M-TR138

# MARINE HARBOR SURVEY
# USING THE
# G-882 TRANSVERSE GRADIOMETER
# WITH
# ANALYTIC SIGNAL PROCESSING

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Geometrics
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Data courtesy of the US Navy

# MFS Hawaii survey

## Equipment:

Geometrics 1.5 Meter Transverse Gradiometer consisting of:

1. G-882, S/N 882156, with depth and altimeter
2. G-882, S/N 882186 with depth
3. Gradiometer tow bar assembly
4. 61 Meter Clevis Tow Cable with Kellems Grip
5. Power Supply and Inverter for boat operation
6. DC/Data Junction Box

Magnetometer array was towed from a point on the aft deck forward of and centered between the outboard engines. Distance between the GPS antenna and the magnetometer sensors was 27 Meters.

Trimble AgGPS 132 DGPS with Parallel Steering Option DGPS provided by Omni Star GPS antenna was mounted on top of the aft part of the boat cabin for survey operations.

Compaq EVO N800c laptop computer with Windows XP Professional operating system and MagLog data logging software RS 232 data converted to USB by Keyspan 4-port USB Serial converter, model USA-49.

## Operations:

Equipment arrived Honolulu on Friday, 7 September 2007. Assembly of the magnetometer tow frame took place during late morning and early afternoon of Tuesday, 11 September 2007.

We conducted a test in water at the Range House dock on Tuesday, 11 September 2007. During the test, magnetometer and tow frame operation was normal, but the GPS was not receiving Differential corrections. Omni Star Houston corrected this problem at the end of the workday and a test of the GPS confirmed reception of Differential correction data.

The majority of survey operations were conducted on Wednesday, 12 September 2007. Geometrics prepared a preliminary map on site at the end of the day. Data were electronically transmitted to Geometrics for processing by a Geophysicist.

A report from Geometrics Geophysicist Thursday morning, 13 September 2007, indicated we should re-survey 5 lines (originally MagLog lines 7, 10, 13, 30, 31) due to navigation problems and 2 lines (originally MagLog lines 16, 19) to verify positioning of the magnetometers. A request was also made for three tie lines to be surveyed. The seven lines and the Northern most tie line were surveyed without incident. However, the tow frame caught an underwater snag near the North East corner of the dock during survey of the middle tie line. Damage to the tow frame and tow cable from the snag caused us to suspend survey operations at this time.

The system was removed from the boat and packed for return shipment in the late morning and early afternoon.

Geometrics Geophysicist delivered a set of preliminary maps at the end of the day on Thursday, 13 September 2007. These maps did not include data re-surveyed in the morning.

## Data Processing.

### *Correcting data for diurnal variation.*

Special base station magnetic field recording was not employed during this survey. However, magnetic observatory data is available on line, via the INTERMAGNET network. INTERMAGNET data is measured with proton magnetometers with 1 minute intervals at various locations around the world. The closest observatory to the survey is USGS observatory located at Ewa Beach, HI. Data is available with one day delay. After survey was completed, diurnal data for September 12 and 13 was downloaded. Magnetic field record is presented on figure 1 as a function of local time.

"Geometrics" MagMap2000 software was used to reduce base station time stamps to local time (-10 hours) and correct data logged with MagLog NT Interpolator device. Both data sets (raw and diurnally corrected) were used to produce total magnetic field maps. Comparison of the two maps shows that significant improvement has been reached using Eva Beach diurnal data, and it would be difficult to produce a reasonable total field map without availability of the base station data.

It should be noted however that pseudo analytic signal processing and dipole position estimation does require data to be corrected for time variation (see below).

