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Detection of unexploded ordnance (UXO) using marine magnetic gradiometer data

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Key Words: magnetic, marine, underwater UXO, Euler, analytic signal, detection, magnetization

ABSTRACT

Recent development of marine magnetic gradient systems, using arrays of sensors, has made it possible to survey large contaminated areas very quickly. However, underwater Unexploded Ordnances (UXO) can be moved by water currents. Because of this mobility, the cleanup process in such situations becomes dynamic rather than static. This implies that detection should occur in near real-time for successful remediation. Therefore, there is a need for a fast interpretation method to rapidly detect signatures of underwater objects in marine magnetic data.

In this paper, we present a fast method for location and characterization of underwater UXOs. The approach utilises gradient interpretation techniques (analytic signal and Euler methods) to locate the objects precisely. Then, using an iterative linear least-squares technique, we obtain the magnetization characteristics of the sources. The approach was applied to a theoretical marine magnetic anomaly, with random errors, over a known source. We demonstrate the practical utility of the method using marine magnetic gradient data from Japan.

INTRODUCTION

The magnetic method is one of the most appropriate geophysical techniques for locating and mapping the distribution of ferro-metallic objects. Measurement of perturbations in the direction and/or strength of the Earth's magnetic field are used to locate underground ferro-magnetic objects (e.g., Watanabe and Abe, 1964; Watanabe, 1973; Kotani, 1999; Gamey et al., 2000). Recent development of marine magnetic gradiometer systems, using arrays of sensors, has made it possible to cover large contaminated areas more rapidly than was possible with a single vertical gradiometer. However, one of the drawbacks of these developments is the large volume of data that is acquired.

The ability to analyse and interpret large volumes of data has not kept pace with the advances in data gathering, storage, and processing speed. Another difficulty when dealing with marine magnetic data is that underwater Unexploded Ordnances (UXO) are susceptible to transport by water movement, and their positions can change. Because of this factor, the cleanup process for underwater UXO is dynamic rather than static. This implies that interpretation and detection should occur in near real-time for successful remediation. Therefore, there is a need for an interpretation technique that can be used to map the location of underwater UXO quickly and accurately. Marine magnetic data are usually interpreted using manual interpretation methods, which are based on non-linear inversion of the measured gradient magnetic data to estimate magnetic source parameters of underwater UXO. However, manual methods of detection cannot effectively process such large datasets in a suitably short time.

A variety of semi-automatic methods, based on the use of gradients or derivatives of magnetic field anomalies, have been developed for the determination of geometric parameters such as locations of boundaries and depths of the causative sources. As faster computers and commercial software have become widely available, these techniques are being used more extensively. Examples of these techniques are the analytic signal and Euler methods. In this paper, we describe a fast procedure for target location and characterization of underwater steel objects. In our procedure, target location is initially estimated using an analytic signal approach (Salem et al., 2002). The Euler method (Reid et al., 1990) is then used to define more precisely the actual location of the source. Using this estimated source location, magnetization source parameters are estimated using an iterative linear least-squares approach. The practical utility of the procedure is demonstrated using theoretical and field examples of marine magnetic gradient data.

Vertical gradient response of UXO

Magnetic signatures of ferro-metallic objects can be simulated using one of two methods. In a simple simulation, a ferro-metallic object can be simulated by an equivalent source such as a point source, or a vertical or horizontal line of sources. Alternatively, we can represent the object by a model that accounts for the shape and orientation effects, as described by Talwani (1965), Blakely (1995), and Altshluer (1996). Although there may be significant variations from one object to another, it is best to model magnetic signatures of ferro-metallic objects in a mathematical best-fit sense (Ravat, 1996) and to avoid detailed modelling. For ferro-metallic objects such as UXO, we can simulate their magnetic signatures using equivalent dipole sources.

