Using A Transverse Marine Gradiometer (TVG) as submarine pipeline location tool

Mikhail Tchernychev, Geometrics Inc, San Jose, CA

James Kulpa, Environmental Data Solutions, San Rafael, CA

Ross Johnson, Geometrics Inc, San Jose, CA

***Abstract*— In this paper we present a method and case study of locating a submarine gas pipeline using a pair of marine magnetometers in transverse configuration. The targets of the survey were a 12" main gas pipeline and a 4" return condensate line located in San-Francisco bay near Ryer Island / port Chicago. The equipment used was a "Geometrics" Transverse Gradiometer (TVG) which consists of two quantum magnetometers operating at a 10 Hz rate. Use of two magnetic sensors allowed for computing the Quasi-Analytic Signal (QAS), which greatly simplifies the anomaly signature presentation. Maps of the survey along with an estimated depth of the transect relative to the sea bottom are presented**

Keywords—marine magnetometers; magnetometer survey; pipeline locating; total magnetic field; analytical signal.

I. INTRODUCTION

Submarine cables and pipelines often cannot be seen by conventional acoustic methods (sonar). Electromagnetic pipe tracking systems are range limited and not always successful for small pipelines or significant burial depths. Most pipelines are made of steel and therefore are readily detected by a total field magnetometer. Many marine DC power cables have steel armor and are also magnetic. These current-carrying cables produce a magnetic field perturbation due to the current itself, which makes these objects an easy target for a marine magnetometer.

The Ryer pipeline survey was ordered by the California State Land Commission to determine if the pipeline might be exposed at the bottom of the navigation channel. The first attempt to locate the pipeline was made with sub-bottom profiler equipment, which proved unsuccessful. The TVG system easily located the pipeline anomaly and tracked it using multiple survey lines perpendicular to the run of the pipeline.

II. THE METHOD

The methodology used in this presentation is relatively new and is reviewed in [1]. Two high sensitivity high sample rate Marine Cesium Total Field Magnetometers are used in transverse mode with 1.5 m separation. The synchronized magnetometers provide the magnitude of the Earth's magnetic field as well as tow depth and sensor array elevation above the sea floor. Assuming constant magnetization along the pipeline, the theory [2] predicts a uniform 2D magnetic field as

$$T_{2D}=M/r^2 \quad (1)$$

where M is magnetic moment of the unit length of the object, r is distance from the object to the sensor and T is predicted magnetic anomaly. The formula (1) can only be used for approximate estimates at the survey planning stage because magnetic properties of the pipeline vary along the pipe, resulting in complex total field anomalies.

It is possible to simplify the total field map by use of the Analytic Signal (AS) technique [3] which is defined as

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

where G_x, G_y, G_z are orthogonal components of the gradient vector of the total magnetic field. The AS creates bell-shaped positive anomalies above the pipelines; the maximums of these anomalies give a good estimate of the XY position of the object.

The transverse gradient G_y is measured directly by taking the difference between the two synchronized sensors, G_x can be computed using the high speed consecutive readings along the path, but G_z is an unknown variable and must be computed. Therefore G_z is *estimated* with FFT using potential properties of the magnetic field [4] and resulting A is termed as *Quasi-Analytic Signal (QAS)*. This computational technique is illustrated on figure 1.

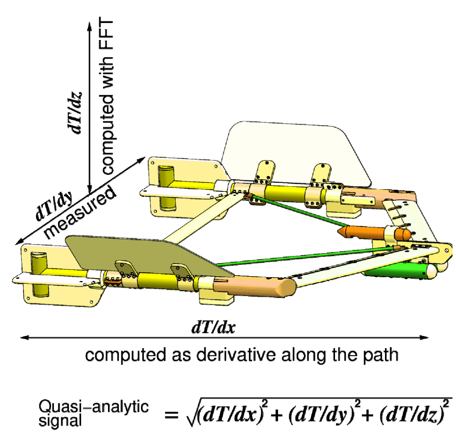

Fig. 1. To QAS calcuation

QAS computation and contouring greatly simplifies field signatures as shown in figure 2.

