Total Magnetic Field Transverse Gradiometer as UXO locating tool: case study on Oahu, Navy Degaussing Range, Hawaii.

Mikhail Tchernychev (misha@mail.geometrics.com), Jeff Johnston jeff@mail.geometrics.com), Ross Johnson (ross@geometrics.com)
Geometrics, Inc. 2190 Fortune Drive, San Jose, CA, 95131, USA

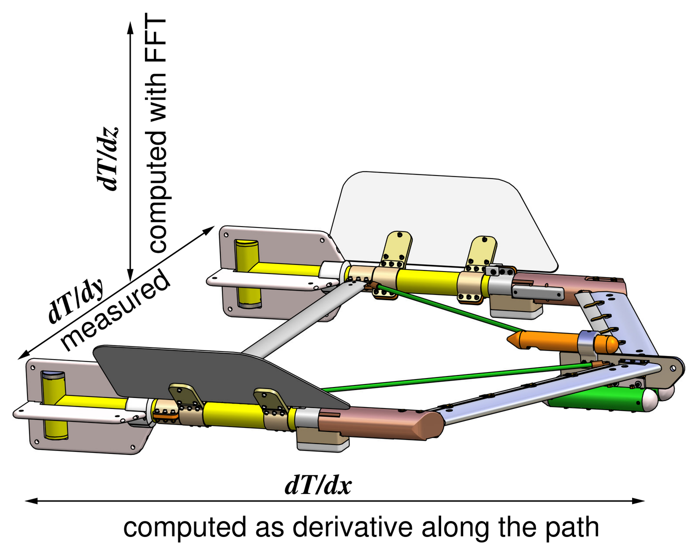
Introduction

This presentation is based on the Marine Transverse Magnetic Gradiometer (TG) Data acquired during survey at the Navy Degaussing range on Oahu. The objective of the survey was to locate magnetic debris possibly including Unexploded Ordinance (UXO), which could interfere with ship degaussing operations. The survey was conducted with a towed TG consisting of two synchronized cesium vapor magnetometers separated by 1.2 m.

Two techniques for Transverse Gradiometer (TG) data processing are described here. First, the survey data is presented as a Quasi-Analytic Signal Map, representing the computed magnitude of the total magnetic gradient vector. This quantity is also known as the Analytic Signal. With this approach only the two horizontal components of the gradient need be measured, specifically the transverse and longitudinal components.

In the second technique, the survey data was processed using the two independent total field channels and a Dipole Field Matching algorithm to determine target position and depth. It allows target position estimation using only a single pass through the survey area, eliminating the necessity of compiling and analyzing a magnetic field map.

The complete set of report documents is presented. This includes Total Field and Quasi-Analytic Signal maps, spread sheet of targets and target anomaly pages. Each page includes a zoomed in portion of the map, graphs of observed and calculated magnetic fields and digital target information.



$$\text{Quasi-analytic signal} = \sqrt{(dT/dx)^2 + (dT/dy)^2 + (dT/dz)^2}$$

Figure 1 Geometrics Transverse Gradiometer, similar to the one used in Pearl Harbor project. Annotations show how Quasi-Analytic Signal is computed.

Gradiometer Hardware

A classical rigid transverse gradiometer system was used as shown on Figure1. It consists of two standard high speed and high sensitivity cesium vapor magnetometers mounted at 1.2-meter separation on a rigid frame. An echo-sounder (altimeter) is mounted in the middle of the tow frame. Dual dihedral wings are attached to the magnetometers at a 45° angle to improve hydrodynamic stability. The magnetometer sensors have high precision depth transducers installed for depth recording, which are also used to estimate tilt angle of the system in the water. The magnetic sensors, depth sensors and altimeter are synchronized to 1 ms interval. The default system sample rate is 10Hz.

Data processing techniques.

Using Transverse Gradiometer to compute Quasi-Analytic Signal.

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

- It is always positive.
- It has a simplified signature: only single-maximum anomalies are normally present.
- It allows estimation of horizontal coordinates of the local object just by taking maximums of the anomalies
- It simplifies depth computation with half-width rules or Euler deconvolution.

