Detection and classification of underwater targets by magnetic gradiometry

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SHORT ABSTRACT: *This paper describes the theoretical analysis of a method to detect and classify objects from magnetic maps. The method, originally designed to detect buried UXO by land survey with a magnetometer, is adapted here for underwater survey with a gradiometer. Evaluation is performed on simulated data in order to predict the performance of the adapted algorithm to this new situation. We have simulated a gradiometer composed of three magnetometers that measure the intensity of the magnetic field. The paper presents results obtained by the classification algorithm using the gradient maps as input to locate the targets and estimate their depths and magnetic moments. Examples illustrating the influence of the sampling grid and errors in the location of the gradiometer underwater on the detection and classification performance are also presented.*
Keywords: *gradiometry, mine detection, modelisation, classification.*

1 INTRODUCTION

The detection of old sea mines from previous wars or new mines from more recent conflicts is a major activity to secure waterways. Although sonar and other acoustic methods are usually used for this task, magnetic sensors can be a solution when mines are buried. Detection of mines or other unexploded ordnance by magnetic methods has been studied for many years [1, 2, 3]. Classification of buried objects by magnetic methods is a complex problem which is not completely solved at this moment [4, 5]. As targets are simulated as magnetic dipoles the three components of the magnetic dipole must be estimated in order to help the identification of the target. Legitimate targets such as mines can therefore be classified based on four numerical values: the three components of the magnetic moment and the distance between the target and the gradiometer – in practice, this distance is the depth.

Scalar magnetometers measure the sum of the ambient magnetic field and the magnetic field generated by the target. There is no unicity of the magnetic moment that produces a given intensity of the measured magnetic field. Different objects may produce similar magnetic measurements and therefore be inverted as similar magnetic moments. This makes the identification of the target difficult based on the reconstruction of a magnetic dipole.

For this reason some authors suggest to build a database of targets with their magnetic moments [5]. Then after a survey the database could be used to look for targets that are the most likely to have produced the measurements knowing the Earth's magnetic field in the survey area. Classification would then not cover only the estimation of the magnetic moment but also the identification of the target. When no such database exists classification is limited to the estimation of the magnetic moment of the dipole.

The reconstruction of the dipole can be done by a complete inversion of the model using parameter estimation algorithms. The problem is non-linear and requires therefore accurate initial values.

Some of these values can be obtained by physical considerations or derived from mathematical equations. Reference [5] describes an algorithm called the Automated Wavelet Detection (AWD) to provide these initial values in the case of land survey. The algorithm is applied to a real situation and its results used as initial value to a full inversion method. The evaluation of the AWD algorithm was done by comparing its results to the results of the full inversion method.

2 OBJECTIVES OF THE PAPER

This paper has two objectives. First is to present slight adaptations of the AWD algorithm to fit with the constraints of underwater survey where the main difference is that the measurement sampling is less dense because the distance between two tracks is larger than what can be achieved during a land survey. This has an impact on the quality of the magnetic maps that are generated and therefore on the results of the algorithm. The second objective is to evaluate the algorithm on synthetic examples in order to be able to compare the results with the real magnetic moment that produced the anomaly magnetic field.
In what follows we consider an underwater survey performed by a gradiometer measuring the three gradients of the intensity of the magnetic field. A map of the intensity of the magnetic field is also assumed to be available. The whole survey is simulated, from the trajectory of the sensor to the data acquisition and the building of maps.

3 DESCRIPTION OF THE CLASSIFICATION ALGORITHM

3.1 Introduction

We describe here a modified version of the AWD algorithm. Please refer to [5] for the original algorithm.
Six parameters must be estimated: two parameters define the location of the target; one is the depth where the target is located; the magnetic moment is described by three parameters, the magnitude, the angle from a horizontal plane (inclination) and the angle from the North within a horizontal plane (azimuth).
This algorithm takes advantage of the fact that the magnetic anomaly generated by a magnetic dipole has the direction of the dipole magnetic moment as symmetry axis. A target can then theoretically be detected by the presence of a local maximum and a local minimum located in the direction along the magnetic moment. The first step of the algorithm is to detect the two local extrema. From them the azimuth of the magnetic moment is derived. The algorithm also uses the fact that the location of the magnetic dipole lies on the line joining the two extrema. In the presence of the Earth's magnetic field, the local extrema in the measured magnetic field may be slightly displaced. The estimation of the azimuth may be slightly wrong and the magnetic dipole may not exactly lie on the line joining the two extrema.

