TRANSVERSE TOTAL MAGNETIC FIELD GRADIOMETER MARINE SURVEY IN HAWAII: THE QUASI-ANALYTIC SIGNAL APPROACH AND MULTI-CHANNEL TOTAL FIELD DIPOLE MODELING.

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Abstract

In this paper we present two techniques for Transverse Gradiometer (TG) data processing and their practical application. Using our method, the transverse gradient is measured using dual sensors. The longitudinal gradient is obtained using profile data history and the vertical gradient component is computed synthetically based on 2-D potential field theory using the Total Field along the profile. The magnitude of the gradient vector with vertical synthetic component is termed the Quasi-Analytic Signal. Data was also processed using the two Total Field channels and a Dipole Field matching algorithm. Positives and negatives of the differing approaches are discussed. An example of this processing method is shown for a TG survey conducted at a Navy Degaussing range in Pearl Harbor. This survey was conducted using a dual cesium vapor marine gradiometer with 1.2 m sensor separation. The data collected during the survey was presented as a Quasi-Analytic Signal Map, which is based on computation of the magnitude of the total magnetic gradient vector.

Introduction

Transverse and longitudinal magnetic gradient measurements have been employed for a number of years for target search and geologic survey. The techniques have advantages over conventional Total Field magnetic surveys including independence from Earth's field time variations and higher frequency content of the data. As a result local anomalies are clearer and in some cases the data can be simplified using Analytic Signal calculations. Systems with sufficient sensor separation can be treated as two parallel Total Field lines thus doubling production rate. There are also some disadvantages. In general, the gradient is less sensitive to deep sources and the system is more difficult to deploy and tow. The risk of losing the equipment is higher and the overall system is more expensive to transport.

We will present two approaches to the processing transverse gradiometer data: first as part of the gradient vector analysis and two, as dual Total Field measurements. In the first case we reduce two Total Field channels to the Quasi-Analytic Signal, which we posit is a good substitute for the fully measured Analytic Signal. To support our contention, numerical modeling was performed (Tchernychev at al, 2008) and the results are briefly outlined in this article. Quasi-Analytic Signal computation does not require any definitive object model and leads to significant data simplification. In particular, horizontal locations of the anomalous objects can in most cases be taken directly as locations of the signal maximums and depth can be estimated using simple "half-width" rules. However we see that this approach may not work well for sparsely separated survey lines.

The second approach utilizes two Total Field channels and a dipole model to estimate object location. The Open Source Inversion library (Tchernychev, Snyder, 2007) was used to carry out these computations. It has limited applicability because the code operates on only relatively small objects, but it allows locating objects not directly below the gradiometer. Dipole matching also does not require diurnal correction or Total Field map compilation.

We have used both these methods to process data collected at the Navy Degaussing Range, and the results are presented below.

Data processing techniques

Using a Transverse Gradiometer to compute the Quasi-Analytic Signal

Analytic Signal is widely used in the magnetic data interpretation (Roest, 1992), (Salem, 2002). It has the following advantages:

- It is always positive.
- It has a simplified signature because anomalies have one polarity.
- It provides an estimation of the horizontal coordinates of the object from the coordinates of the anomaly maximums.
- It simplifies depth computation using half-width rules or Euler deconvolution.

The Analytic Signal is defined as $A = \sqrt{G_x^2 + G_y^2 + G_z^2}$ where G_x, G_y, G_z are orthogonal components of the gradient vector of the total magnetic field. The Analytic Signal can be directly measured with a synchronized array of sensors or it can be computed using the measurements from two synchronized sensors deployed in the form of a transverse gradiometer (Quasi-Analytic Signal). In this article we consider the latter configuration.

With a transverse gradiometer, only the component perpendicular to the direction of travel is measured directly. The longitudinal component is obtained using data acquisition history along the path and may contain both temporal derivatives as well as gradient information. The vertical gradient component G_z can be estimated using well-known potential properties of the total magnetic field by filtering in the frequency domain (Blakely, 1995).