*The Analytic signa*l 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 c an be directly measured with the synchronized array of three or more sensors or it can be estimated using the measurements from just two synchronized sensors deployed in the form of a transverse gradiometer. In latter case it is termed the Quasi-Analytic Signal.

Figure 1 illustrates how the Quasi-Analytic Signal is computed with the 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 can be estimated using well-known potential properties of the total magnetic field (Blakely, 1995) by filtering in the frequency domain.

It has been shown (Tchernychev at al, 2008) that Quasi-Analytic Signal analysis provides a good approximation for Analytic Signal values measured with three or more sensors.

Dipole Matching

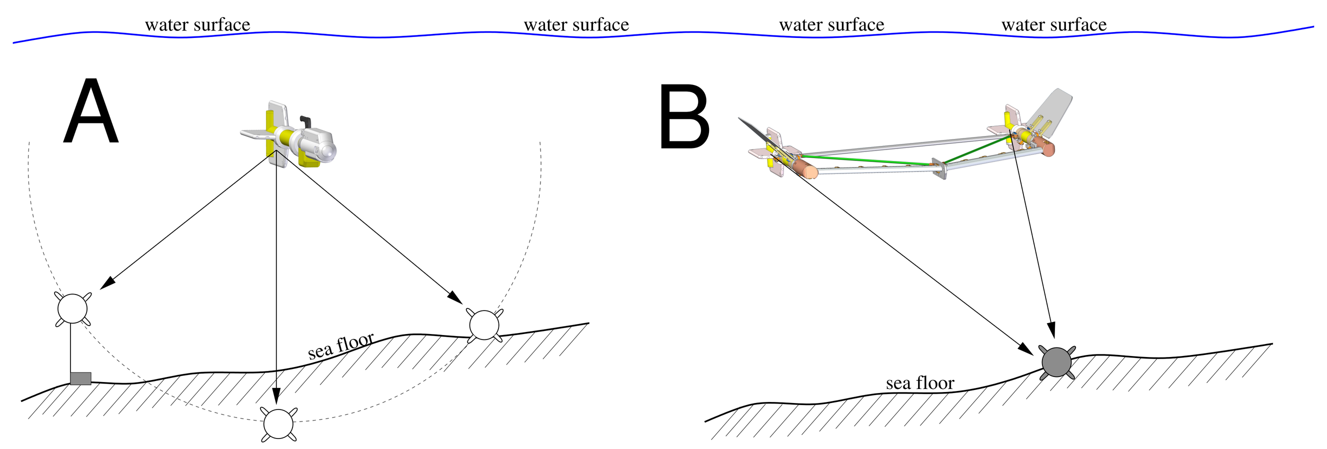


Figure 2 If a single magnetometer is used (A), only the distance from the sensor to the target can be estimated, which leaves an uncertainty in the target position. With a transverse gradiometer (B), true X,Y,Z location of the target can be estimated.

The transverse gradiometer (Figure 2B) can also be treated as a magnetometer sensor array. It has a substantial advantage over the single magnetometer (Figure 2A). With such an array it is possible to estimate X,Y,Z target location by inverting two total field magnetometer channels simultaneously using a dipole model (Tchernychev, 2007). The parameters to be estimated are X,Y,Z of the dipole, magnetic moment J_x, J_y, J_z and average Earth's magnetic field value in the area. The latter can be modeled with a linear function. Because only a short segment of the data is used for the inversion, magnetic time variation influence can be neglected: the time variation affects both sensors simultaneously and is automatically included in the Earth's field parameter estimation.With two sensors there is no need for multiple passes over the same anomaly, even though this would increase the accuracy of estimation. A rigid gradiometer frame guarantees that relative positions on the sensors are fixed during one pass thus reducing position misfit common for multiple passes.