The vertical component of the magnetic induction B_z (produced by a dipole source located at point x_o, y_o, and z_o, and measured at point x, y, and z) is given by Blakely (1995) as

$$B_z = K\frac{(3\,d(z-z_o) - r^2 n)}{r^5}, \qquad (1)$$

where K is the dipole moment,

$$r = \left[(x-x_o)^2 + (y-y_o)^2 + (z-z_o)^2\right]^{1/2}$$

is the distance from the dipole to the observation point, and d and n are quantities related to the magnetization direction of the dipole source. If a is the magnetic inclination and b is magnetic

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declination, these quantities are defined as

$$n = \sin(a) \tag{2}$$

and

$$\begin{aligned} d = {} & (x - x_o)\cos(a)\cos(b) + \\ & (y - y_o)\cos(a)\sin(b) + (z - z_o)\sin(a) \end{aligned} . \tag{3}$$

The vertical gradiometer response ΔB_z of the vertical component B_z can be defined by taking the derivative of equation (1) with respect to the variable z as follows:

$$\Delta B_z = 3K\frac{dr^2 + 2r^2 n(z - z_o) - 5d(z - z_o)^2}{r^7} . \tag{4}$$

Solving equation (4) for both location and magnetization parameters is a non-linear problem. Such problems are notoriously difficult to solve for more than one parameter (Hansen and Suciu, 1999; Abdelrahman et al., 2001). To avoid this difficulty, we develop a procedure in which the location and magnetization of the buried sources are estimated in two steps using linear least squares methods. Generally, solving linear geophysical problems is fast and very suitable for automatic interpretation. The details of our procedure are described below.

The procedure

Our procedure utilises the analytic signal and Euler methods *to get information about the location of the source quickly. Then,* using this estimate of the source location, information about the magnetization is obtained.

Initial estimate of the location based on the analytic signal method

Salem et al. (2002) and Salem and Ravat (2003) developed a method in which depth to compact magnetic sources is estimated from the ratio of the amplitude of the analytic signal (*AAS*) to the higher order analytic signal. Following their approach, using data for the vertical gradient of the vertical component of the magnetic field (ΔB_z), the depth z_0 is given by

$$z_o = 5\frac{|AAS_1|_{x=0,y=0}}{|AAS_2|_{x=0,y=0}} , \tag{5}$$

where AAS_1 and AAS_2 are first and second order analytic signal of the measured vertical gradient of the vertical component and are given by

$$|AAS_1| = \sqrt{\left(\frac{\partial(\Delta B_z)}{\partial x}\right)^2 + \left(\frac{\partial(\Delta B_z)}{\partial y}\right)^2 + \left(\frac{\partial(\Delta B_z)}{\partial z}\right)^2} \tag{6}$$

and

$$|AAS_2| = \sqrt{\left(\frac{\partial^2(\Delta B_z)}{\partial z \partial x}\right)^2 + \left(\frac{\partial^2(\Delta B_z)}{\partial z \partial y}\right)^2 + \left(\frac{\partial^2(\Delta B_z)}{\partial z^2}\right)^2} . \tag{7}$$

The *AAS* can be easily computed in a number of ways. The horizontal derivatives can be calculated directly from gridded vertical gradient data using a simple 3 × 3 difference filter. Alternatively, both the horizontal and vertical derivatives can be calculated in the frequency domain using conventional Fast Fourier Transform (FFT) techniques (Blakely, 1995).

To apply the analytic signal method, we first locate the values of the maxima of AAS_1 using the procedure given by Blakely and Simpson (1986) and modified slightly by Roest et al. (1992). In this method, a linearity index is determined to describe the nature of detected maxima (e.g., index 1 for linear anomalies and index 4 for circular anomalies). For dipolar magnetic anomalies, an index of 4 would be useful because these anomalies, in most cases, are circular and have a local extension.

Estimation of the depth in this case is completely independent on the magnetization direction of the dipole source (Salem et al., 2002). However, location errors may occur because the method uses single values at the peaks. Therefore, we consider this source location to be an initial estimate and seek a more precise location using the Euler method, which uses several data values and utilises a least squares approach.

