EMPIRICAL TRANSVERSE GRADIOMETER DATA PROCESSING

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1. Introduction

We present a new empirical approach in the treatment of transverse gradiometer data. The highlights are:

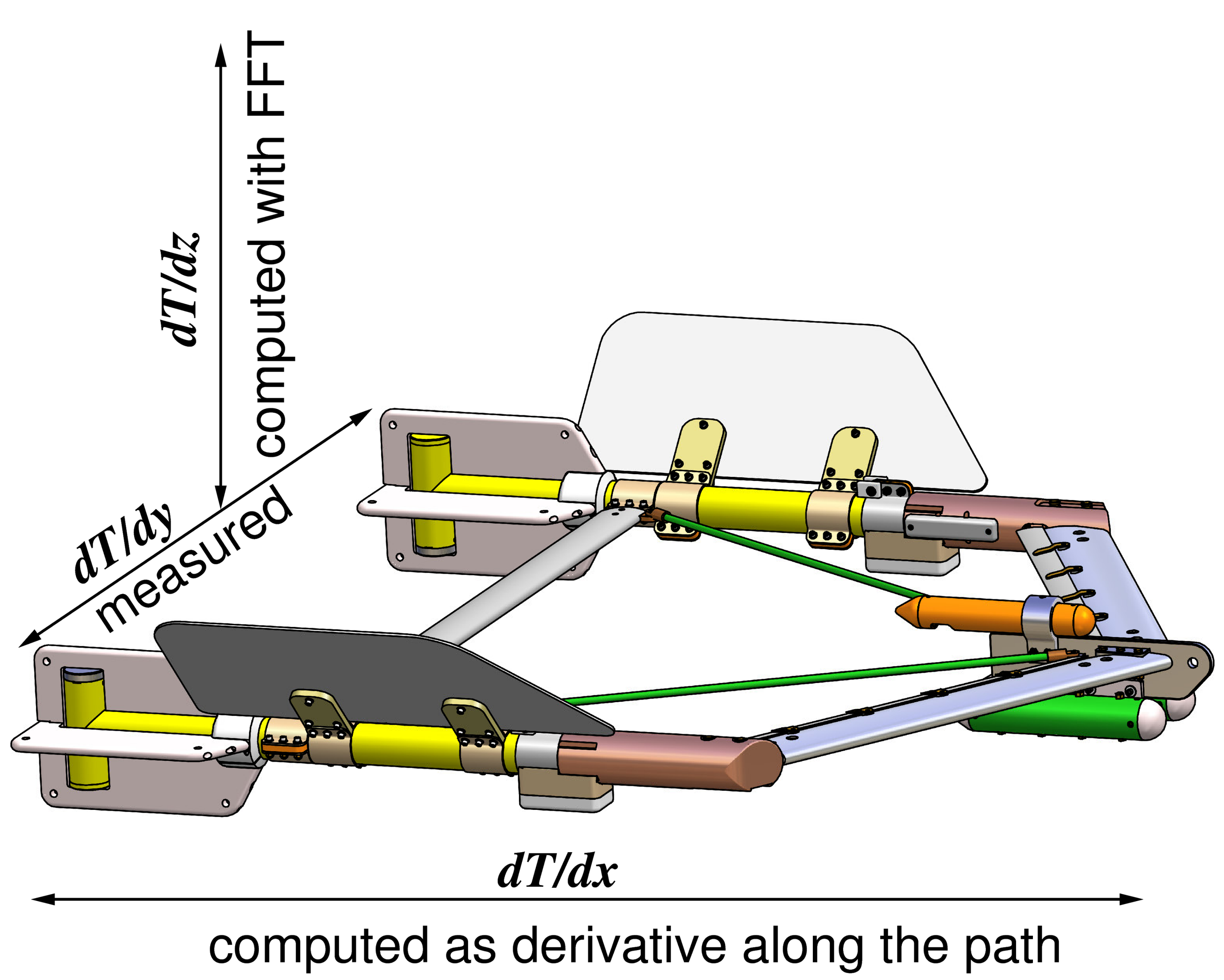
- We show how to estimate the Analytical Signal using Transverse Gradiometer (TG) data on a line-by-line basis. This is termed the *Quasi-Analytic Signal*.
- We show that estimated Quasi-Analytic Signal is a good substitute for the Analytic signal as measured with three or more sensors or computed using dense Total Field measurements. Numerical examples and observations are presented.
- We explore the usefulness of a Transverse Gradiometer as a Marine Pipeline location tool. Simple empirical formulas for depth and location are presented. We believe that these formulas deliver approximate but reliable depth estimates.
- We present Marine Transverse Gradient data as Total Field and Quasi-Analytic signal maps (courtesy of the US Navy).