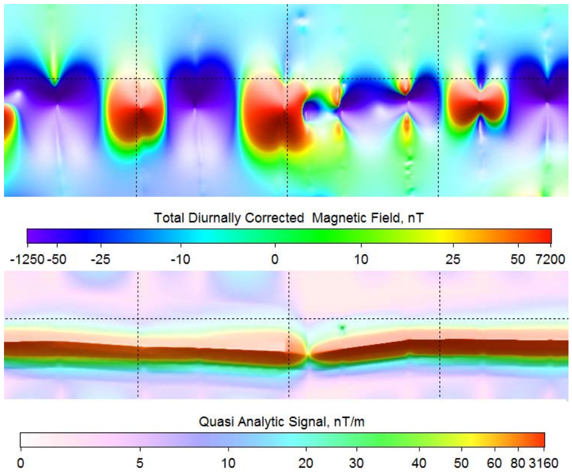

Fig. 2. Top: Total magnetic field measured as part of Ryer Island pipeline project. Bottom: the same area converted to QAS

The depth of the object can be estimated using the half-width of the QAS anomaly, but a better approach is to derive an expression for the QAS model assuming uniform magnetic properties. To derive an expression for AS we need to differentiate (1) and substitute the results into (2). Taking into account that $G_y = 0$ for 2D case and substituting $r = \sqrt{((x - x_0)^2 + h^2)}$, we have:

$$A_{2D} = 2M / \sqrt{((x - x_0)^2 + h^2)^3} \quad (3)$$

where M is magnetization, x_0 horizontal coordinate of the pipeline along profile, and h is vertical distance to the object. Formula (3) assumes that the survey lines are perpendicular to the pipeline and have a constant elevation h. In practice the angle between the survey line and the linear object could be as small as 45°; then the resulting depth h should be corrected by $|sin(a)|$ where a is the angle of incidence. The values of x_o, M, and h are estimated using non-linear optimization and the QAS profile data, and depth of burial computed by subtracting TVG altitude above the seafloor [1]. Because (3) assumes uniform magnetization along the pipeline, it will work best in areas where the field has a minimal transverse gradient and therefore both left and right magnetometer channels record similar field strengths.

Figure 3 shows one of the lines with the measured total magnetic field (top) and computed and modeled by (3) QAS (bottom). It can be seen that the complex total field structure is converted into a simple QAS anomaly, which can be perfectly defined by (3). However the top section of figure 3 exhibits significant gradient G_y across the profile line as is clearly seen by the difference between the two sensors. Therefore this particular intersection may not be well suited to report the derived depth because equation (3) is derived from the 2D case. During our interpretation we manually removed lines with the most significant divergence between sensors; for instance we did not use the line shown in figure 3 for interpretation.

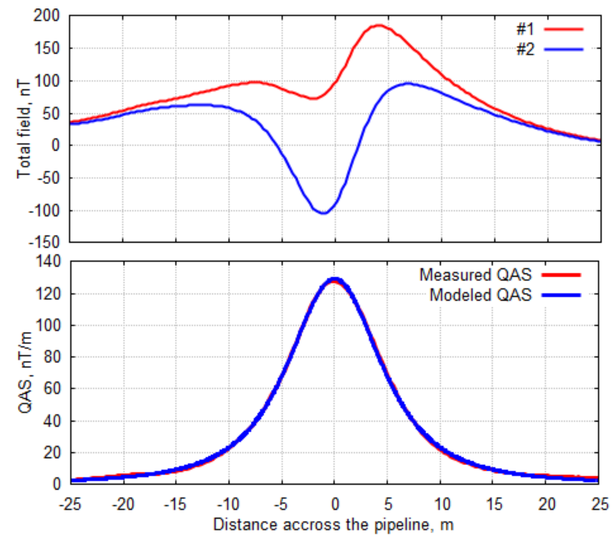

Fig. 3. Measured total field values (top) and corresponding QAS (bottom) with results of the modeling using equation (2) (blue). The estimated h=6.8m, which yields burial depth of 4.7m after removing of TVG hight (2.1m)

The above reasoning leads us to the conclusion that depth estimates derived by 2D rules such as (3) would be only approximate in most cases because the gradient along the pipeline can be significant. Ideally we would only use survey lines where the two TVG sensors record the same field, but this would be a rarity during a typical pipeline survey. One way to overcome this problem would be have reference points where the depth of burial is known and use an adaptive "half-width" rule: employing an empirically derived factor where a percentage of the width of the anomaly at given amplitude matches a known depth. Otherwise we could assume that derived depth is only valid in the general case, and not at every particular intersection of the survey line with the linear object. In this case we can use an averaged or smoothed depth determination.