The validity and limitations of such an approximation were evaluated using numerical and dipole modeling at different field inclinations (I) and declinations (D) (Tchernychev, 2008). Figure 1 presents the results from that study where a dipole with an induced moment of 100 Am^2 was placed 10 m below the observation surface and the field computed in a 100m x 100m area around it. The dipole's horizontal location was at 0,0 m. Numerical simulation was performed using a transverse system with 1.5 m sensor separation and line spacing of 0.1 m. To compute the true Analytic Signal a third sensor was added in the middle of the array at 0.5 m elevation. We conclude the following:

- Both Quasi-Analytic and Analytic Signal plots produce similar field signatures. In all cases these signatures are quite different from the Total Field signatures.
- The central section (approximately 90% of the anomaly) is very similar for both types of Analytic Signal computation.
- At lower signal levels the techniques exhibit significant differences. However this difference is only seen at very small anomaly values (<0.1 nT/m, note non-linear color scales).

The modeling results clarified that the two-sensor Quasi-Analytic Signal system could be used as a substitute for the three-sensor Analytic Signal system. Note that the horizontal stability of the platform is important. Our estimates show that roll angles in the range of ± 25° can be tolerated.

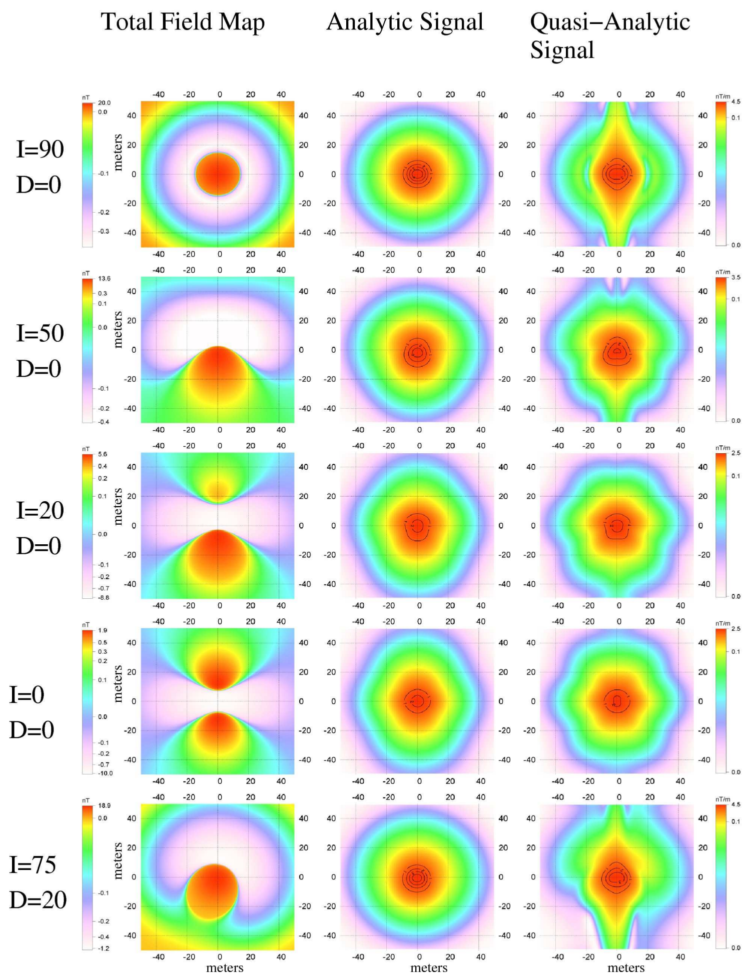

Figure 1 Comparison of the Analytic and Quasi-Analytic Signals using dipole models at different magnetic field inclinations (I) and declinations (D). Total Field color scale is on the left and Analytic Signal color scale is on the right of the Figure.

Dipole matching.