Precise source location estimation using the Euler method

Potential fields and their components satisfy Laplace's equation outside the source regions; the equation is homogeneous for specific source geometries (Blakely, 1995). A homogeneous equation also satisfies Euler's equation. The 3D form of Euler's equation is given by Reid et al. (1990). For vertical magnetic gradiometer data, the form can be rewritten as

$$\begin{aligned} & x\frac{\partial(\Delta B_z)}{\partial x} + y\frac{\partial(\Delta B_z)}{\partial y} + z\frac{\partial(\Delta B_z)}{\partial z} + 4\Delta B_z = \\ & x_o\frac{\partial(\Delta B_z)}{\partial x} + y_o\frac{\partial(\Delta B_z)}{\partial y} + z_o\frac{\partial(\Delta B_z)}{\partial z} \end{aligned} , \tag{8}$$

where the value 4 is the structural index of the dipole source. By considering four or more neighbouring observations at a time in a data window, a source location (x_o, y_o, z_o) can be computed by solving a linear system of equations generated from equation (8). Here, we use a single data window, centred at the initial horizontal location that is obtained using the analytic signal method.

Estimation of source magnetization parameters

Once the source location is estimated using the Euler method, source magnetization parameters can be obtained using a simple method. The method is based on using tentative sets of inclination and declination and estimating the magnetic moment from the observed vertical gradiometer data. The set of inclination and declination that is associated with minimum errors in a least-squares sense is selected.

To understand the idea, let us assume two candidate values for the inclination and declination. Then equation (4) can be written as

$$\Delta B_z = K_{I,D}G(I,D,x_0,y_0,z_0) , \tag{9}$$

where $G(I, D, x_0, y_0, z_0)$ is a function of the geometry of the estimated source location parameters and the tentative values of the inclination I and declination D. In a least-square sense, the magnetic moment can be estimated as

$$K_{I,D} = \frac{\sum^{N} \Delta B_z G(I,D,x_0,y_0,z_0)}{\sum^{N} (G(I,D,x_0,y_0,z_0))^2} , \tag{10}$$

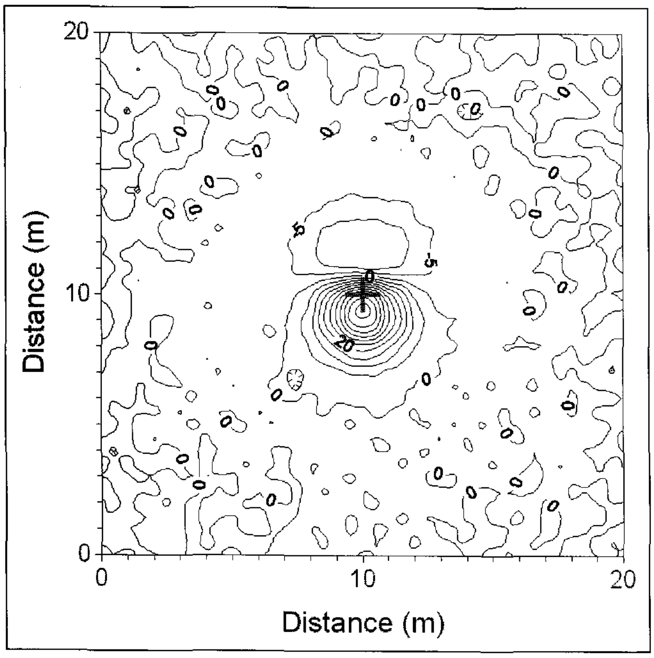

Fig. 1. Vertical gradient magnetic anomaly for a dipole source located at a horizontal location of $x = 10$, $y = 10$, and at a depth of 3 m. Contour interval is 5 nT/m. The dipole is induced in magnetic field with inclination of 30°, declination of 0°, and has magnetic moment of 10 A.m^2.