2. Analytic Signal

Analytic signal processing is widely used in magnetic data interpretation [1,2]. 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 the horizontal coordinates of the local object by simply locating the maximums of the anomalies.
- It simplifies depth computation using half-width rules or Euler deconvolution.

The Analytic signal can be defined as $A=\sqrt{G_x^2+G_y^2+G_z^2}$ where $G_x=dT/dx$, $G_y=dT/dy$, $G_z=dT/dz$ are orthogonal components of the vector magnitude of the gradient of the total magnetic field. The instantaneous analytic signal can be directly measured using a synchronized array of sensors. This measurement requires at least three magnetic sensors be deployed.



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

Figure 1. Computing Quasi-Analytic signal using Transverse Gradiometer

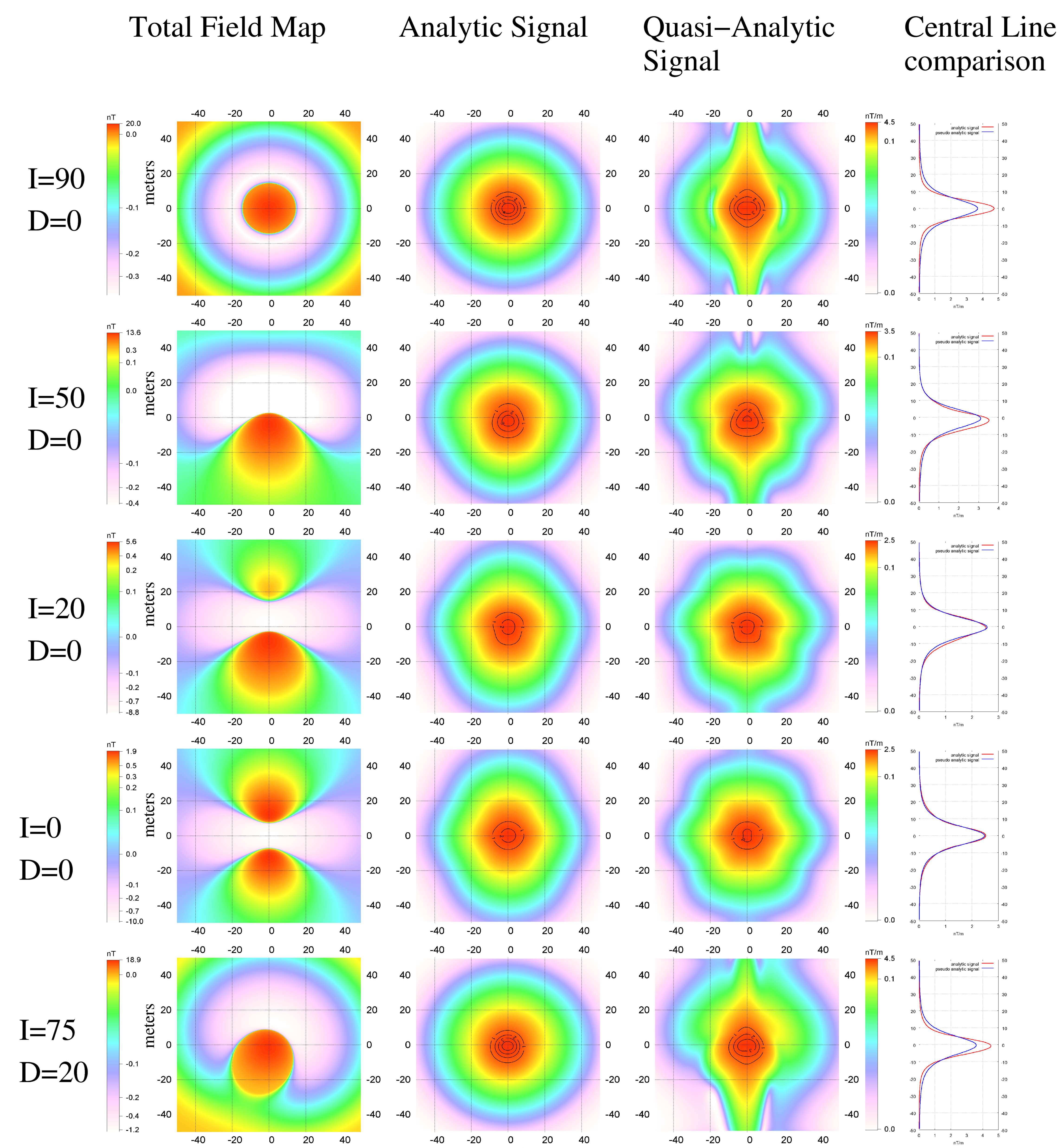


Figure 2. Comparison of the Analytic and Quasi-Analytic signals using dipole model at different environments

If a dense grid of the Total Magnetic field data is available, the Analytic Signal also can be computed using potential field properties [3]. This is typically done with a FFT (Fast Fourier Transform).

However an acceptable quality approximation of the Analytic Signal can be obtained with just two synchronized magnetic sensors in form of transverse gradiometer.

1. Compute Transverse component G_Y of the gradient vector as a difference of two magnetometer channels divided by separation.

2. Compute Longitudinal component G_x using the average of two sensors and data history along the profile.

3. Estimate the vertical derivative G_z using well-known potential field theory (see for example [3]). Although this estimate is based on the assumption that the measured field does not vary in the direction perpendicular to the data profile, we find the results acceptable and useful.