The transverse gradiometer also can be treated as a simple magnetometer sensor array. It is possible to estimate the target location by inverting two Total Field magnetometer channels simultaneously using an anomaly model, the simplest being the dipole model. The parameters to be estimated are X, Y, Z locations of the dipole and the magnetic moment J_x, J_y, J_z. The average Earth's magnetic field value is assumed to be linear. Because only a short segment of the data is selected for inversion, magnetic time variation influences are reduced. As time variation affects both sensors simultaneously, it is automatically included in the Earth's field parameter estimation (Tchernychev, 2007). A rigid gradiometer frame guarantees that relative positions of the sensors are fixed during one pass thus reducing position misfit common for multiple passes.

The Survey

The objective of the survey was to locate magnetic objects on the seafloor, which could interfere with Navy degaussing operations. The US Navy selected an area of approximately 500m x 700m. The line separation was selected as approximately 10 meters. The survey was completed over two days in September 2007 and the data was transferred to “Geometrics” for processing.

At the time of this article publication, no report of dive operations is available.

Transverse gradiometer hardware

We used a classical rigid transverse gradiometer system shown on Figure 2. It consisted of two standard high resolution, high sensitivity cesium vapor magnetometers mounted at 1.5-meter separation on the rigid frame[1]. An echo sounder (altimeter) was mounted in the middle of the tow frame. Two dihedral wings were attached to the magnetometers at 45° angles to improve hydrodynamic stability. Both magnetometer sensors included high precision depth transducers. They are also used to estimate the tilt angle of the system while undertow. Magnetic sensors, depth sensor and altimeter were synchronized to 1 ms interval with the logging software. The default system sample rate was 10Hz.

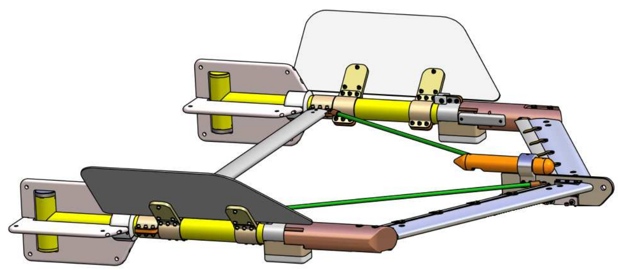

Figure 2 Transverse gradiometer drawing of the system used for Navy Degaussing Range Survey.

Multiple sea trials demonstrated that this towed platform is stable in the water column regardless of the speed and direction. No rollovers, porpoising or other problems were observed. We found it was possible to accelerate the boat to 10 knots without risk of unexpected platform behavior. This can be crucial in case of emergency. Because the magnetometers are sampling at high speed (10 Hz or more) this means that the typical survey speed can be increased providing a higher survey production rate.

Total Field and Quasi-Analytic Signal Maps.

We used the individual magnetometer channels of the gradiometer were to produce the Total Field Magnetic Map (Figure 3). The grid was interpolated on a 0.25 x 0.25 m cell size using the Gridding in Tension method (Smith, 1990). It is overlaid with the dipole inversion results shown with cross symbols. Each cross is the result of a two-channel dipole inversion where the interpreter manually selected the data intervals.

It can be seen that the Total Field map exhibits a significant geological trend, which makes it more difficult to pick local targets of interest. It would be beneficial to high-pass the gridded or profile data to highlight local anomalies. However any filtering process distorts the shape of the field and could introduce false anomalies. Therefore filtering can only be used for qualitative analysis of the data in the “mag and flag” mode where no attempt is made to estimate the position and depth of the source.

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[1] For the Hawaii survey, 1.2 m separation was used.