3.2 Locating the local extrema

There is a mathematical condition to identify a local extremum. Let B be the intensity of the magnetic field. There is a local extremum at (x, y) in the plane defined by $z = z_0$ if the following condition applies:

$$\frac{\partial B}{\partial x}(x, y, z_0) = 0 \tag{1}$$

$$\frac{\partial B}{\partial y}(x, y, z_0) = 0 \tag{2}$$

$$\frac{\partial^2}{\partial x^2} B(x, y, z_0) \cdot \frac{\partial^2}{\partial y^2} B(x, y, z_0) - \frac{\partial^2}{\partial x \partial y} B(x, y, z_0) \cdot \frac{\partial^2}{\partial y \partial x} B(x, y, z_0) > 0 \tag{3}$$

Numerical derivations of the gradients in x and y of the intensity of the magnetic field provided by the gradiometer give all the elements of the equation. The locations of local extrema can therefore be estimated. This is a simplified version of the original algorithm where wavelets are not used in this step.

3.3 Matching maxima and minima corresponding to the same targets

The extrema with the highest absolute value is selected if its value is larger than a given threshold. If there are extrema near it with opposite sign, the one with the largest absolute value is matched with it. The process then continue with the remaining extrema.

The case of a vertical magnetic dipole is rare and also easier to process—it generated only one extremum. We will not consider it here.

3.4 Estimation of dipole orientation and depth

There are many methods to estimate depth of targets based on magnetic or gradiometric maps; [5] uses a method from [6] where the depth d is given by:

$$d\left(x, y, z\right) = -3 \frac{B\left(x, y, z\right)}{\frac{\partial}{\partial z} B\left(x, y, z\right)} \tag{4}$$

where

$$\frac{\partial B}{\partial x}\left(x, y, z\right) = \frac{\partial B}{\partial y}\left(x, y, z\right) = 0 \tag{5}$$

This method is not applicable in underwater survey because since the sampling grid is coarse the precision of the location where the horizontal derivates are close to 0 is poor. In this paper the rest of the algorithm will be executed with a range of depths around the expected depth and the best results will be selected as explained below.

Since the magnetic field generated by a magnetic dipole is proportional to the magnitude of the magnetic moment, it is possible to normalise the measurement in order to estimate first the position and orientation of the dipole; the magnitude of the magnetic moment will be estimated afterwards by scaling.

The orientation of the dipole can be defined by two angles: its azimuth and its inclination. In the horizontal plane the dipole is expected to be in the direction passing through the two extrema. This is only an estimation because the Earth's magnetic field may alter slightly the location of the extrema. Simulation can be used to predict the output of the gradiometer along the profile defined by the two extrema with various values for depth and inclination. The magnetic moment is chosen to be a unit vector because its magnitude will be estimate as a last step. The profile is chosen to go beyong both extrema by 20%.

For each depth value between $5\ \mathrm{m}$ and $20\ \mathrm{m}$ the vertical gradient along the profile is estimated for various values of the inclination. For each depth the inclination which is selected is the one that best predicts the distance between the extrema. Then the couple depth-inclination that best predicts the ratio between the vertical gradients at the two extrema is selected.

The algorithm therefore requires an accurate estimation of the vertical gradient at the two extrema to get an accurate ratio. In practice since the maps are interpolated from coarse data acquisition, errors may be expected and this stage of the algorithm.

3.5 Estimation of the dipole location

Since the location of the dipole is known to be—approximately—between the two extrema the problem is reduced to finding the location along that line. This location is estimated by selecting the translation that best align the predicted extrema with the measured extrema.

3.6 Estimation of the magnitude of the magnetic moment

The magnitude of the magnetic moment is estimated by scaling the gradient generated with the parameters estimated as above to fit the measured gradient.

4 THE SIMULATION

We consider a survey performed by a gradiometer towed behind a ship. Many different gradiometer configurations are available and have been studied [7, 8, 9, 10, 11]. The gradiometer here is composed of three magnetometers measuring the intensity of the magnetic field. These measurements are combined to produced the three components of the gradient of the intensity of the field.