3. Numerical modeling comparison: two-sensor (transverse) system vs. three sensors

We use a dipole model to compare the true gradient measured with three sensors and the Quasi-analytic signal obtained with just two sensors. This model is chosen because of its simplicity and also because the dipole exhibits the most adverse conditions for the Quasi-Analytic signal computation, i.e. the dipole field is not uniform in any direction. Therefore G_z which is based on 2-D theory is not likely to be computed accurately.

A dipole with an induced moment of 100 Am^2 was placed at 10 m below the observation surface and the field was computed in the square 100 x 100 m around it. The dipole horizontal location was at 0,0 m. Numerical simulation was generated using a transverse sensor system with 1.5 m sensor separation and a line spacing of 0.1 m. To compute true Analytic signal, a third sensor was added in the middle of the array at 0.5 m elevation. The computation was iterated at various Inclinations and Declinations of the Earth's field. The comparison plot presented on figure 2 (right-top).

What can be concluded?

- Quasi-Analytic and Analytic plots produce similar field signatures. These signatures can be quite different from the Total Field map signatures.
- The center part (approximately 90% of the anomaly) is very similar for both types of Analytic signal computation.
- Lower signal levels exhibit significant differences. However these differences are only seen at signal levels less than 0.1 nT/m (note non-linear color scales).
- The match is much better at low geomagnetic latitudes (low Earth's field inclination).

We summarize the line graphs on the right side of the comparison plot in figure 2 as a function of the Earth's field inclination in Figure 3 below.