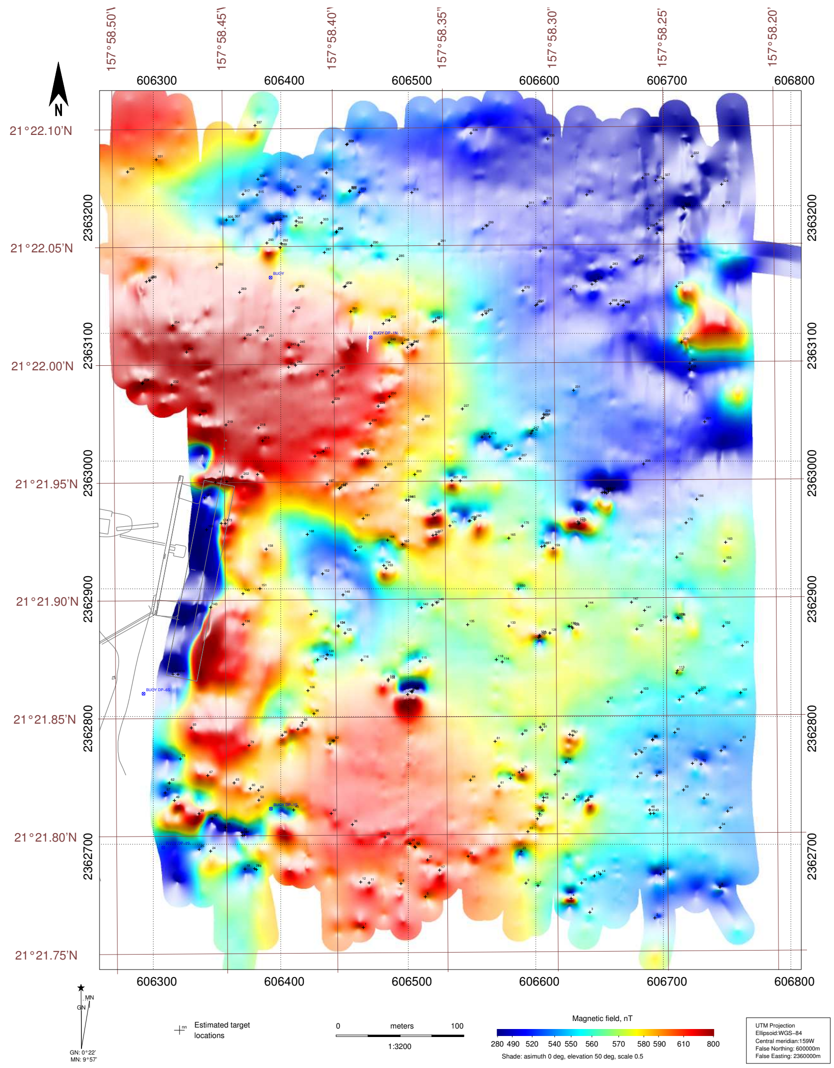

Figure 3 Total Magnetic Field map for Navy Degaussing range, diurnally corrected. Profile dipole inversion results are shown with cross symbols (see below). A pier structure and buoys are shown in outline.

The Quasi-Analytic Signal map generated from the transverse gradient data provided us with a Total Field Map with high-pass qualities. Transverse, Longitudinal and Vertical gradients were calculated individually for each profile and the spatial reference was re-located to the middle of the transverse gradiometer. Raw magnetic field measurements (prior to diurnal correction) were used to demonstrate the robustness of the method, because in most marine surveys a base station record is not available. Quasi-Analytic Signal data were interpolated in the same manner as for the Total Field. The resulting map is presented in Figure 4.