A survey is simulated over an area and the magnetic and gradiometric maps are produced. These maps are analysed following the algorithm described above to detect and classify ferro-magnetic targets.
A model of the entire survey has been built to be able to compare and evaluate detection and classification algorithms [12]. The model takes into account the targets, the trajectory of the sensor, the geometry of the sensor, the Earth's magnetic field at the survey location, errors in the measurement of the location and orientation of the sensor underwater, and the algorithms to interpolate the data and generate maps.
In this paper we present the evaluation of the algorithm. The main criterion to evaluate the algorithm is the evolution of the quality of the estimation of the depth and the magnitude of the magnetic moment as a function of the sampling grid and the error in the location of the gradiometer underwater.
The parameters of the simulation are the following.

- The North Sea is selected as the location of the survey. The Earth's magnetic field is chosen to be constant with the following values: declination: $-0.574°$, inclination: $66.496°$ and intensity: $48\,639$ nT.
- The speed of the ship is 5 knots along fifty 90-metre-long parallel tracks oriented in the North-South direction; the default distance between two tracks in 2 m but simulation will also be done with a range of distances to study the influence of this factor.
- The gradiometer is composed of three magnetometers, providing together the three componants of the intensity of the magnetic field; the acquisition frequency is 10 Hz; this means that there is one data acquisition every 26 cm along the track.
- The gradiometer is moving in a horizontal plane.
- The target is estimated by a magnetic dipole, located 10 m below the gradiometer; its magnetic moment is 30 Am^2; its azimuth $20°$ and its inclination $-3°$. The magnetic moment is located between two consecutive tracks of the gradiometer trajectory.
- Magnetic maps are built with a resolution of 10 cm.

5 RESULTS AND DISCUSSION

5.1 Effects of sampling grid

In this example different surveys are simulated with distances between two parallel tracks ranging from 0.5 m to 20 m. During a real survey, the choice of this inter-track distance is extremely important. Using a short distance will slow down the whole survey and increase its cost. If the inter-track distance is too large small targets may be missed.
The location of the gradiometer underwater is supposed to be known without error. The influence of these location errors is studied in the second simulation.
Fig. 1 presents the errors on the estimation of the azimuth of the magnetic dipole as a function of the distance between two tracks.
The target used in this synthetic example generates extrema that are located some 4 m apart in the West-East direction. As long as the distance between two North-South tracks is below that distance, the azimuth is estimated with an error below $2°$. Above that value the azimuth increases progressively because the locations of the extrema are no longer estimated precisely.
Fig. 2 presents the errors on the estimation of the location of the magnetic dipole as a function of the distance between two tracks.
The error starts to increase when the inter-track distance is above a little more than twice the distance between the extrema. The location estimation is more robust than the azimuth estimation.
The depth error has a similar behaviour, as can be seen in **Fig. 3**.
The error in the estimation of the magnitude of the magnetic moment, presented in **Fig. 4**, follows the same trend when the inter-track distance is above a little more than twice the extrema distance. Its behaviour for smaller inter-track distance values is, however, more unpredictable. The measured magnetic field around the two extrema varies a lot with distance. If too few data are acquired, the interpolation of the magnetic field may be inaccurate in this region.

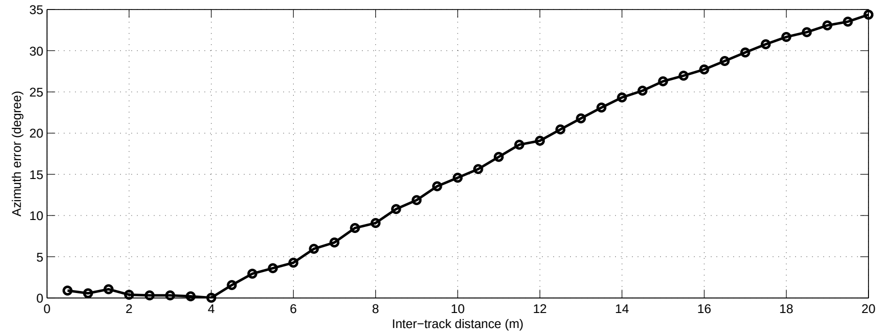

Fig. 1: Azimuth errors (in degree) as a function of the distance between two tracks (in metre)