III. SURVEY

The survey area consists of three major sections: a narrow deep channel in the North, a large shoal in the middle and a wide and deep navigation channel in the South. The shoal area is so shallow that it was only possible to survey at high tide, with a short 15-20 meters tow cable. After the shoal area was surveyed the operator moved to the shallow area at Southern shore. Unfortunately at this very shallow area the tow cable was snagged and damaged. This event limited the cable deployments for the remainder of the survey to 20 meters. This had adverse effects on the remainder of the survey but it did allow checking and comparing delectability of the pipeline at different elevations. Normally the deeper navigation channel would be

[1] "Half width" rule for (3) would be in fact at level of $1/(2\sqrt{2})$ or ~35%

surveyed at 2-3 m above the bottom, but due to the limited cable length it was surveyed at approximately 10-12 m above the seafloor.

The total field and QAS maps are presented on figures 4 and 5. The total field data was diurnally corrected using USGS Fresno magnetic field base station data. It can be seen that the QAS map anomaly becomes less distinct in the deeper areas due to the TVG elevation.

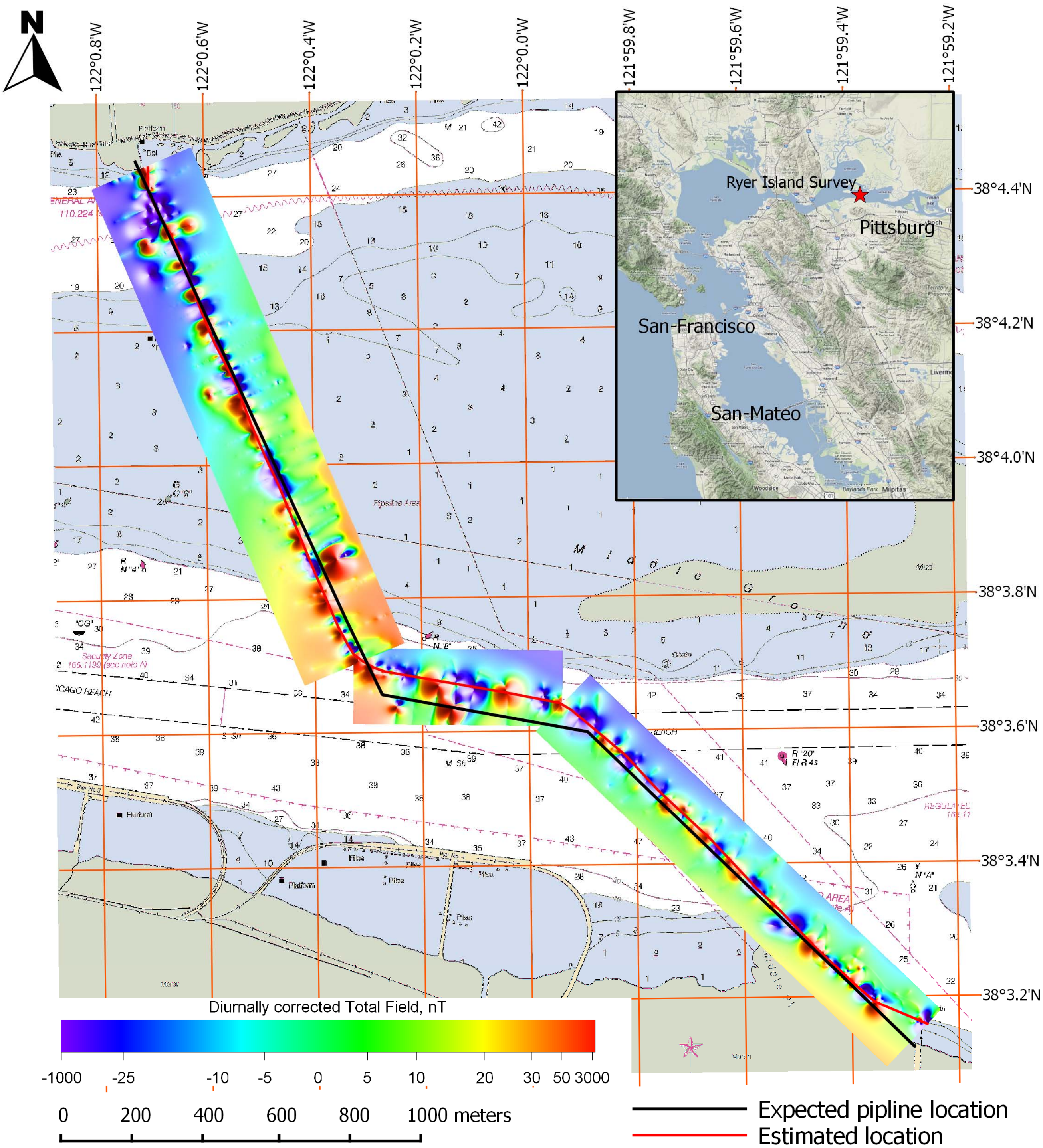

Fig. 4. Total magnetic field map for Ryer Island project. Black line shows expected location of the pipeline and red line shows location found by the survey. Survey line separaion was approximately 50 m. The background is US navigation map for the area, depth in feet Mean Low Lowest Water (MLLW)