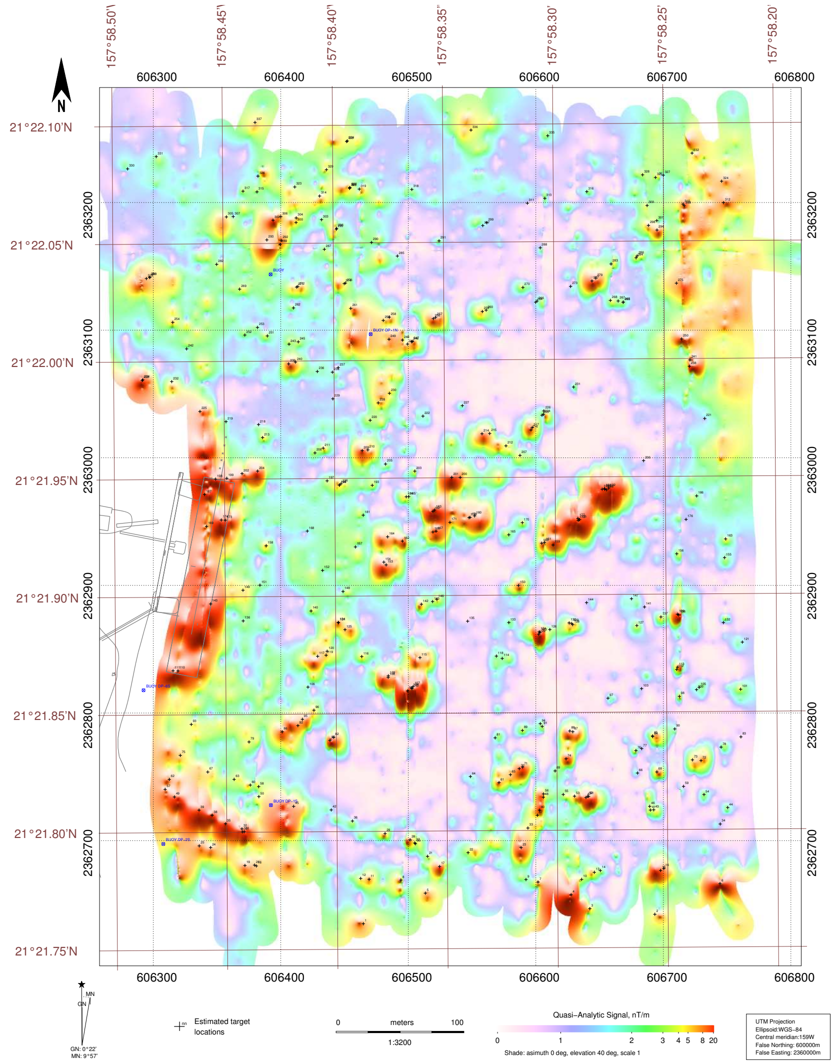

Figure 4 Quasi-Analytic Signal map for Navy Degaussing Range, interpolated from profiles. Results of dipole inversion (the same as on Figure 3) are shown with cross symbols.

It can be seen that field in Figure 4 is greatly simplified compared with the Total Field Map. It is possible to estimate the horizontal locations of the targets directly from the map[2]. Half-widths of the anomalies may be used as depth estimates. However, it is clear that the results of dipole inversion do not always coincide with maximum values of the Quasi Analytic gradient.

One of the essential properties of the Quasi-Analytic approach is that it is computed on a line-by-line basis. Therefore dense coverage is not required. This is of particular benefit in marine surveys where it is difficult to get dense coverage and therefore grid based analytical methods (Blakely, 1995) cannot be used to compute Analytic Signal Maps. A stacked-profile presentation mode is sufficient for transverse gradiometer Quasi-Analytic Signal data, especially useful for pipeline-locating surveys.

[2] In this article only results of dipole inversion are used as target locations.