Data processing flow

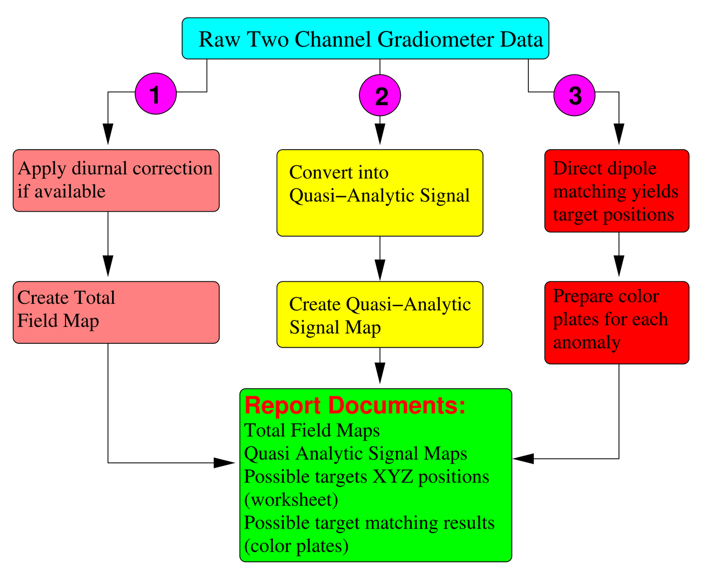


Figure 3 Transverse Gradiometer Data processing routes.

Transverse gradiometer data can be treated in the following manner:

- **Traditional approach**. Two Total Field Channels are used to interpolate a Total Field Map. Each channel is treated with its respective positions. Diurnal correction is needed. In many cases the map may be obscured by low-frequency geological and man-made anomalies. A single source anomaly signature can be complex and include positive and negative lobes, which complicate target location. High-pass filtering of the profile data to remove low-frequency geologic signal may be needed prior to map interpolation. Filtering may distort the shapes of the anomalies. The outcome is the Total Field Map, which represents both geological and local (such as UXO) magnetic anomalies. Horizontal UXO location can be roughly estimated using the position between positive and negative lobes of the magnetic anomaly.
- **Quasi-Analytic Signal Approach.** Two Total Field Channels are converted into Quasi-Analytic Signal, thus yielding only one channel, re-positioned to the center of the gradiometer. This simplifies overall field signature and also filters out low-frequency geologic structures. Diurnal correction is not required. The single source (UXO) anomaly is bell shaped and has its maximum located approximately above the target. Thus the horizontal coordinates of the UXO magnetic sources are readily determined. The depth can be estimated based on half–width maximum anomaly rules. The Quasi-Analytic overview map is better suited for local target location than Total Field Maps.
- **Direct Profile Data Interpretation.** Two Total Field channels can be used to estimate target location. No diurnal correction is required. Anomalies are hand picked from the profile data by the interpreter. Future software development will automate this procedure and provide for real time UXO location.

