Magnetic Gradient Arrays for Marine UXO Surveys

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Introduction

A gradient can be defined as the rate of change with respect to distance of a variable quantity. Magnetic gradient surveys measure the rate of change of the earth's magnetic field between two or more locations simultaneously. These magnetic gradient data are generally not susceptible to diurnal variations in the earth's magnetic field, minor magnetic storms and certain other sources of noise. In typical marine surveys with sparse line coverage, anomalies observed in measured gradients are easier to identify than when using total magnetic field alone. The addition of gradient data can also provide for more consistent geological and geophysical interpretations. In this paper we will demonstrate some benefits of collecting and using magnetic gradient data for locating ferrous targets such as unexploded ordnance (UXO) or explosive remnants of war (ERW) in marine environments, with the aim to reduce survey costs and provide quality results.

Design considerations for marine UXO surveys

In the offshore marine environment it is critical to reduce risks for infrastructure development projects by identifying potential UXO targets. Missing potential UXO can be dangerous and costly. There are two sets of costs to consider in a marine geophysical survey design: acquisition costs and data processing or analysis costs.

To successfully collect marine data requires a survey vessel, crew and sensors. The cost for a survey vessel and crew vary depending on the region, survey location, vessel size, survey equipment (sensors), and time of year. The vessel and crew costs are many orders of magnitude more than the cost of renting or buying magnetometer sensors. Therefore, surveying with multiple sensors is advantageous, by acquiring gradient data between sensors as well as a wider swath of data coverage per survey line.

A magnetic gradient survey measures the difference in magnetic field between two magnetic sensors. However, a gradient survey is more than simply towing two or more sensors behind a vessel. Due to inaccuracies in positioning the individual sensors relative to one another, accurate gradient measurements cannot be readily determined for several individually towed sensors. By mounting sensors in a rigid array, it is possible to accurately determine gradient measurements between each pair of sensors. Sensors can be mounted in a variety of different configurations measuring one or sometimes all three gradients. A typical configuration has several sensors mounted in an evenly spaced line perpendicular to the survey direction, as the cross-line horizontal gradient is the most difficult to calculate without having dense line spacing. The configuration and gradients measured should be based on the overall aims of a survey.

Survey contractors often buy magnetometers and construct their own gradient arrays on towed platforms. Increasing the number of magnetometers towed can help widen the line spacing needed for full coverage, helping with vessel costs. In addition, these extra data increase our confidence in the target parameters that we interpret from the data.

The cost difference of data processing and analysis for individual or single sensor vs. multi or gradient array sensor surveys is minimal. Using purpose-built workflows, processing tools are easily configured to handle data from gradient arrays, with only a minor amount of additional time required for the analyst to review the additional sensor data.

Benefits of magnetic gradient surveys

The main goal of marine UXO surveys is to reduce risk to people and property. Therefore it is essential that surveys and analysis be of the highest quality possible. Measured gradients in a survey can be advantageous in a number of ways, to:

- Maximise coverage of the survey area
- Improve confidence through comparing two or more sensors
- Provide more reliable target or anomaly picking
- Reduce the chance of misinterpreting target size; and
- Improve modelling results of selected target anomalies.

In this paper we focus on the advantages of magnetic gradient surveys, but these gradient data should be accompanied by the individual total field values from each sensor to yield optimal analysis results.

Using gradient measurements in UXO surveys

A total field magnetic anomaly can be complex and depends on the survey latitude and longitude, as well as the orientation of the magnetic source and other parameters. Interpretation of magnetic data can be simplified by calculating the analytic signal (AS) which can be thought of as a map of the magnetization of the ground (MacLeod et al, 1993). Unlike total field or gradient data on their own, the analytic signal produces a map where the anomaly is always positive and is centred above a magnetic source. The analytical signal is therefore very effective in determining target location from a magnetic anomaly (Salem et al., 2002).

The analytic signal is defined as:

$$AS = \sqrt{\left(\frac{dB}{dx}\right)^2 + \left(\frac{dB}{dy}\right)^2 + \left(\frac{dB}{dz}\right)^2}$$

Where: B is the magnetic field, and
$\left(\frac{dB}{dx}\right)$, $\left(\frac{dB}{dy}\right)$, and $\left(\frac{dB}{dz}\right)$ are the spatial derivatives of B in x, y and z directions.

The derivatives can be calculated from total field magnetic data, where the sample spacing is close enough, using Fast Fourier transforms (FFTs). These spatial derivatives are also equivalent to the measured gradients across the line, along the line and vertically. While FFTs can be used to calculate the derivatives, these calculations tend to emphasize high frequency noise in the data. Given that the derivatives are equivalent to the measured gradients, where possible it is best to directly measure the gradients, ideally all three (Hrvoic and Pozza, 2006). However, the horizontal across-line gradient is the key gradient to measure, as it cannot be calculated for a single profile of data and is subject to the most noise if calculated using FFTs.