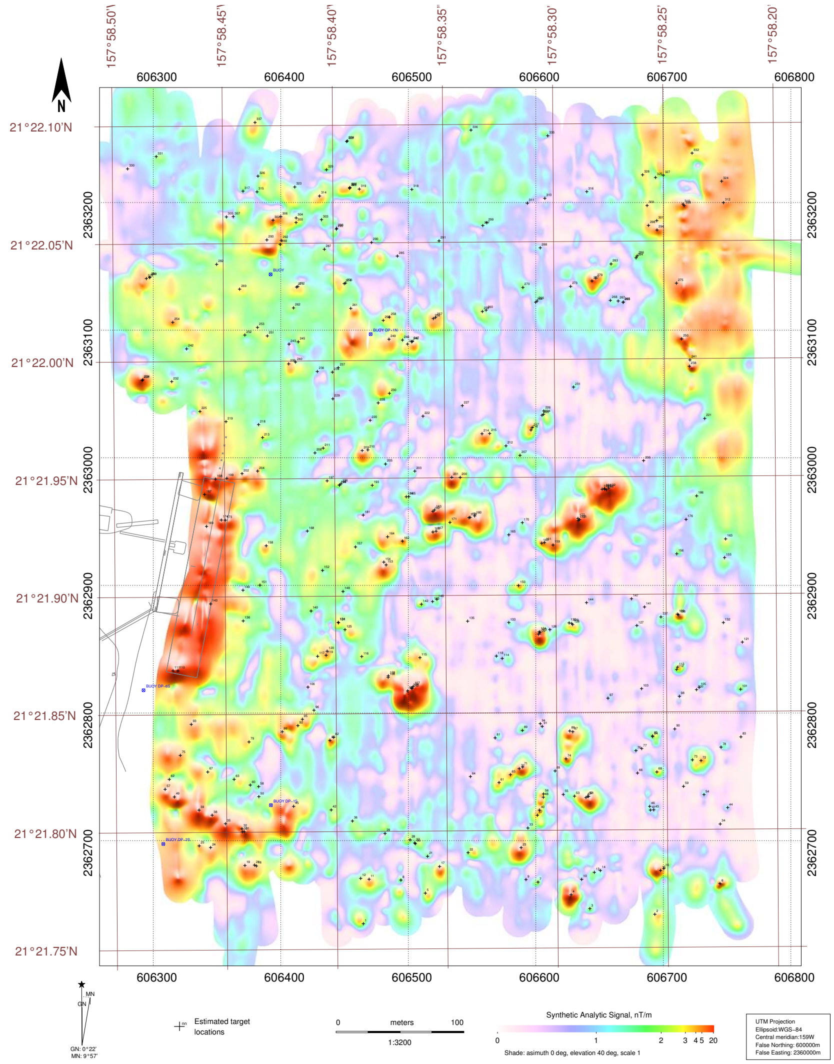

Figure 5 Synthetic Analytic Signal Map. Cross symbols denote target locations (the same as Figure 3, 4). This map is derived directly from the Total Field Map and therefore includes diurnal correction of the data.

The survey data was collected with line-to-line separation sufficient to produce an Analytic Signal map by synthetic computation. The computation procedure is well known (Blakely, 1995) and is grid based. Horizontal derivatives are obtained as finite-differences in the spatial domain or by filtering in the frequency domain. The vertical derivative is computed in the frequency domain. It is interesting to compare the Quasi-Analytic Signal map computed on profile basis with the synthetic Analytic Signal map computed directly from the Total Field. Note that the latter uses diurnally corrected data, unlike that used for the Quasi-Analytic Signal map.

The synthetic Analytic Signal Map is presented in Figure 5. It can be seen that it retains the main features of Quasi-Analytic Signal map shown in Figure 4.

Target position estimation

Although it is possible to use the Quasi-Analytic Signal for target position estimation, in this study it was used only to generate a map. Most of the target positions for the Navy Degaussing Survey were estimated using one pass of the transverse gradiometer and dipole inversion. Here we describe one of these targets in details.

Figure 6 shows two passes with the Transverse Gradiometer. Two lines are shown: line #1 is from South to North and line #2 is from North to South. Clear magnetic anomalies were recorded on both lines and are presented in Figure 7. Line #1 exhibits a negative anomaly and line #2 exhibits a positive anomaly. The difference in the magnetic field recorded by the two sensors on each pass is only in the range of 2nT in amplitude. It can be seen that the inner sensor recorded less magnetic anomaly than outer sensor. The polarity of the observed anomalies suggests that the source of the magnetic disturbance is between the lines. Average water depth in the area is 12.7 meters[3]. Line #1 was made with average gradiometer tow depth of 9 meters; line #2 was slightly higher at 8.4 meters. The minimum distance between centers of lines #1 and #2 is approximately 4.2 meters.