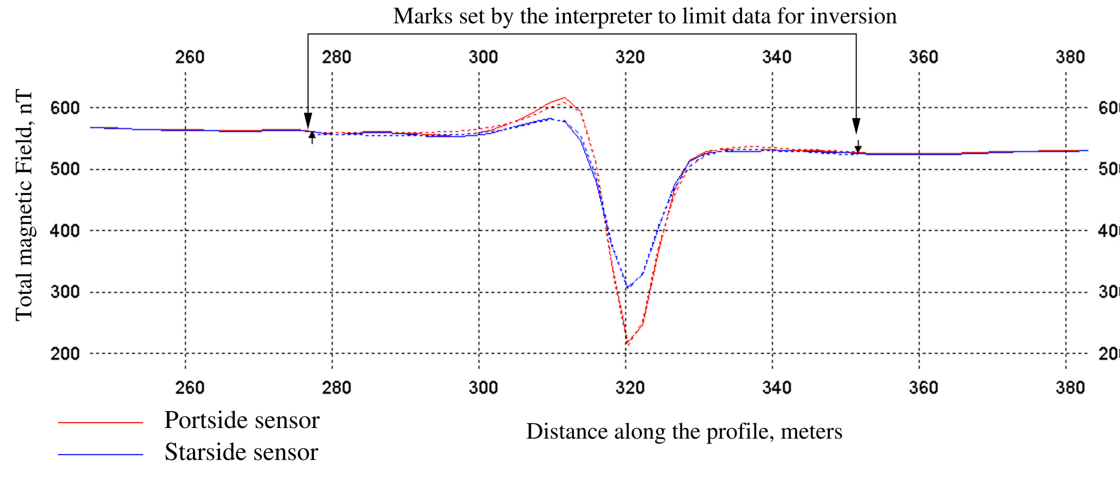


Figure 4 Sample screen shot of profile data interpretation. Interpreter selects the area of interest by putting two marks (up and down arrows) on the graphs. The program estimates the dipole location using data limited by the marks. After the fit is complete, a synthetic field (field created by computed dipole) is plotted with dashed lines. Estimation results such as position, depth, amplitude, direction of magnetization, etc. are saved in a spreadsheet.