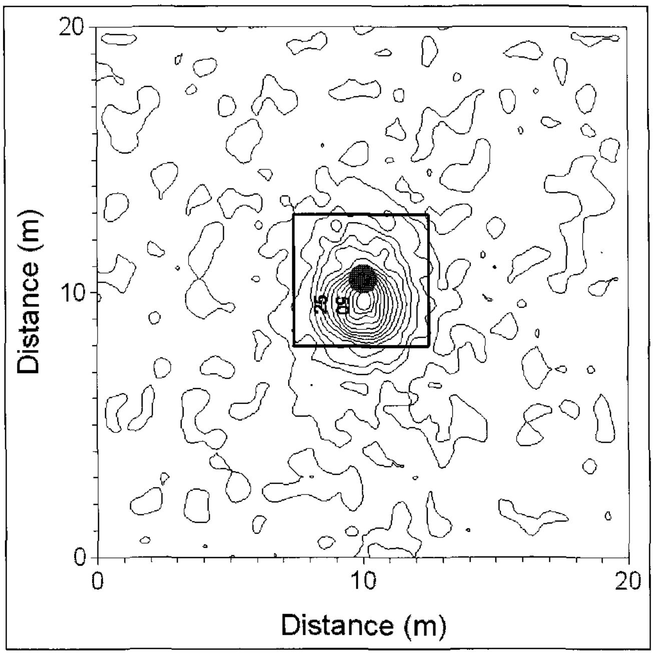

Fig. 2. Analytic signal of the vertical gradient magnetic anomaly shown in Figure 1. Contour interval 5 nT/m^2. Circle shows the estimated horizontal location using the analytic signal method. Square indicates the data window for the Euler method.

where N is a number of selected data around the estimated source location. Equation (10) is applied with different sets of inclination and declination and for each set of candidate values, a root mean square (RMS) error is calculated between the observed data and the theoretical values based on the estimated parameters. The inclination, declination, and the calculated moment that gives minimum error are selected.

Implementation

The present procedure can be implemented as

1. Interpolate the vertical gradiometer magnetic data to a regular grid for further calculation of the derivatives.
2. Calculate the derivatives and the requisite analytic signal (equations 6 and 7).
3. Find the locations of maximum values of the analytic signal.
4. For each location detected, do the following

   Estimate the depth using equation (5).

   If the estimated depth is within an expected range, apply the Euler method around the estimated location to get an improved solution for the source location.

   Using the estimated source location and a set of tentative values for the declination and inclination, estimate values for the magnetic moment. The solution that yields minimum misfit is selected.

Theoretical example

To demonstrate the feasibility of the present procedure, we present a synthetic example for a dipole source. The dipole has an induced magnetic moment of 10 A.m^2 in an ambient magnetic field with an inclination of 30° and a declination of 0°. The data are calculated at an interval of 0.5 m on a grid of 20 m × 20 m extent, with the dipole placed at the centre of the grid ($x = 10$ m and $y = 10$ m from the origin) and at a depth of 3 m. The data have been contaminated by an additive random noise with zero mean and a standard deviation of 1 nT/m. Figure 1 is the resulting magnetic anomaly map of the vertical gradient of the vertical component. The analytic signal for these theoretical data were computed in the frequency domain, then transformed to the space domain (Figure 2). Our procedure has then been applied to the theoretical data to estimate the source parameters. The location of the analytic signal maximum was detected at $x_0 = 10$ m, $y_0 = 9.5$ m, and the depth was calculated to be 2.47 m. The errors are less than 0.6 m in all source location parameters.

We then applied the Euler method to estimate more precisely the source location parameters around the estimated horizontal location. Generally, the choice of the window size for the Euler method is a function of data quality and the degree of interference of anomalies from nearby sources. For noisy data, larger window sizes (in terms of number of observations) are required. On the other hand, smaller windows are appropriate to reduce interference effects of nearby sources. A single data window with a size of 5 m × 5 m was used. This size was found adequate to estimate the source location from the noisy data, and gave a result ($x_0 = 10.0$ m, $y_0 = 9.9$ m, $z_0 = 2.9$ m) with an error less than 0.1 m in any parameter. This indicates that our gradient interpretation techniques could provide good solutions for the source location; taking into account that the data is contaminated with noise and this noise is greatly amplified in the calculation of derivatives of the field. For field data with higher noise levels, noise-reducing techniques such as upward continuation and low-pass filtering can be employed to improve the signal-to-noise ratio of the magnetic anomalies before calculation of the requisite derivatives. This will improve the process of estimating source location parameters.