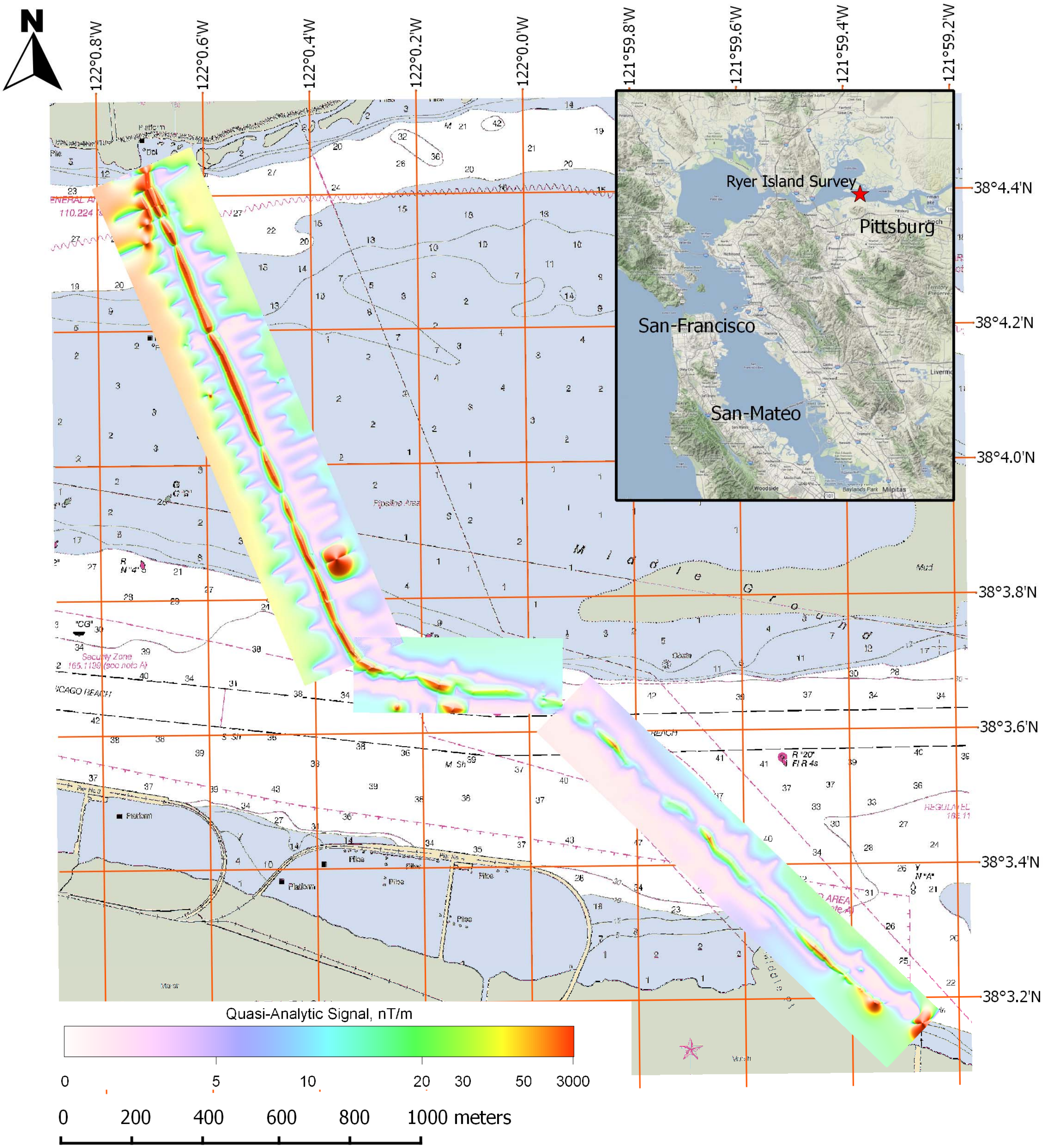

Fig. 5. QAS map for Ryer Island project. It can be seen that it is greatly simplified compared to the total filed map. A special interpoltion technique was used to connect points between data profiles.

The total field anomalies recorded during the survey ranged from about 800 nT at the shoal to about 80 nT in the navigation channel. The maximum value of the QAS signal indicates the XY location of the pipeline, which is compared with expected location based on the total filed map (fig. 4). It can be seen that there is a significant difference between the two estimates (~60 m) especially in the navigation channel area.

IV. Depth Estimations

The pipeline depth profile estimation is shown on figure 6 along with bathymetry profile.

It can be seen that point by point estimated depth is noisy with variations about ±2 m.

