconvolution results on Figure 3d.

While only a few of the test targets can be positively identified by the total field magnetics, they are better represented by the calculated vertical gradient. However, even with the vertical gradient there still exists the problem of locating the center of the source and more importantly, the effects of permanent magnetization. The 3D analytic results show a positive peak over the center of each UXO, with the shape indicative of the type and orientation. The Euler results generally agree with the location of the known test objects. The quality of these results are poor, however, as they are dependent on sampling density, which in this case was only at one meter (three foot) intervals.

Fort Devens

The results of the Naval Research Laboratory magnetic survey at Fort Devens are presented in Figure 4. The Total Magnetic Field is plotted on Figure 4a, the Calculated Vertical Gradient on Figure 4b, the Analytic Signal on Figure 4c, and the Euler results on Figure 4d. The 3D analytic signal clearly outlined the center of each of the anomalies which matched well with the locations provided to the authors. The shape and amplitude of the analytic signal peaks can provide information on the type, orientation and depth of the sources. At the time of this paper, information pertaining to the true characteristics of the sources are not available.

The Euler results were calculated using a SI of 2.75. The calculated depths ranged from zero to four meters as illustrated in Figure 4d. Most of the clustered solutions align well with the projected locations of the targets.
Summary

The results of a test survey aimed at mapping buried inert ordnance showed that with proper survey procedures and effective processing, both TEM and magnetics are very suitable for detecting buried ordnance. If possible, both geophysical techniques should be employed to maximize the detection process. Despite the fact that all test targets were very closely interspersed, with the proper data processing one should be able to distinguish each target, and provide a reasonable estimate of target depth.

Utilizing the ratios of two receiver channels for transient electromagnetics and the 3D analytic signal and Euler deconvolution for magnetics offers an effective yet simple method of determining location and apparent depth of UXO. The quality of gridded data and interpreted results is dependent on the sensor height above sources, line spacing and sample density, grid interval and the line or sample interval, leveling and other systematic errors (Yaghoobian et al., 1992). Cost effective instrumentation and software are available to obtain and analyze the necessary data for ordnance detection.

The processing, presentation and interpretation software used in this paper are part of the Geosoft OASIS-MPS, a PC-based software package designed for earth science applications.

Bibliography