To estimate the magnetization source parameters, the estimated source location values were used together with tentative sets of inclination and declination at an interval of 5°. Our procedure again gave good results for the magnetization source parameters (predicting inclination = 30°, declination = 0°, and magnetic moment is 9.6 A.m^2). The inclination and declination are estimated exactly and the error in the estimated magnetic moment is less than 5%. These results were obtained in a few seconds. This indicates that our procedure can provide acceptable results in a short time, which is necessary for successful remediation. However, care should be taken when interpreting the magnetic moment estimated using our procedure because our estimation process is based on the assumption that the magnetization is produced only by induction. In practice, it is difficult to use induced magnetization to simulate the magnetic signature of UXO. Actual signatures can be separated to three contributions: remanent magnetization, induced magnetization, and demagnetization effects. Magnetization parameters estimated using the procedures in this paper should be considered to be parameters of a dipole source whose magnetization is equivalent to the resultant magnetization of the source body. If the calculated magnetization direction is not in the same direction of the induced magnetic field, this indicates that remanent magnetization or demagnetization effects are probably contributing to the observed anomaly. Generally, such effective magnetic parameters will be very useful for a quick evaluation of the objects detected. More advanced techniques, such as full inversion, may use these parameters as initial solutions to obtain further information about the possible magnetization types.

Field Example

In summer of 2003, Kobe Steel Ltd conducted an experimental marine magnetic survey in the Kanda Port, Kyushu Island, Japan as part of a technology demonstration and validation (Asahina et al., 2003). In this survey, a boat with a GPS positioning system was used and 16 fluxgate vertical magnetic gradiometers (Figure 3) were towed behind the boat. Each vertical gradiometer consists of two vertical component sensors separated by 1 m. The horizontal distance between each gradiometer is 0.5 m, and this array system is able to cover a swathe of 7.5 m across the survey track. The sampling rate of this system is approximately 0.2 m.

In this experimental test, different types of UXO objects were buried at depths between 0 and 1 m below the sea bottom in an area of approximately 440 m^2. Measuring the exact value for the depth of each object was difficult. Measurements were made at a distance of 1 m above the sea bottom along three tracks with a length of 20 m. The magnetic field of the Earth at the test site has an inclination of 47.3° and a declination of -6.5°. Figure 4 shows a plan view of the surveyed area and Table 1 lists the seeded objects.

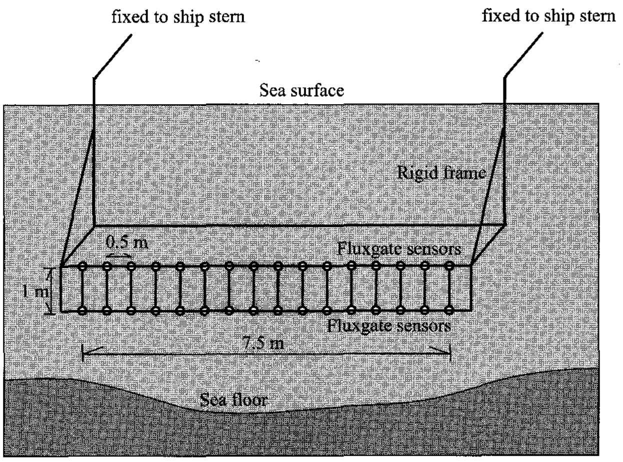

Fig. 3. A simplified sketch of the 16 vertical fluxgate gradiometers system of Kobe Steel Ltd., to be towed by a survey boat.

The observed magnetic data were interpolated onto a grid interval of 0.25 m. Figure 5 is the vertical gradient map of the experimental test area. To improve the signal-to-noise ratio of the observed magnetic anomalies, we have applied upward continuation

Item	x_0 (m)	y_0 (m)	Weight (kg)	Diameter/length (mm)
A1	17.9	16.9	4.1	39.1/430
A2	17.8	12.4	Unknown	Unknown
A3	15.5	14.5	Unknown	Unknown
A4	12.9	12.8	12.65	176.8/765
A5	12.8	16.9	Unknown	Unknown
A6	8.2	15.8	Unknown	Unknown
A7	7.4	11	Unknown	Unknown
A8	5.4	9.9	6.02	93.5/180
A9	2.8	12.1	12.05	101.6/514
A10	5.9	15.1	12.05	101.6/514

Table 1. List of Underwater UXO tested by Kobe Steel Ltd. in the Kanda Port, north Kyushu, Japan