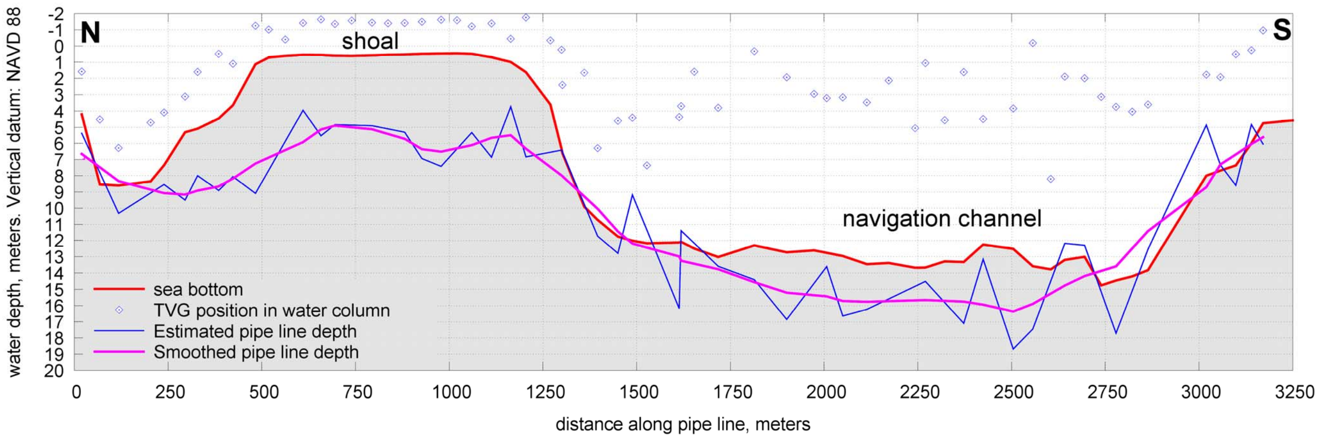

Fig. 6. Estimated pipeline depth profile is plotted on top of the batymetric data along the pipeline route. Data was collected mostly in the East-West direction, normal to the plot. The horizontal scale is greatly compressed (3.25km) compared to the vertical scale (22m). Red indicates the tide corrected seafloor bottom, the blue line indicates point by point depth estimates using the QAS profile anomalies. Only intersections with low transverse gradient were used and this contributed to the sharp variations in the depth estimates. The smoothed (mangenta) biural depth estimates appeared as most probable depth profile. The TVG positions in the water column over the shoal are negative due to tide corrected depths. Depth profie was recored by a hydrographic survey pripr to the TVGsurvey.