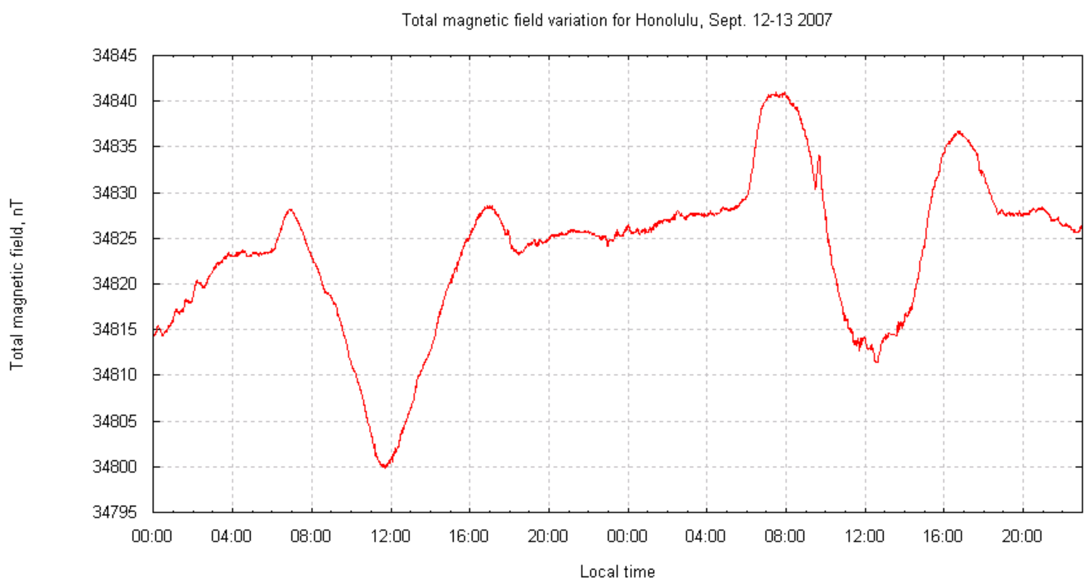


*Figure 1: Proton magnetometer record from Eva Beach USGS observatory*

### *Common map procedures.*

For this project all maps were computed using 0.25m cell size, total cells 2201x2753. South West corner of each map is located at 606258, 2362602. North East corner is located at 606808 ,2363290. UTM projection for zone 4, central meridian 159W, WGS-

84 was used for maps and target locations. Each map was interpolated using gridding with tension method implemented in GMT “surface” routine [1]. After interpolation all grids were clipped using original data lines with radius 12m (all grid nodes further from the lines were marked as blank). All maps were printed as PDF files using MagPick software at scale 1:2500 (25 meters in 1 cm) and marked with UTM and Lat/Lon coordinate meshes.

## *Computing of the Pseudo-analytic signal.*

Analytic signal is widely used in magnetic data interpretation, see for instance [2]. In this project we have used it to simplify total field map and present the result as easily used maps.

Data for this survey was obtained with transverse gradiometer which enables pseudo-analytic signal computation. Generally speaking, to compute real 3-D analytic signal four magnetic sensors should be used to measure three components of magnetic gradient. Analytic signal then is computed as a magnitude of the the gradient vector:

$$A=\sqrt{G_x^2+G_y^2+G_z^2}$$

Where $G_x, G_y$ and $G_z$ are derivatives of the Earth's total field $T$ along the coordinate axis. It can be noted here that derivatives are not affected by the time variation of the Earth's field magnetic field.

Unlike the Earth's magnetic field, analytic signal field has a simplified structure. It is always positive and known to produce unipolar anomalies at places were total field is represented by positive and negative anomalies. For instance, a simple point source [1] typically produces positive and negative total field anomalies in the Northern hemisphere. The same object produces analytic signal with only one positive anomaly. Furthermore, XY location of the object is tied to the point between minimum and maximum of the magnetic field; for the analytic signal object location can be typically found at place of the maximum. Therefore it is beneficial to obtain a map of the analytic signal.

Strictly speaking the transverse gradiometer does not allow 3-D analytic signal computation. It truly measures only one component of the magnetic field gradient – the one perpendicular to the survey direction. However another horizontal component (along the survey path) can be computed using history along the path. This is actually time derivative and could be affected by Earth's field time variations, but because time intervals are very short (in order of a few seconds) this influence is negligible.