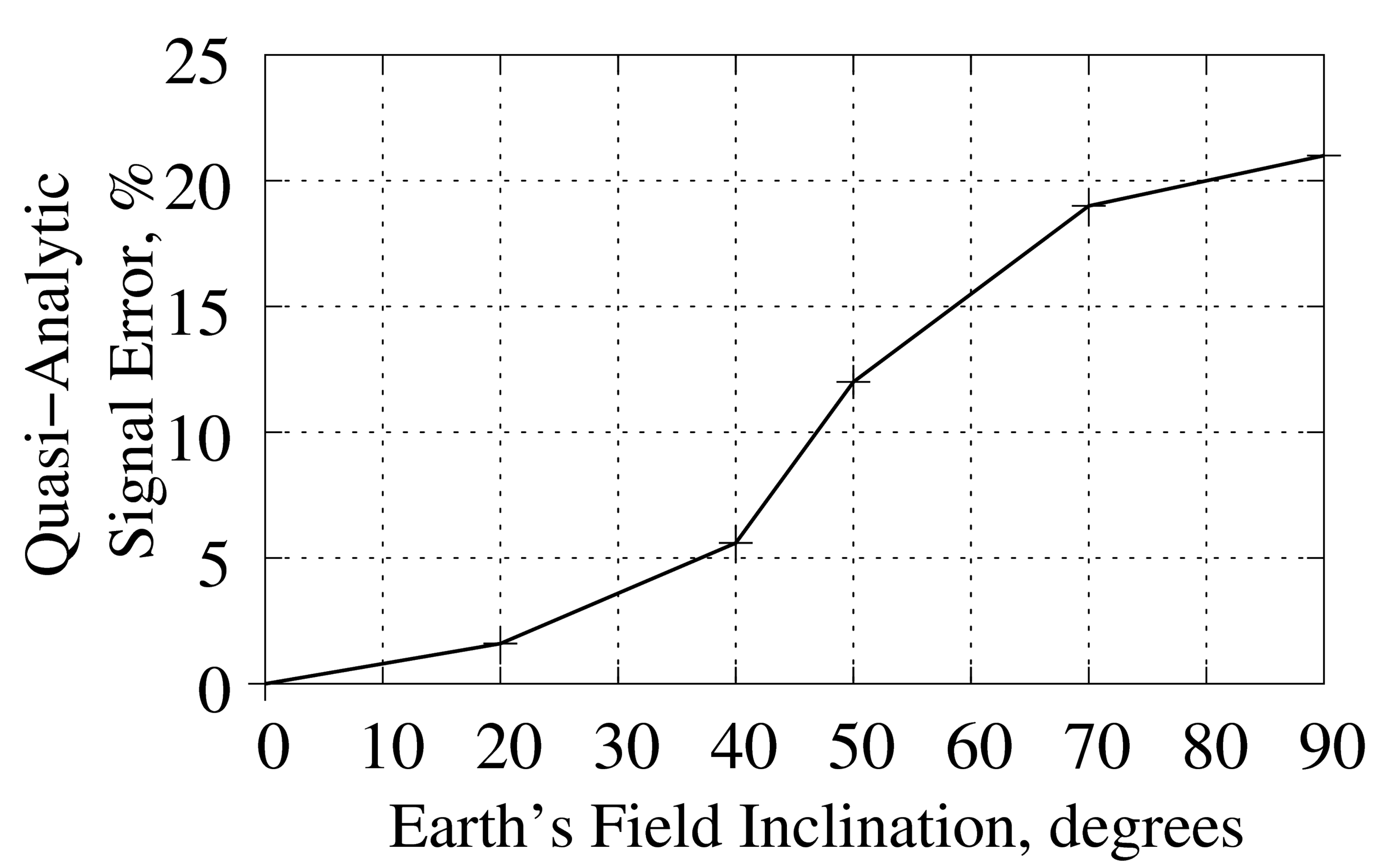


Figure 3 shows relative errors in Quasi-Analytic Signal as a function of Inclination based on a dipole model. This plot shows roughly how much signal is lost when three sensor system is replaced with two sensors and Quasy-Analytic signal is computed in place of true Analytic Signal.

We should note that another source of error is the horizontal stability of the platform. The type of noise caused by platform roll does not affect three sensor systems as much because the gradient is measured in orthogonal directions and the Analytic Signal amplitude is computed as a magnitude of the vector. However for 2-sensor gradiometer systems, platform rolling will distort the gradient. To illustrate this effect we re-model the case of I=75, D=20 with smooth +/- 25 degrees roll along the profiles. The roll phase (starting angle) is random for each profile.