The variation is higher in the navigation channel where the TVG elevation above the seafloor was much higher than is the shoal area. The overall estimated burial depth along the route mimics the bathymetry profile but it is smoother, showing 3-4 m burial depth in the shoal and 1-2 m depth in the channel. Note that the TVG altitude does not correlate with the sea bottom profile, while the pipe burial depth does. The pipeline appeared to be visible on the banks of the channel.

V. Discussion and Conclusions

The survey showed that a 12” steel pipeline is clearly detectable by the magnetometer at up to ~12m altitude. This means that pipelines of this diameter could be detected buried 8-10 m in the sediments, and would most likely not be visible by any other means. Taking into account the approximately 80 nT total field anomaly at 12 m altitude and using (1) we can estimate that the same object should produce a 10 nT anomaly at ~34 m distance. The length of the survey line e required to fully record this anomaly would be about 400 m compared to the typical length of approximately 100 m for this survey. For ~10 nT anomaly to be detectable the environmental magnetic noise must be well below ~10 nT. When considering an anomaly level of 1nT, which is easily recorded by modern quantum marine magnetometers, one can conclude that the pipeline could be detected at up to 100 m distance which would require a survey line length of 1000 m. Such long anomalies might go undetectable because they tend to blend into the geological signal.

QAS computation was invaluable in locating the pipeline in the XY plane but not as precise in determining the depth. One reason for the depth estimate variance was the assumption that the magnetization along the pipe was homogenous.. Some noise may have been introduced during the modeling process due to vertical gradient calculation procedure. Modeling also implied that all measured readings had the same depth due to a limitation of the non-linear optimization software, when in fact the TVG depth changed along the survey lines, especially in the navigation channel where the operator tried to compensate for the short cable by reducing boat speed.

Another limitation is that the pipeline was considered horizontal in XY plane for each particular intersection while it is certainly not true for the banks of the navigation channel.

It was noted that using a half-width rule instead of optimization process produced similar depth estimates but with greater variance. It appears that only smoothed burial depth estimates could be assumed to be reasonably accurate, which makes it a necessity to have at least 10-20 profile intersections. This requirement informs users of the TVG QAS method as to proper survey design, meaning in some instances more survey lines must be acquired for better depth estimation.

Other factors affected the estimate variability are the cleanliness of the echo sounder altitude information and the attitude of the TVG frame while towing. The altimeter and attitude error could be as much as ±0.3 m which contributes to the depth of burial estimate.

In general the survey was successful because pipeline was clearly detected and reasonable depth estimates were delivered. The survey showed advantages and limitations of the marine magnetometer as a pipeline detection tool: easy XY location determination and occasional large variance in the burial depth estimates.

ACKNOWLEDGMENTS

We would like to thank the California State Land commission for making this data available to us, as well as Environmental Solutions staff for conducting both bathymetry and magnetometer surveys.

We also would like to acknowledge use of Open Source software packages such as gnuplot (www.gnuplot.info) and Quantum GIS (www.qgis.org)) and thank their developers and Open Source community to making these invaluable tools freely available.

The results presented in this paper partially rely on the data collected at Fresno USGS observatory. We thank USGS, for supporting its operation and INTERMAGNET for promoting high standards of magnetic observatory practice (www.intermagnet.org).

REFERENCES

[1] Tchernychev, M., Johnston, J., Johnson, R. 2008. Empirical transverse gradiometer data processing method: Quasi-Analytic Signal approach. AGU proceedings, 2008.

[2] Breiner, S. 1973, Application Manual for Portable Magnetometers. Geometrics, Inc

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

[4] Blakely, R.J., 1995. Potential Theory in Gravity and Magnetic Applications Cambridge Univ. Press, Cambridge.