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1 Object can be considered as point source, or dipole, if maximum linear dimension is 3 or more times less than distance to the point of measurement.

Therefore two horizontal components $G_x, G_y$ can be readily computed. However third component $G_z$ is still unknown and there is no physical measurement to substitute for that. Help comes from the potential field theory (see for example [3]) which states that potential field can be re-computed at any point from the surface where it is known. This procedure is widely used and is called upward continuation. There are 3-D and 2-D procedures. In the last case field is considered to be uniform in the direction perpendicular to the profile line (which is generally not true). However it delivers some reasonable approximation for the missing term $G_z$ . Therefore pseudo analytic signal can be computed using the following procedure:

1. Compute transverse gradient using difference of two magnetic sensors and separation between the sensors : $G_t=(T_2-T_1)/S$ where $T_{1,} T_2$ are magnetic fields measured by two sensors at the same time, $S$ is sensor separation, in meters.
2. Compute longitudinal gradient $G_l=\frac{(T_1^{t_2}+T_2^{t_2})/2-(T_1^{t_1}+T_2^{t_1})/2}{L}$ where $T_i^{t_j}$ is reading of the sensor $i$ at time $t_j$ and $t_2>t_1$ $L$ is the distance array traveled between $t_1$ and $t_2$ . Typically $t_1$ and $t_2$ selected so distance $L$ is comparable with sensor separation .
3. Compute magnetic field at elevation $H$ using average of two sensor readings and 2-D upward continuation. $H$ is typically the same as the sensor separation $S$ . Compute vertical gradient as $G_h=(T_h-T_0)/H$ where $T_0$ is average of two sensors along the profile, and $T_h$ is upward continued version of this average.
4. Finally, compute pseudo-analytic signal as $A=\sqrt{G_t^2+G_l^2+G_h^2}$ . Compute also position of the middle line of the magnetometer array to attribute pseudo analytic signal.

During this survey survey magnetometer separation of 4 ft (1.22 meters) in the array and therefore was also used to compute pseudo analytic signal. Result was presented as color shaded relief map.

Typical usage of this map would be just to look for maximums, and go there to investigate possible magnetic targets. In this report pseudo analytic signal included mostly for presentation purposes, there were no target estimates based on this quantity.

## *Using array measurements to estimate target locations.*

Target estimation was entirely based on work [4] and MagPick software. Here is brief description of the interpretation procedure.

There was an attempt made to explain each of the profile magnetic anomalies using dipole model. Each anomaly was recorded with two sensors, and both fields have to be explained. The simplest dipole model was used. This model physically corresponds to the uniformly magnetized sphere or spheroid. The model is characterized by its position (X, Y, and Z) and magnetic moment ( $J_x, J_y, J_z$ ). All these parameters can be easily estimated using non-linear optimization routines. The standard variations of those parameters are also estimated using linearisation near the solution point and fit between observed and synthetic data.

In addition to the dipole background field model also has been used to estimate ambient magnetic field in the area. This model is linear and was represented by first degree (A*X+B*Y+C*Z+D) or second degree ($A2*X^2 + B2*Y^2 + A1*X + B1*Y + C*Z + D$) polynomials (X, Y, Z are position coordinates). Therefore 4 or 6 additional parameters are to be estimated along with main dipole parameters[2]. Second degree polynomial was used for most of the targets in that area. Using of the model is necessary to remove Earth's magnetic field.

Note that because only short pieces of data lines were used, influence of the Earth's magnetic field time variation is negligible.

Based on all of above considerations number of the estimated parameters for each interpretation act was minimum 10 ( 6 dipole parameters and 4 linear background field parameters) or 12 ( 6 dipole parameters, 6 second degree polynomial).