Survey maps

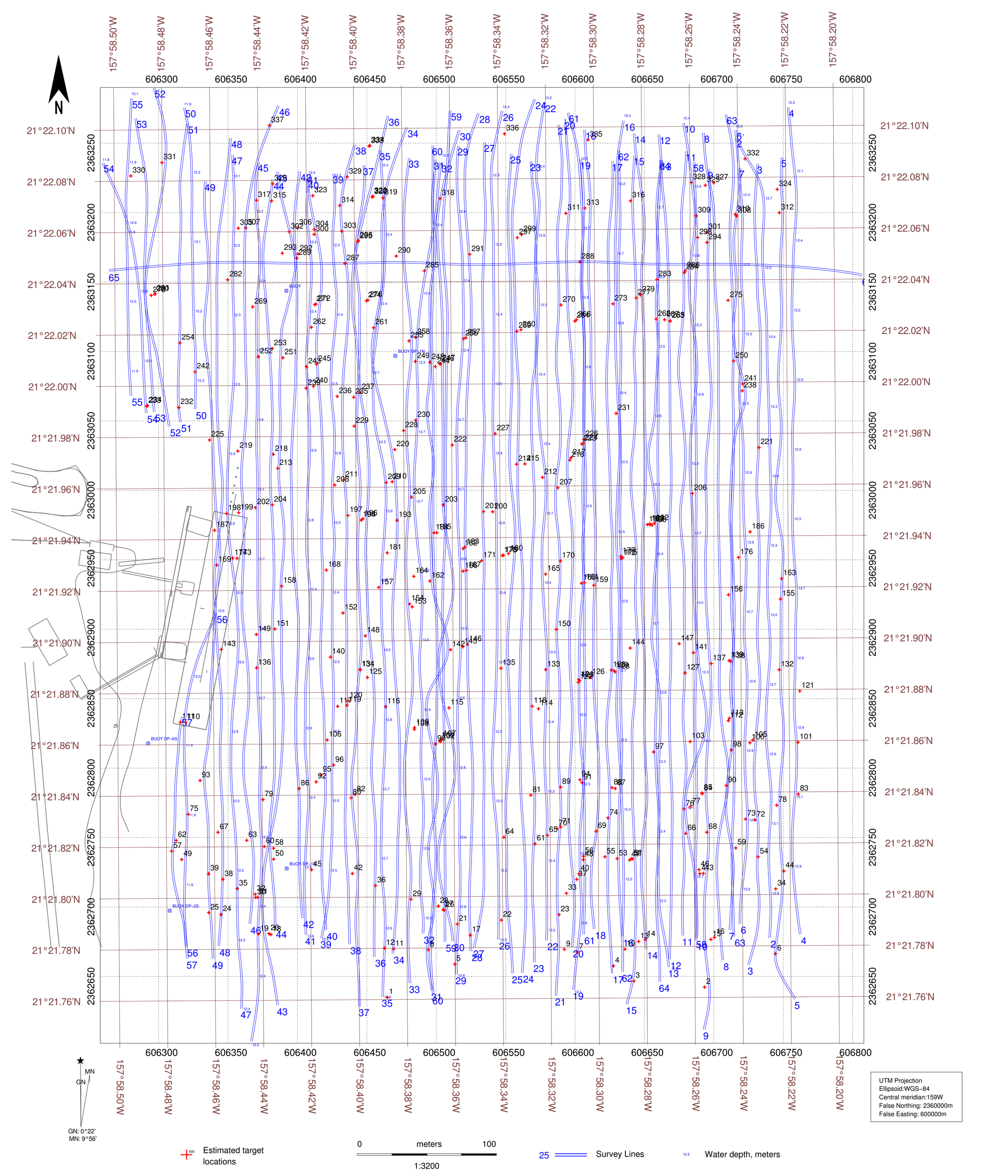


Figure 5 Survey data acquisition lines. Approximate line separation is 10 m. Tracks of both sensors are shown, with sensor separation of 1.2 m. Map is annotated with water depth as it was recorded by on-board altimeter and depth sensors. Estimated target locations are shown in red.