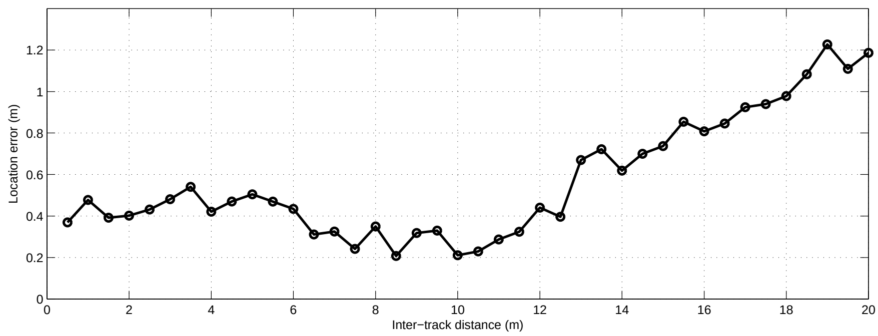

Fig. 2: Location errors (in metre) as a function of the distance between two tracks (in metre)

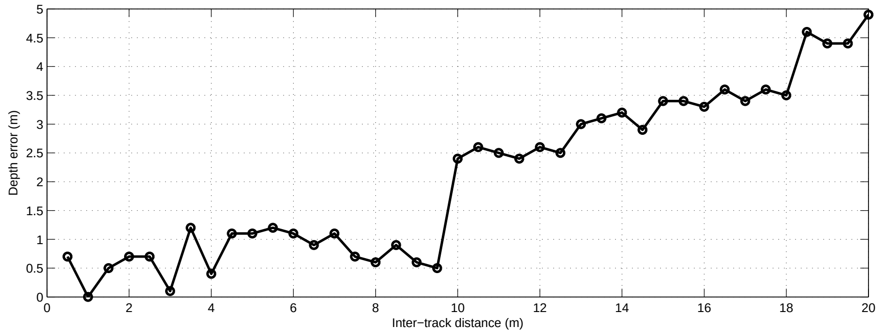

Fig. 3: Errors in the estimation of the depth (in metre) as a function of the distance between two tracks (in metre)

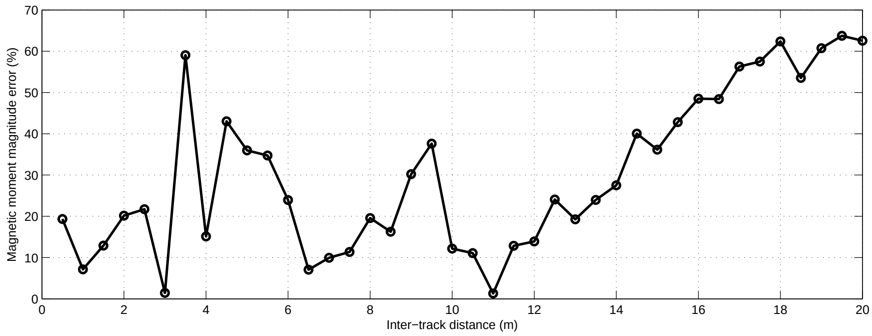

Fig. 4: Errors in the estimation of the magnitude of the magnetic moment (in %) as a function of distance between two tracks (in metre)

Since the dipole is always located between two consecutive tracks in this simulation, when the inter-track distance is above a little more than twice the distance between the extrema, no data is acquired above the dipole. The estimation of the magnetic field may be less accurate above the dipole, but since the magnetic field varies more smoothly away from the dipole, the errors of the algorithm progress also more smoothly then.

5.2 Effects of the noise

In this second simulation, the inter-track distance is kept at 2 m. A uniform noise is added to the location of the gradiometer with maximum values ranging from 0 m to 6.5 m. For each maximum value of noise, 25 surveys are simulated and the medians of the errors of the location, depth and magnitude of the magnetic moment are computed.

Fig. 5 presents the errors on the estimation of the location of the magnetic dipole and **Fig. 6** presents the errors in the estimation of the depth, both as a function of the noise. The errors rise progressively with the noise.