As shown in Figures 1 and 2, using even the simplest of gradient arrays, two sensors in a transverse or across line configuration, it is possible to calculate the analytical signal even for a single survey line (Tchernychev, 2009). The required horizontal derivative along the line and a vertical derivative can be calculated by virtue of the dense data samples along the line. Using measured horizontal gradient data in this way (and vertical gradients if also measured), results in an easier and more reliable interpretation of the magnetic anomalies.

While the magnetic gradient can simplify data processing, the total field data should not be abandoned. The use of total field and gradient data together allows for a better understanding of the nature of the anomalies. With a purpose-built workflow, there is little additional effort required to process the gradient data and total field data.

One of the challenges of processing total field magnetic data for marine UXO surveys is removing the effects of the temporal or diurnal variations in the earth's magnetic field. In terrestrial surveys this correction can easily be applied by collecting magnetic data at a local base or reference station during the survey, and subtracting from the survey data. However this can be difficult to accomplish while surveying at sea. As all sensors are similarly impacted by this type of diurnal noise, the measured gradients (which are simply differences between sensors) are relatively immune to it. However, by examining total field data from each of the sensors in an array, it is possible to better understand the nature of this temporal noise, along with the effect of regional geologic variations. All of the sensors in the array will measure the same variations, allowing for better definition of long wavelength filters to remove these sources of noise.

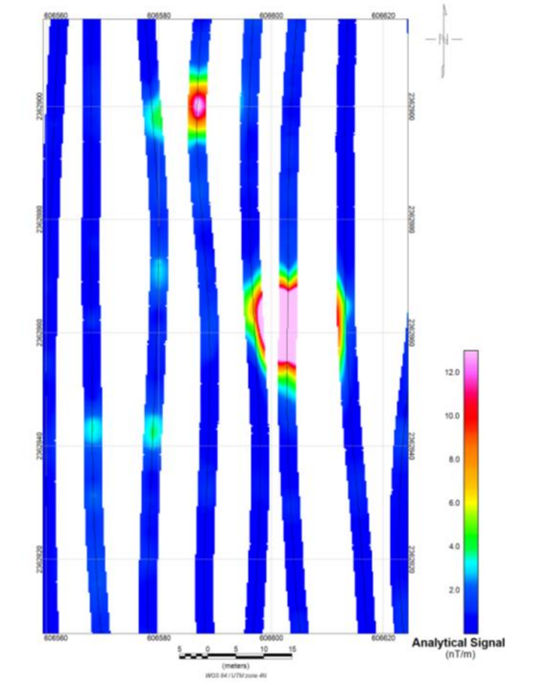

Figure 2*: Example of analytical signal calculated from a gradient survey despite lack of full survey coverage. Data courtesy of Geometrics Inc.*

Impact of positional errors on interpretation

Position and altitude (or XYZ location) of magnetometers can have a significant impact on the quality of interpretation of magnetic data. Positioning errors for underwater surveys are well understood and have well-defined correction procedures. However, depending on the type of GPS and USBL equipment used, even the most accurate position of the underwater sensors can have a minimum error range of 1-5 meters (Lekkerkerk & Theijs, 2011).

Altimeters are typically mounted on the survey platform and are effectively echo sounders with accuracy conditional on calibration frequency and seabed material. The altimeter accuracy (distance from platform to seabed) is usually more reliable than horizontal positioning in the marine environment. Single magnetometers require individual positioning along with a dedicated altimeter, whereas on gradient array frames, the locations of the sensors can be determined from a single position, one altimeter and a pitch and roll sensor.

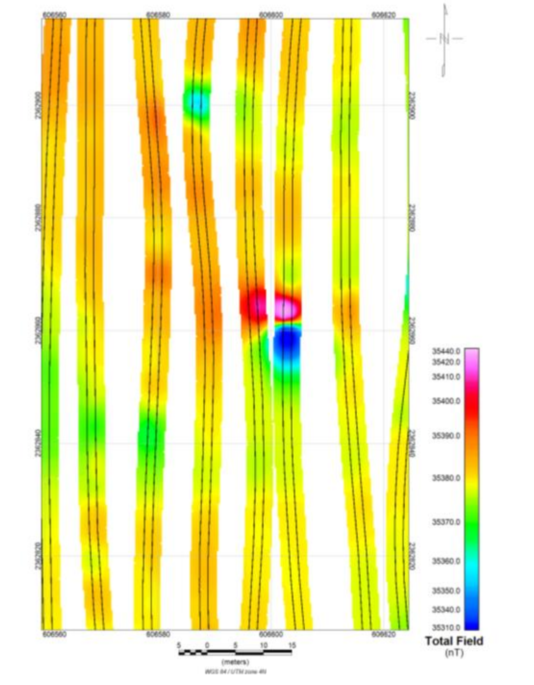

Figure 1*: Example of total field magnetic data from a gradient survey with two sensors. Data courtesy of Geometrics Inc.*