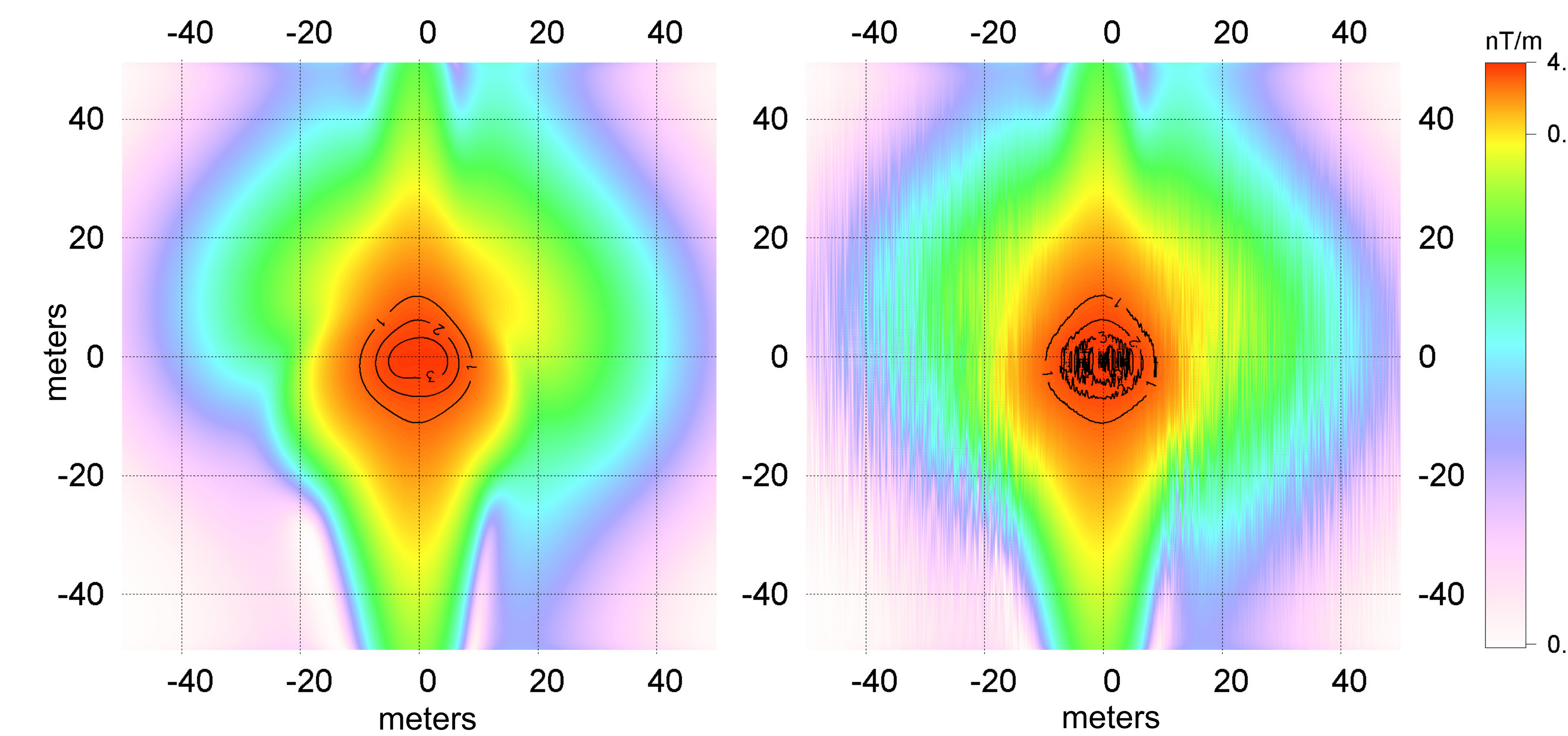


Figure 4. Right: Roll noise of +/- 25 degrees added to the transverse gradiometer system. Left: Quasi-Analytic Signal without roll noise. Remarkably the overall signal signature is not materially effected.