The interpretation procedure is the following:

1. Interpreter is presented with linear graphs of magnetic field for each line. Each graph has two recordings for port side (channel #1) and starboard side (channel #2) magnetic sensors.
2. Based on the signal frequency content, anomalies of interest are picked by hand. For this survey typical wavelength for interpreted anomalies was less then 20-50m. Interpreter selects beginning and end of each anomalous signal.
3. An automatic routine is called to estimate parameters of the dipole. Result of the computation (dipole position, depth and amplitude) is presented along with the synthetic field. If solution converges properly, least squares fit between observed and modeled fields is small.
4. Interpreter examines the results. If estimated parameters and fit appeared to be reasonable, the target is saved in the target list. Complete protocol of the inversion, including observed and synthetic fields, is saved as well.
5. After interpretation is completed for all targets (337 in this project), the target list is sorted South to North, and new target numbers are assigned. All protocol files are joined together to produce master inversion file for the project. A spreadsheet with target locations is also created.

2 Those are coefficients A,D,C,D or A1, B1, A2, B2, C, D depending on degree of approximation.

6. GMT script is launched to produce protocol pages for each inversion. Each page includes fragment of the total magnetic field map with the target of interest marked as a star, linear graphs of observed and synthetic fields for QC purposes, and estimated target parameters.

*Target spreadsheet format.*

Target location spreadsheet has the following columns:

1. ID – target number, goes from South to North.
2. X(m) Y(m) Z(m) Target position in UTM coordinates and depth below the sea floor. To estimate Z, altimeter and depth sensor readings of the magnetometer fish were used.
3. Lat Lon – target position in the geographical coordinates, WGS-84. They are included for convenience.
4. Amlp(nT) This is amplitude of the the synthetic anomaly, after ambient field is taken away. It shows importance of the anomaly; however, low amplitudes does not necessarily mean that anomaly is not important; it could be low due to far distance to the target.
5. FIT(nT) This value shows quality of the inversion. It is least squares fit between observed and computed fields. For all anomalies in the spreadsheet fit is acceptable (otherwise they would not be included).
6. MASS(kg) Simple mass estimate, not necessarily true. It is based on the fact that 1000 kg of steel typically correspond to $10^5$ cgs units of magnetic momentum (see for instance [5]). It should be noted that real mass could differ by the order of magnitude because magnetic properties of the metal vary in a very large limits.
7. Jtotal(cgs) Total magnetic moment of the target dipole, in cgs units, which is $J_{total} = \sqrt{J_x^2 + J_y^2 + J_z^2}$
8. INCL(deg) – angle between magnetic moment of the estimated dipole and horizontal plane, positive down, in degrees.
9. DECL(deg) – angle between magnetic moment of the estimated dipole and geographical North, counted clockwise, in degrees.
10. ANGLE(deg) - angle between magnetic moment of the estimated dipole and Earth's magnetic field.
11. DX(m) DY(m) DZ(m) Estimated standard deviations on the target position.
12. MAGDEPTH(m) – magnetometer depth below the sea surface in the area of the target, in meters.
13. MAGALT(m) – magnetometer altitude above sea floor in the area of the target, in meters. Sum of the columns (12) and (13) yields total water depth in the area.
14. LINE – MagLog line number.
15. DATE TIME - date and time of the closest measured data point.
16. REF – reference – list of the anomalies in 10 m radius from the current target, in the format target/maglog line/distance. This column is blank if there are no other

targets in 10 m radius.

Most important are columns ID, X, Y, Z, Lat, Lon, MASS (or Jtotal). Columns INCL, DECL, ANGLE, are related to the UXO type of survey and not applicable in this case. DX, DY, DZ are typically small; they don't take into account clustering of the targets (see below). MAGDEPTH, MAGALT, LINE, DATE, TIME, REF are reference values to allow going back to the original magnetic field record if needed, or to find nearby targets (if any).

### *Anomaly page format*

Each anomaly is presented on the separate page, and all pages are bundled in one PDF file. Page consist of three panes: map pane (left top) , graph pane(right top) and textual information pane at the bottom of the page.