Any positioning error impacts the ability to correctly locate the anomalous features and leads to poorer results when modelling and interpreting the data. Freely towed individual magnetometers tend to have increased uncertainty due the accumulation of the errors relating to position and altitude. With gradient arrays this is limited to the location of the frame, as the relative location of each sensor is accurately known. In addition, individually towed magnetometers typically have a much greater range of altitude variation between survey lines, compared to gradient array frames.

There are a number of post-processing tools to correct and spatially interpolate magnetic data. Corrections include 1D and 2D smoothing filters and other interpolation methods, and care must be taken to not introduce additional noise or artefacts into the data. Arrays generally have fewer and simpler corrections required than single sensor data.

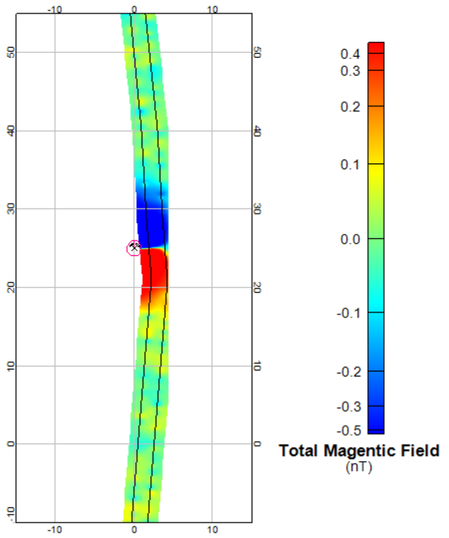

***Figure 3**: Example of synthetic gradient array data showing the ability to model a target "offline". The circle is the target location and the cross the modelled location.*

Modelling of UXO targets

After data corrections have been applied, analysts typically model the data to yield more information about targets such as estimated burial depths and magnetic moment, which can give an indication of whether the buried target is likely to be a UXO. The identification of potential UXO requires any model results and interpretations to have a high level of confidence associated with them. This confidence is highly dependent on data quality, which is impacted by the discussions above and many other factors during data acquisition.

Modelling the magnetic field provides superior results from a fixed frame gradient array rather than a single sensor. While it is ideal to measure all three gradients (across line, along line and vertical), as noted previously measuring the horizontal gradient alone does permit us to model the data with more confidence, even with the inherent navigation corrections that will persistently occur with offshore marine surveys. Figure 3 shows an example of accurately locating a target to one side of a single survey line of gradient array data. This would not be possible with single sensor data.

Noise in the single sensor data (from position uncertainty or otherwise), often results in difficulty fitting a model to the observed data, and thus unreliable modelling results. Having a gradient array with a fixed frame of sensors helps produce better models and more dependable results.

Conclusions

It is cost effective for marine UXO surveys to collect gradient array data. Collecting marine gradiometer or gradient array data has a number of benefits that improve overall survey quality resulting in greater confidence in the picked targets and improved analysis results from inversion modelling. This helps to reduce the number of anomalies or targets that are potential UXO and need to be investigated, saving significant time and money.

References

Breiner, S. [1999] Application Manual for Portable Magnetometers. Geometrics, Inc.

Hrvoic D, and Pozza M [2006] Mapping marine ferrous targets using real-time 3D analytic signal data. The Leading Edge, 25(1), 54-56.

Lekkerkerk H-J and Thesjs M-J [2011]. Handbook of Offshore Surveying Volume II. Positioning & Tides

MacLeod I, Jones K, and Dai T [1993]. 3-D analytic signal in the interpretation of total magnetic field data at low magnetic latitudes. Exploration Geophysics, 24(3/4), 679-688.

Salem A, Ravat D, Gamey J, Ushijima K [2002] Analytic signal approach and its applicability in environmental magnetic investigations. Journal of Applied Geophysics 49 (2002) 231– 244.

Tchernychev M, Johnston J, and Johnson R [2009] Transverse Total Magnetic Field Gradiometer Marine Survey in Hawaii: The Quasi-Analytic Signal Approach and Multi-Channel Total Field Dipole Modelling. Symposium on the Application of Geophysics to Engineering and Environmental Problems 2009: pp. 424-43