4. Controlled environment measurement: pipeline object.

One of the possible Quasi-Analytic Signal applications is a marine pipeline locator. The typical gas or oil marine pipeline is constructed of many segments welded together or mechanically joined with flanges. Each section can be expected to have its own magnetic properties due to it handling history (electromagnets may have been applied to move the pipe). Because of this, the total magnetic field anomalies along the pipe exhibit a number of maximums and minimums. The complex nature of the anomaly pattern coupled with the likely presence of other local magnetic objects makes it difficult to correlate anomalies along the pipeline and use them to estimate pipeline position and burial depth. From our experience the Quasi-Analytic Signal can greatly simplify the overall map as well as provide a means to estimate the pipeline position.

To illustrate how the Quasi-Analytic Signal can help to locate a pipeline, we simulated a marine setting by constructing a small pipeline on land. The constructed pipeline included five 21-foot sections of steel water pipe 1.5" in diameter. These segments were placed end-to-end on the ground and aligned east to west. A magnetic survey of the site was then completed using a cesium vapor land transverse gradiometer. The survey lines were run North-South, perpendicular to the alignment of the pipes. The transverse gradiometer sensor separation was 0.5 meters and the elevation above the segments was 0.85 m. The area was surveyed at a walking pace with the gradiometer sampling at 10 samples per second. The survey lines were positioned so that the total field was measured along tracks that were 0.25 m apart. A proton-precession magnetometer was operated near by to provide base station measurements for diurnal variation removal and correction.

The data was processed to yield the Quasi-Analytic signal using the proposed empirical method. Because of the high spatial density of the data, it was also possible to compute the Analytic signal using synthetic derivatives [3]. Figure 5 shows presentation of all three analyses.

The pipeline's horizontal location can be simply taken as location of the along-line anomaly maximums. To estimate the depth of the pipeline, a "half-width" rule was used for each Quasi-Analytic Signal profile anomaly. This was done on line-by-line basis. To make the procedure flexible, the width of the anomaly (as percentage of the maximum) is user-selectable. This delivers an estimate of the depth to the middle of the pipeline. Table 1 summarizes the results of the depth estimates for the above field experiment:

The results lead us to propose an adaptive pipeline depth estimate process. The user may employ a known pipeline burial to tune the signal "half-width" level at a certain geographical location and then apply this tuning to the unknown pipeline objects.