Item	x_0 (m)	y_0 (m)	z_0* (m)	Moment (A.m^2)	Inclination (degree)	Declination (degree)
A1	17.7	16.7	0.60	0.77	4	354
A2	17.7	12.3	0.60	0.66	0	352
A3	15.1	14.5	1.54	2.58	0	138
A4	12.3	12.5	0.59	2.49	12	2
A5	12.4	17.2	0.71	0.53	12	146
A6	8.09	15.6	0.51	3.20	6	356
A7	6.84	10.9	0.66	0.48	16	12
A8	5.8	9.79	0.47	0.74	6	2
A9	2.92	11.9	0.50	1.20	6	344
A10	6.48	14.4	0.52	0.21	64	288

*Depth value after subtraction of the upward continuation distance (0.25 m) and the sensor altitude (1 m).

Table 2. Results of testing the marine magnetic data shown in Figure 5.

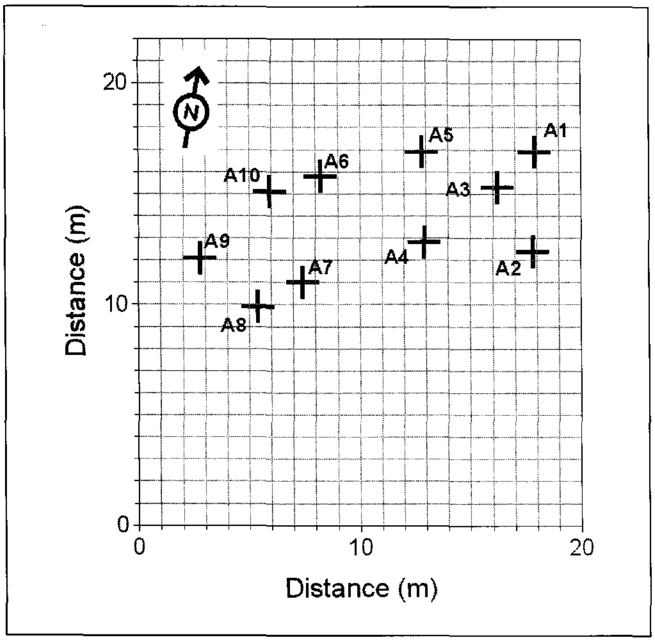

Fig. 4. Horizontal location of the seeded UXO items, and layout of the surveyed test area in Kanda Port, Kyushu Island, Japan.

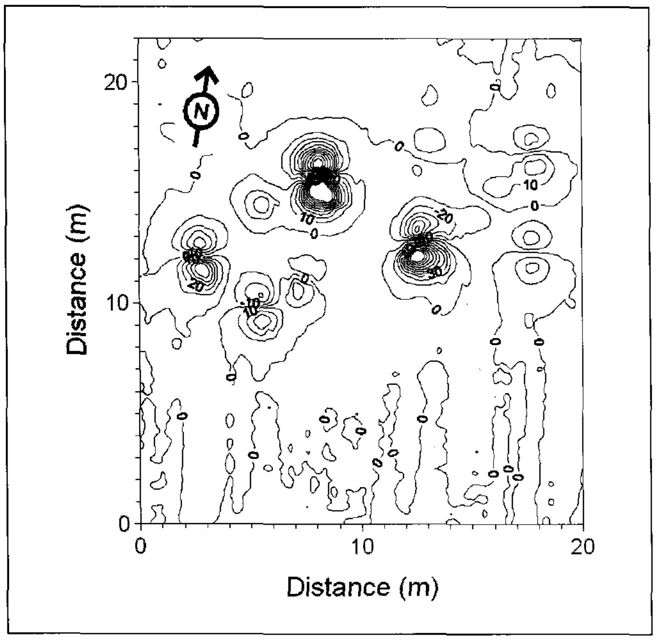

Fig. 5. Vertical gradient magnetic data measured over underwater UXO in Kanda Port, Kyushu Island, Japan. Contour interval is 10 nT/m.

by 0.25 m. The requisite derivatives for the analytic signal and Euler method were computed in the frequency domain using the FFT method. Figure 6 is the AAS_1 map of the observed data, after applying upward continuation. It can be seen that the *AAS* map reflects the existence of magnetic objects. Generally, *AAS* maps better represent the location of shallow magnetic anomalies than vertical gradient maps, because the *AAS* values are all positive, and are more centred over their sources, leading to easier interpretation of their approximate horizontal locations.