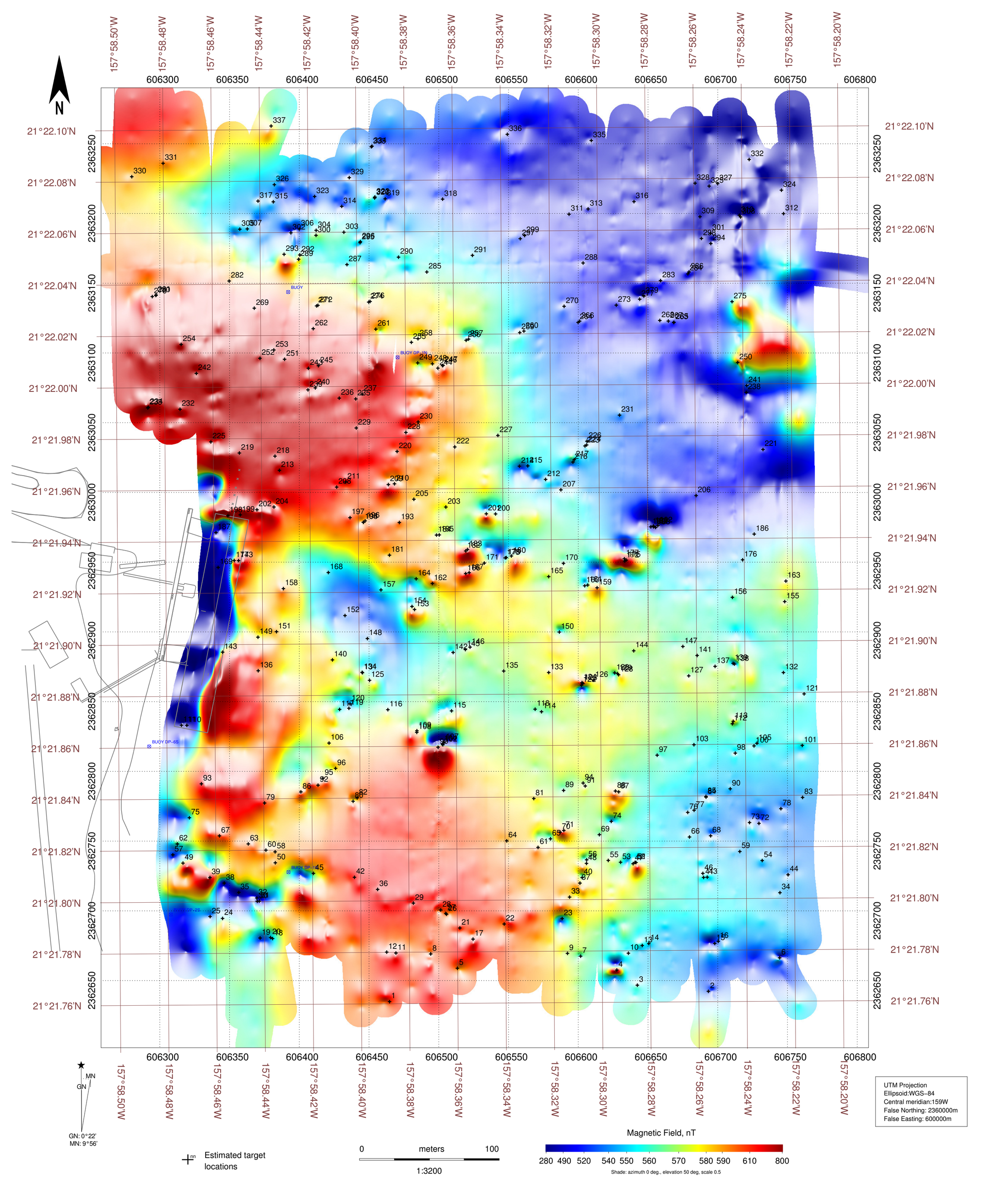


Figure 6 Total Field Map with diurnally corrected data. Substantial geological trend can be seen across the area. Target locations are annotated in black.