METHOD: A QUASI-ANALYTIC SIGNAL APPROACH

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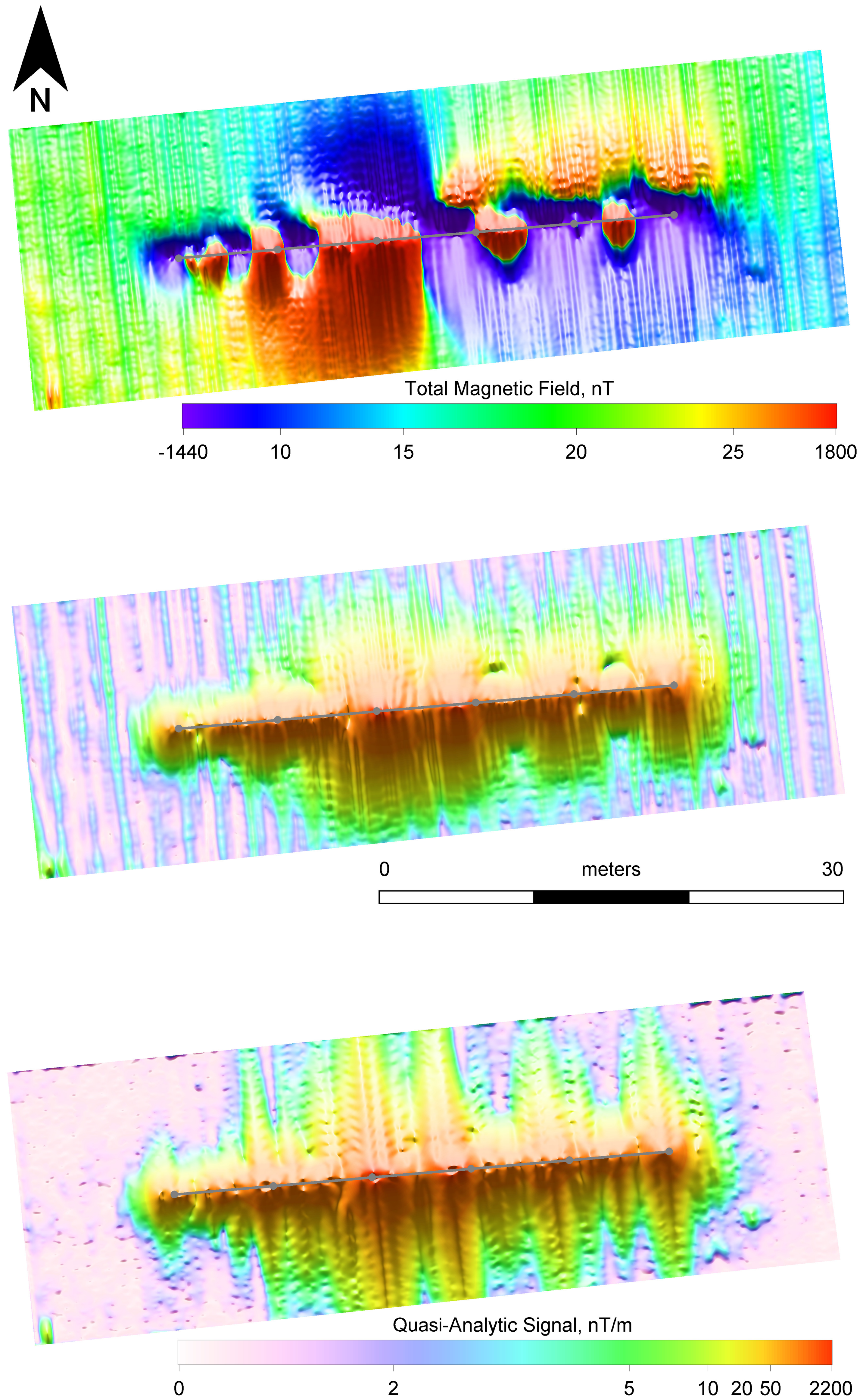

Figure 5. Diurnally corrected Total Magnetic Field Map (top) Synthetic Analytic Signal computed using Total Field grid (middle) and Quasi-Analytic Signal computed on line-by-line basis (bottom). Pipeline segments are shown in gray.

	Signal level 50%	Signal level 60%
WE pipeline direction	0.95+/- 0.17 m	0.81+/- 0.16 m
SN pipeline direction (not shown)	1.00+/- 0.12 m	0.84+/- 0.16 m

Table 1. Depth estimates for controlled pipeline survey. True depth is 0.85 m.

5. Field data example: Hawaii Navy Degaussing Range Marine Survey.

A Transverse Gradiometer marine survey was conducted at the Navy Degaussing range in Hawaii on September 11, 2007. We used 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 as well as a Total Field Map (Figure 6).
We note that an acceptable quality Quasi-Analytic signal map can be obtained in the actual Marine environment, where pitching and rolling of the system is normal. Navy divers successfully used the map to locate dozens of magnetic objects on the seafloor.

Conclusions

- **We employed Quasi-Analytic signal processing to map Transverse Gradiometer data. The map provided more than adequate analytic signal enhancements and filter capabilities.**
- **It was shown that Quasi-Analytic signal patterns closely resemble those of the measured or synthetically computed Analytic Signal.**
- **We introduce marine pipeline location method using simple models.**
- **Quasi-Analytic signal computation is profile based; therefore no dense coverage of the area is required. Even a few data lines are sufficient to estimate depth and location of the marine pipeline or cable.The horizontal stability of the platform is important, but modest roll angles do not significantly interfere with the mapped result.**