We present the dipole inversion results based only on line #1, only on line #2 and with both lines in Figure 7 and in Table 1. We illustrate the "quality of fit" in Figure 8, which shows observed and synthetic fields and their respective models. Table 1 summarizes the estimates.

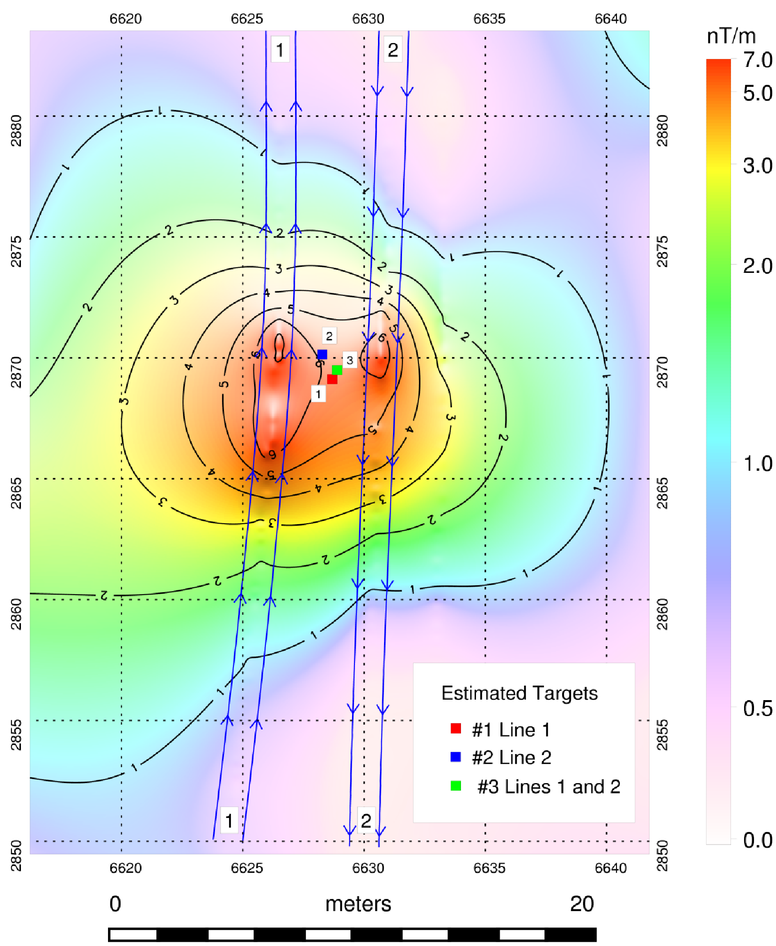

Figure 6 Transverse Gradiometer data interpretation using simultaneous inversion from two Total Field channels. Two passes over the target are shown. Sequential estimations were made using only data from line #1, only line #2 and both lines. Quasi-Analytic Signal is shown as a background map.

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[3] Gradiometer depth and altitude were estimated using on-board altimeter and pressure sensors. Total water depth was derived from these data.

Table 1: Dipole interpretation results. Depth is below seafloor. The typical standard deviation for position estimates is ±0.1 m. The table also shows estimated Earth field inclination, declination and value of the target magnetic moment.