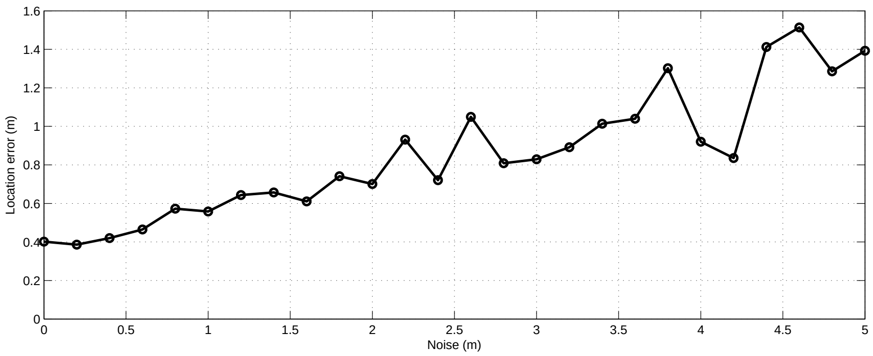

Fig. 5: Location errors (in metre) as a function of the noise (in metre)

Fig. 7 presents the errors in the estimation of the magnitude of the magnetic moment as a function of the noise. They are correlated to the errors in the estimation of depth because the algorithm is composed of several consecutive steps, each using the estimation of the previous one. Then when errors occur at a given step they tend to propagate to the next.

6 CONCLUSIONS

A simplified version of the AWD algorithm adapted to underwater survey has been evaluated on synthetic examples. This evaluation was done against the real values of the magnetic dipoles, which

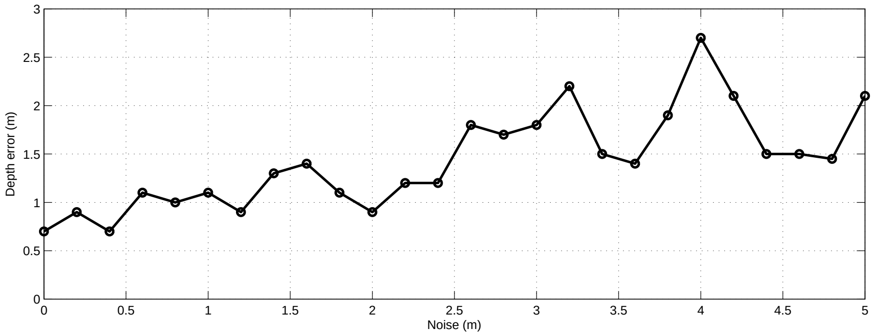

Fig. 6: Errors in the estimation of the depth (in metre) as a function of the noise (in metre)

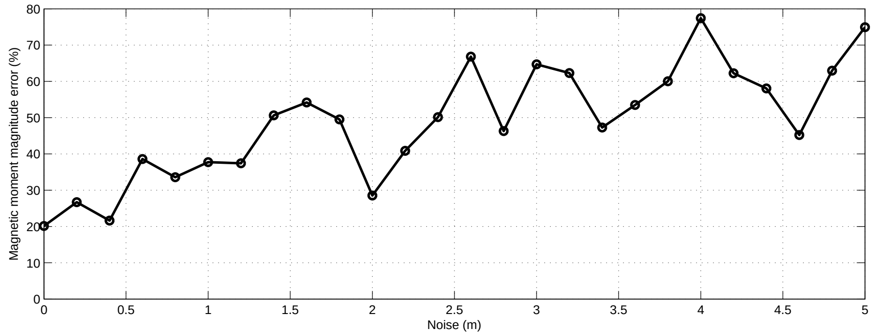

Fig. 7: Errors in the estimation of the magnitude of the magnetic moment (in %) as a function of the noise (in metre)

is not possible when the algorithm is tested in real situations.
Several conclusions can be drawn from these simulations. First, the errors of the algorithm increase progressively with the errors in the location of the gradiometer. It is therefore extremely important to have an accuracte estimation of the location of the sensor underwater.
Second, the distance between two tracks in the sensor trajectory has an impact on this algorithm especially when it is whithin the size of the magnetic anomaly generated by the target. Having several tracks over the target increases the quality of classification. Having only a few tracks, however, may generate artifacts that can decrease the estimation of the magnitude of the magnetic moment.
Third, since the different parameters are estimated in sequence, errors may propagate from one step to the next.

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