1. Map pane displays portion of diurnally corrected magnetic field as a shaded color map. Size of the displayed area is 400 x 200 meters. Map is centered around current target, which is marked as white star in the middle of the map. Target ID is displayed in the map header as well as near the target itself. The rest of the targets are displayed with crosses (+) along with their Ids, printed in reduced font. Map projection is UTM, and axis are annotated with Northing and Easting, with coordinate mesh steps of 100 m. All maps have the same color scale and the same shading parameters as a separate magnetic map. Part of the profile used for the inversion is shown with two line tracks near the target. Direction of the survey shown with the arrow (latter could require magnification if file is being viewed in PDF reader).
2. Graph pane shows measured and computed magnetic fields as function of Northing. For place sake, short Northing notation is used along the horizontal axis (add 2360000 m for full UTM). Horizontal axis goes from South to North. Observed magnetic field is plotted with the solid lines and individual readings are shown with circles. Synthetic (model) magnetic field is shown with dashed lines. This plot is provided for visual comprehension of the quality of modeling.
3. Text pane has the same information as corresponding row of the target worksheet. It is divided into four areas:
    - Region parameters, such as MagLog line, magnetometer depth, altitude and closest data point time.
    - Estimated target parameters: ID, coordinates, magnetic moment, amplitude
    - QC parameters, such as fit and standard position deviation. In addition to spreadsheet parameters page includes degree of the polynomial used to model ambient magnetic field and “improvement ratio”. Latter has the following meaning: for each interpretation area “background only” model first was computed using observed fields and assuming there is no dipole in the area, and fit was stored. Then dipole was added to the model and all

parameters were re-estimated. “Improvement ratio” was computed as ratio of the fits of these two models. Large ratio indicates that there is significant portion of the field is due to the dipole, and not the background.

- 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.

## *Discussion of the results and anomaly clustering.*

One advantage of profile based inversion is that no map interpolation errors are introduced into the solution. However, only two channels were used for each act of the inversion, i. e. profile lines were used independently of each other. This would be appropriate method for sparse or even single line survey, but for dense line survey it would be better to use multiple lines in one inversion. Unfortunately this was not an option for this particular project, given limited time frame and large number of anomalies. As a result of line by line estimation, the same targets are estimated several times (one time per profile. Figure 2 illustrates this idea:

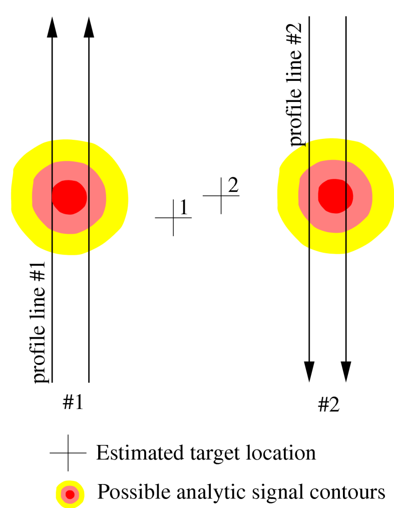


*Figure 2: Target position estimated using different profile lines*

Here is profile #1 yields target position #1 and profile #2 yields position #2. Both profiles consist of two lines (because there are two sensors). The method would not work, if only one line would be used (single magnetometer) because there is no direction information. With a two magnetometer array the sensor closest to the target normally exhibits sharper and higher amplitude anomaly, so it is easy to say on which side of the profile target is.

In the example above targets #1 and #2 are very likely to correspond to a single object. Thus estimates from different survey profiles tends to “cluster”. The tighter is the cluster, the better is quality of the overall estimate. It is also possible that clusters occur between the profiles, where no field in fact has been measured. This poses potential disagreement with analytic signal map. Indeed, both profiles #1 and #2 have maximum in analytic signal. However if separation between profiles is big enough, interpolation routine may not join them together, ending up with two distinct anomalies, as it is shown on figure 2 . This may lead to the potential confusion when target locations and analytic map signal are compared – there could be target clusters at the location where there is no distinct "hill" on the analytic signal map. The only way to overcome this is to survey at smaller profile separations. In any case, preference should be given to estimated target locations.