References

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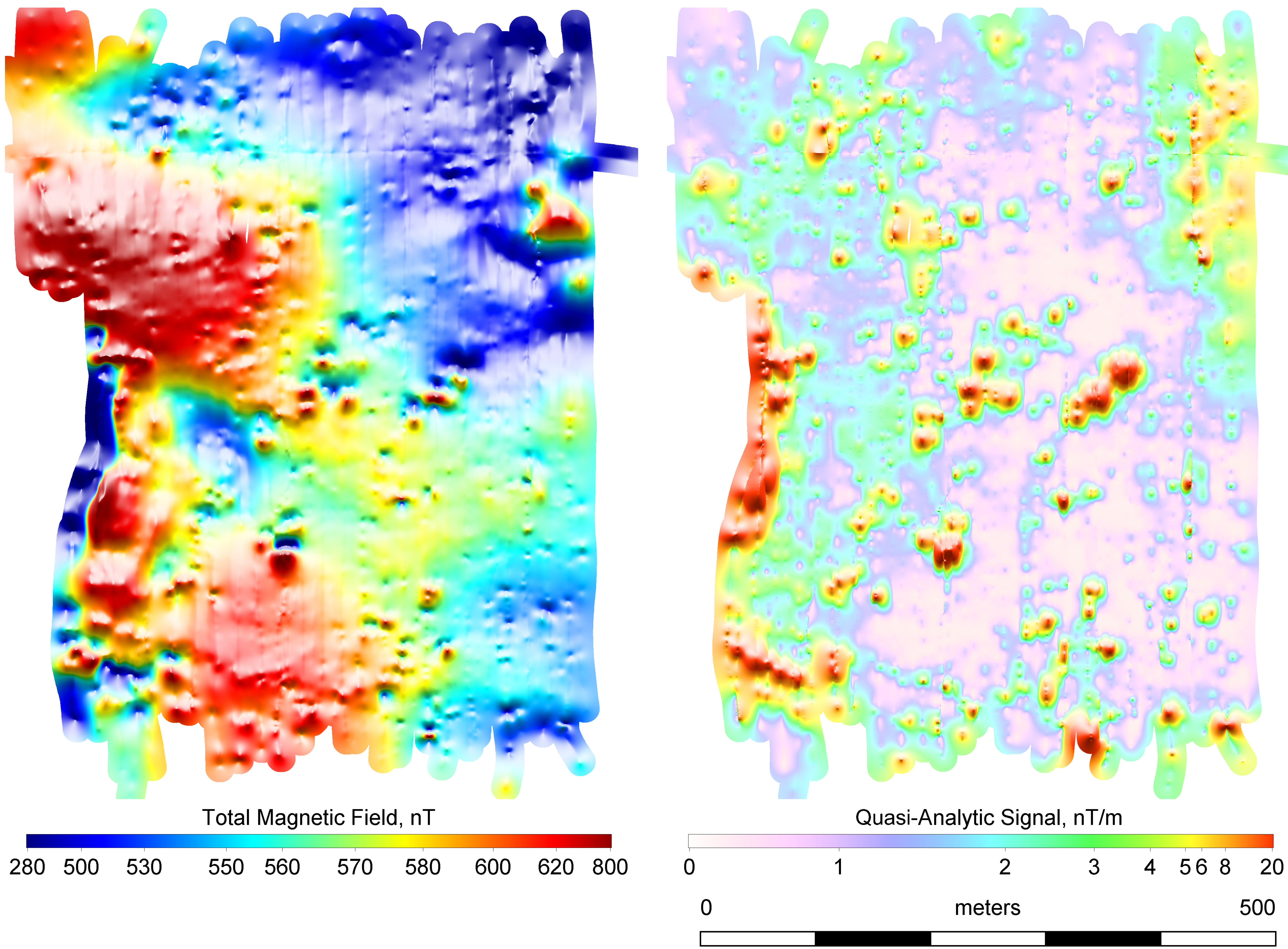

Figure 6. Total Magnetic Field Map Acquired during survey in Hawaii (left) and its Quasi-Analytic Signal counterpart (right). Great field Simplification can be seen on the right pane.