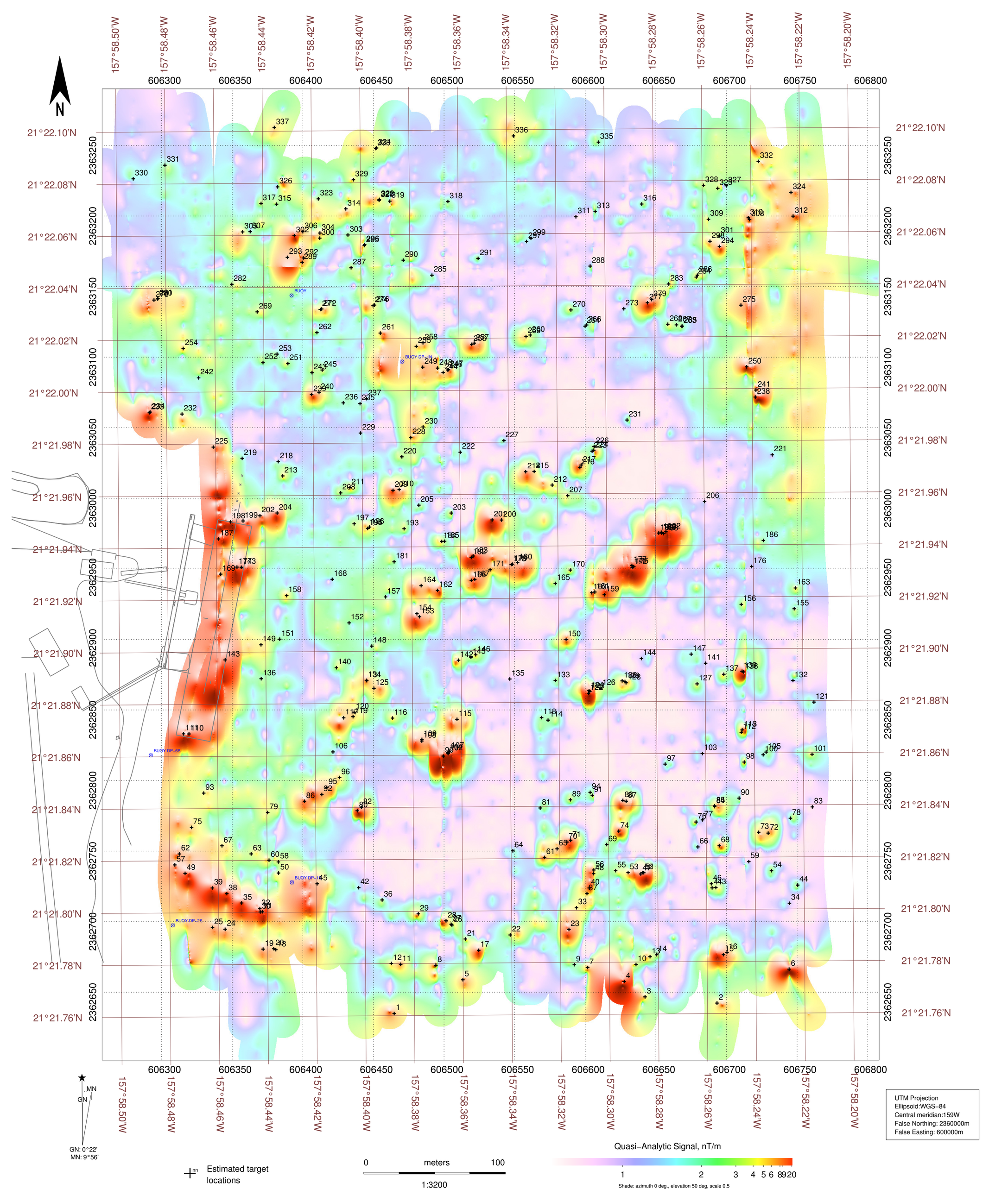


Figure 7 Quasi-Analytic Signal Map provides cleanlier view of the local anomalies of interest. Each anomaly is positive and centered approximately above the object. The map is overlaid with target locations obtained from profile based dipole Total Field Inversion.

Reported target information

Spreadsheet:

Target estimation results were summarized and presented to the customer as a spreadsheet with the columns listed below. The most important columns are underlined.

1. **<u>ID</u>** – Target number. All targets were sorted from South to North.
2. **<u>X(m) Y(m) Z(m)</u>** – Target position in UTM coordinates and depth below the sea floor, defined with gradiometer depth sensor and altimeter, thus eliminating necessity of making water depth corrections due to tides .
3. **<u>Latitude and Longitude</u>** – Target position in the geographical coordinates, WGS-84, was included for customer's convenience.
4. **Amplitude (nT)** – This is the amplitude of the synthetic anomaly, after removal of the ambient field. It is a qualitative measure of the importance of the anomaly; however, low amplitude does not necessarily mean the anomaly is not important; it could be small due to an increased distance to the target.
5. **FIT(nT)** – This is a measure of the quality of the inversion. It is a least squares fit between observed and modeled fields. All anomalies included in the spreadsheet have been analyzed for acceptable fit.
6. **MASS(kg)** – This simple mass estimate is based on the assumption that 1 ton of steel typically has 10^5 cgs units of magnetic moment (Breiner, 1973). It should be noted that real mass could differ by the order of magnitude because magnetic properties of the ferrous metals have large variations.
7. **<u>J total(cgs)</u>** – Total estimated magnetic moment of the target dipole in cgs units.
8. **INCLINATION (degrees)** – The angle between estimated magnetic moment of the dipole and horizontal plane, positive downwards, in degrees.
9. **DECLINATION (degrees)** – The angle between estimated magnetic moment of the dipole and geographical North, counted clockwise, in degrees.
10. **ANGLE (degrees)** – The angle between magnetic moment of the estimated dipole and Earth's magnetic field.
11. **DX, DY, DZ (meters)** – Estimated standard deviations of the target positions, based on the fit between observed and modeled fields.
12. **MAG DEPTH (meters)** – The gradiometer depth below sea surface during the survey.
13. **MAG ALTITUDE (meters)** – The gradiometer altitude above sea floor in the area of the target, in meters. The sum of columns (12) and (13) yields total water depth in the area.
14. **LINE** – Data acquisition line number recorded in the field.
15. **DATE TIME** – The date and time of the profile data of the point closest to the estimated dipole location. Used for reference.
16. **REFERENCE** – A list of anomalies in a 10 m radius from the target of interest, expressed in the format of target ID/acquisition data line/distance (meters). This column is blank if there are no other targets within a 10 m radius.

Anomaly pages

In the final report, each target interpretation is presented on a separate page, and all pages are bundled in one PDF file. This was accomplished with the help of Generic Mapping Tools package (GMT, 2008). Each page consisted of three panes: map pane (left top), graph pane (right top) and textual information pane at the bottom of the page.