	X, meter	Y, meter	Depth, meter	Fit nT	Inclination degrees,	Declination degrees	J_{total} cgs
Line 1	6628.7	2869.1	0.9	0.3	0.4	-78	40794
Line 2	6628.3	2870.1	0.8	0.2	-4.1	-75	47251
1 and 2	6628.9	2869.5	0.7	0.5	4.3	-84	40050

Note that the position estimates are consistent and point to approximately the same location in between the two survey traverses. The Quasi-Analytic Signal map (background on Figure 6) misconstrues the anomalies showing three local maximums as well as a broad main anomaly. If only one line (either #1 or #2) was available to the interpreter and if the Quasi-Analytic Signal was used to estimate target locations, the targets are likely to be misplaced. However, dipole interpretation produces highly coherent results even when only one line is available. Indeed, if line #1 records a negative anomaly and line #2 a positive anomaly, then the object should lie between these lines - unless there are two or more objects present. This example illustrates a potential weakness in the Analytic or Quasi-Analytic Signal approach for reliably locating small objects such as an Unexploded Ordinance (UXO) especially in marine surveys with sparse line spacing, regardless of the number of sensors used to measure the gradient components.

If we consider dipole targets, which are not directly beneath the magnetometer array, Total Field transverse gradiometer data always includes some information about the target location relative to the survey line. For instance, we might find different amplitudes on different channels and possibly different polarities. This information is lost when the data is converted into the single positive Analytic Signal anomaly.

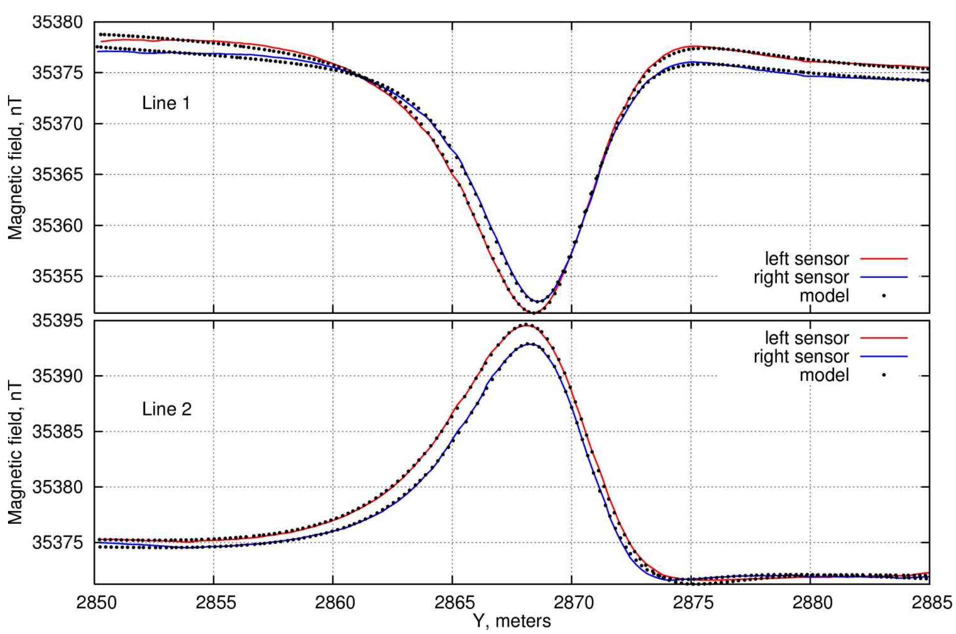

Figure 7 Magnetic field recorded on Line #1 (top) and line #2 (bottom). Respective modeling results are shown with black dots.

Conclusions

Numeric modeling has shown that the computed Quasi-Analytic Signal delivers a good approximation of the Analytic Signal measured with three or more sensors. We compared the Quasi-Analytic Signal with the Analytic Signal computed synthetically using an interpolated Total Field Grid. We found that the results are quite similar. However the Quasi-Analytic Signal analysis has an advantage because it is computed on a profile basis and does not require dense coverage of the area for gridded analysis.

We presented a practical application of a dipole-matching technique and compared this with Quasi-Analytic Signal processing. It appears that dipole matching may have an advantage over the Analytic or Quasi-Analytic Signal approach for small targets. The Analytic Signal may give misleading results when locating isolated targets. However Analytic or Quasi-Analytic signal processing can give a distinct advantage when searching for elongated targets such as pipelines.

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