In applying the procedure, the analytic signal method first detected the initial locations of the sources and then the Euler method was applied, using a data window of 2.5 m × 2.5 m, centred above the initial estimated locations. From the same data window,

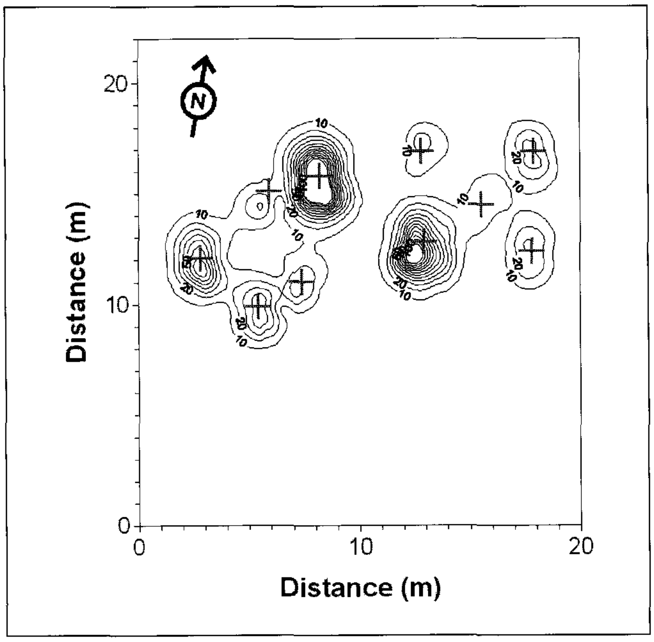

Fig. 6. Analytic signal of the vertical gradient magnetic data of Figure 5. Contour interval 10 nT/m².

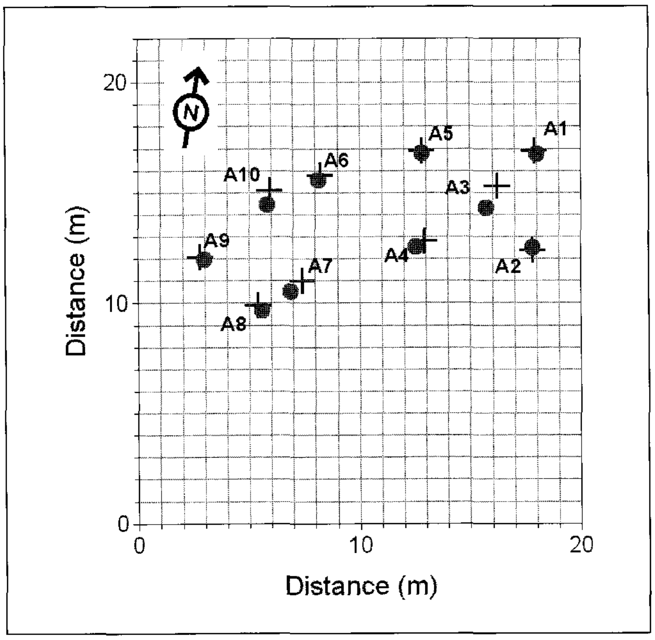

Fig. 7. Results of applying our proposed method to the field data. Circles show the horizontal locations of the detected underwater UXO, and crosses indicate the actual horizontal locations. See Table 2 for a complete description of the results.

magnetization parameters were estimated using a set of tentative sets of inclination and declinations with an interval of 2°. Figure 7 and Table 2 summarize the results of processing the marine field magnetic data using our procedure. As shown, the procedure could detect all the underwater objects with a reasonable degree of accuracy. The estimated horizontal locations are very close to the actual ones, except for item A3. For this object, the estimated horizontal location is shifted about 2 m from the actual location. This shift is most probably due to interference effects from nearby sources.