- **Map pane** displays the portion of diurnally corrected magnetic field as a shaded color map. It is centered on the target of interest, which is marked as a white star in the middle of the map. The Target ID is displayed in the map header as well as near the target itself. The remainders of the targets are displayed with crosses (+) along with their ID's, printed in reduced font. Part of the profile used for the inversion is shown with two line tracks near the target. Direction of the survey is shown with an arrow.
- **Graph pane** shows the measured and computed magnetic fields as a function of UTM Northing, in short notation. Horizontal axis goes from South to North. Observed magnetic field is plotted with the solid lines and individual readings are shown with circles. The modeled synthetic magnetic field is shown with dashed lines. This plot is provided for visual comprehension of the quality of modeling.
- **Text pane** has the same information as the corresponding row of the target worksheet. It is divided into four areas:
  - Region parameters, such as acquisition line, gradiometer depth, altitude and closest data point with time and date.
  - Estimated target parameters: ID, coordinates, magnetic moment, amplitude.
  - QC parameters, such as fit and standard position deviation.
  - If there are other targets in 10 m distance, they are also reported on the page (the same as in spreadsheet) as target ID / MagLog Line / Distance.

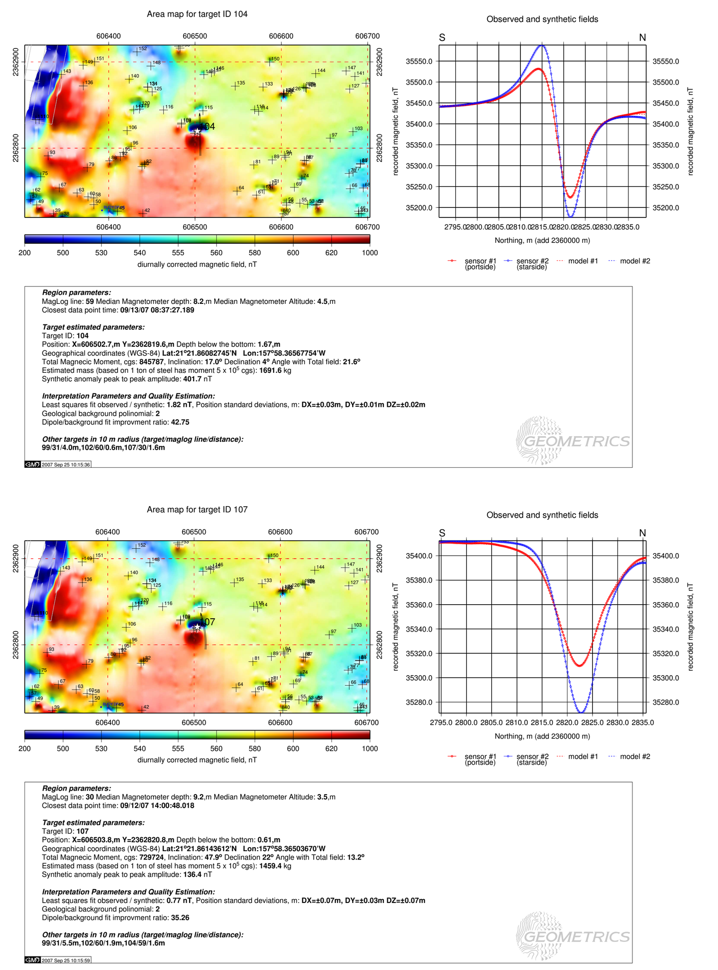


Figure 8 Typical anomaly pages presented in the report. It's very likely that both anomalies are related to the same object. Field signatures are different due to distance variance from the sensor, however inversion results tend to cluster very closely.

Conclusions

- The complete data set acquired with the high performance Geometrics G-882 Transverse Marine Gradiometer has been presented.
- Various techniques were used to process the gradiometer data, including Total Field Maps, Quasi-Analytic Signal Maps and Direct Dipole Matching.
- The Quasi-Analytic Signal map appears to have all the features of the Analytic Signal analysis map which requires more magnetometer sensors and a more complicated deployment scenario.
- The Quasi-Analytic Signal map has certain advantages over the Total Field Map: it provides a cleaner view of the local anomalies and does not require diurnal correction or filtering. Most importantly it greatly simplifies the character of the magnetic signatures.
- Dipole inversion techniques were discussed and the results are presented as a spreadsheet and as color plates.
- The overall processing chain delivers comprehensive information to the customer.

Acknowledgements

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See beneath the surface