Other factors also affect the results, leading to erroneous estimations:

1. Even though each target was assumed to be a dipole, this might be not always be true. Examples are chains, steel cables, ship wrecks. In this case XY position approximately corresponds to center of the object, and depth could be wrong. Note that some of the estimates have negative depth (which means target is located above the sea floor).
2. Not every anomaly could be interpreted with the dipole source, due to blending of geological field with the local one. User may find some anomalies are visible on the map, but there is no target numbers for them.
3. Anomalies at the start or end of lines were not interpreted, if only half of the anomaly was recorded. However they are presented on the maps.

To simplify usage of the results, we have conducted cluster analysis for all the targets using publicly available "cluster" software. The size of the cluster was limited by 5 m. Results are presented in the separate spreadsheet along with the positions of the original targets. This spreadsheet has all the columns as target spreadsheet plus additional columns at the left:

1. ClusterID – cluster ID. Smallest ID has smallest radius
2. ClusterSize(m) – cluster diameter, in meters.
3. Xav(m), Yav(m), Zav(m) Averaged position, UTM, meters,.
4. MassAv(kg) averaged mass.

Note that fields (1-4) are the same for each cluster, and are repeated for each target included in the cluster.

## *Graphics materials included in this report.*

1. Profile location map. This map shows locations of the both sensors on white background to give visual impression of the area coverage. MagLog line numbers are printed at the start and stop of each line. All estimated target locations are plotted with black crosses. User supplied pier and coastline outline is given in gray. Buoys locations is shown in blue.
2. Diurnally corrected total field magnetic map, presented in shaded color. Most of the anomalies can be easily detected just by looking at this map. For presentation purposes field was upward continued by 1 m.
3. Raw total field magnetic map. This map was created using survey data directly, without correction for time variation. It is only included to show improvement due to observatory data.
4. Pseudo Analytic signal map, computed with transverse gradiometer data. Analytic signal profile lines (single) are plotted along with MagLog line numbers and direction of travel. Shaded color is used, with non-linear color scale between 0 and 20 nT/m (all anomalies above 20 nT are presented in red).
5. Pseudo Analytic signal map. The same as above, but with cluster locations and without profile lines.

## *Conclusions.*

1. Magnetic survey has been conducted to the customer's specification using “Geometrics” transverse cesium gradiometer.
2. Data were presented as diurnally corrected total field and analytic signal maps, to allow easy visual target location.
3. Profile based inversion was carried out and results are presented on the map and as spreadsheet.
4. Further clustering of the anomalies was performed to simplify the results.

### *Recommendations.*

Here is our understanding of how data is to be used to perform clearing of the survey area.

1. Start with cluster map. Go from the highest mass/amplitude to the lowest, use analytic signal map and anomaly pages as reference. Pages could be especially useful when it's hard to read target ID from the map.
2. After clusters are cleared, proceed with single anomalies. Again go from highest mass/amplitude to the lowest.
3. During the search, take into account that provided numbers are estimates only. You may want to increase search area to 4-5 meters in diameter.
4. Depending on underwater conditions using diver magnetometer could be a significant plus to pinpoint target location. However, it also could lead to overlooking bigger objects in favor of smaller but closer ones.

## References


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## Software.

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5. Generic Mapping Tools (GMT) v. 4.2.0, Copyright ©1991- 2004 by Paul Wessel and Walter H. F. Smith. SOEST. http://gmt.soest.hawaii.edu/
6. Linux environment SUSE-10.2 with Unix shell (bash) , awk and ESP Ghostscript 8.15.3
7. Cluster v.2.9 by A. Stolcke ,stolcke@icsi.berkeley.edu , home page http://www.icsi.berkeley.edu/ftp/pub/ai/stolcke/software/
8. “Geometrics” proprietary shell scripts and programs.