The estimated depths (after subtracting the upward-continuation distance, 0.25 m, and the sensor height, 1 m) are within the burial depth range (from 0 to 1 m) except for the depth of item A3. As mentioned before, the anomaly of item A3 may be affected by the inference of nearby sources, which will lead to inaccurate results for all source parameters. Using a smaller size of data window may reduce the effect of nearby sources.

The procedure has also provided reasonable results for the magnetization parameters of the underwater objects. Generally, the magnetic inclination of these objects is less than that of the ambient magnetic field. This deviation may be attributed to remanent magnetization or to interference effects. The magnetic anomalies of items A3 and A10 are clearly affected with interference effects. Therefore, remanent magnetization may not be responsible for the deviation in the estimated magnetization directions for these objects. On the other hand, the anomaly of item A5 seems to be free from interference of nearby sources. Therefore, remanent magnetization is most probably included in the anomaly of this source.

The estimated magnetic moments ranged between 0.21 A.m^2 for item A10 and 3.2 A.m^2 for item A6. Item A9 is a bomb with the same shape as item A10, but buried horizontally. Getting different responses from these two objects is not surprising, as the total field induced in an object depends on several factors, including the geometry of the objects as seen from the observation point. Generally, the estimated magnetic moments correlate with the mass of the known objects. This indicates that the magnetic moments can be used to characterize the buried sources.

CONCLUSION

In this paper, we have presented a fast procedure for location and characterization of underwater UXO. The procedure utilises gradient interpretation techniques (analytic signal and Euler methods) to locate the objects precisely. Using an iterative linear least-squares approach, magnetization characteristics of the source are also obtained. The procedure was applied to a theoretical magnetic anomaly with random errors over known source. Good results were obtained. The practical utility of the present method is demonstrated using marine gradient magnetic data from Japan. The procedure is also applicable for any vertical gradient data measured using either ground or airborne systems.

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磁気傾度計を用いた海底のＵＸＯ探査

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要　旨：　近年では、アレイ式磁気傾度計を用いることにより、不発弾・ＵＸＯに汚染された海底の磁気探査も高速に実施できるようになっている。しかし、浅海のＵＸＯは、海流によって移動するため、海底のＵＸＯを探査し、首尾よく除去するためには、膨大な磁気探査データを船上でリアルタイムに処理する技術が必要となる。本論文では、海底のＵＸＯの位置および特性を高速に推定するためのアルゴリズムを提案する。すなわち、まずオイラーデコンボリューションなどにより磁気傾度データの解析を行う。次いで、最小二乗法による反復解析法を用いて磁気ソースを定量的に決定する２段階の手続きが行われる。このプログラムを用いて既知のモデルに対する種々の数値実験を行い、データ解析の精度を明らかにした。さらに、本プログラムを実際に日本の海底磁気探査で取得されたデータの解析に適用して実用性を確かめる。

해양 자력구배 탐사자료를 이용한 UXO 탐지

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요　약: 여러 센서들의 배열을 이용한 최근의 해양 자력구배 측정시스템의 개발을 통하여 넓은 오염지역의 조사를 빠르게 수행할 수 있게 되었다. 그러나 물밑의 UXO 는 조류에 의해 이동할 수 있으며 따라서 이런 환경에서의 복원과정은 정적이라기 보다는 동적이 되었다. 이는 곧 성공적인 복원을 위해서는 탐지가 거의 실시간으로 이루어져야 함을 말한다. 그러므로 해양 자력탐사자료로부터 물밑 물체의 신호를 빠르게 탐지할 수 있는 신속한 해석법이 필요하다. 이 논문에서는 물밑 UXO 의 위치 및 특성을 알아내는 신속한 방법을 소개하였다. 먼저 대상체의 정밀 탐지를 위해 자력구배자료의 해석기법(해석적 신호와 Euler 방법)을 이용하며, 반복적 선형 최소자승법을 이용해 대상체의 자기 특성을 얻어낸다. 이 방법은 알고 있는 대상체에 대해 무작위 잡음을 더한 이론적 해양 자력이상에 적용되었으며, 일본의 해양 자력구배탐사 자료를 이용하여 실질적인 유용성을 예시하였다.

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