Measured is Better

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ABSTRACT

Recent advances in the precision of magnetometers, real-time compensation for the magnetic effects of the aircraft, and accurate positioning of the aircraft using differential GPS have greatly improved the quality of measured magnetic gradients such that they are indeed better than the calculated derivatives.

It is possible to derive the unknown gradients from the total field using either Hilbert or Fourier transformations, but these processes necessitate a priori assumptions about the source body geometry.

Because of the theoretical limitations inherent in calculation of derivatives, and in gradient measurements using three or fewer sensors, the best approach using scalar magnetometers is to measure the three orthogonal gradients simultaneously. This has been limited in the past by lack of sensitivity of the instruments, and aircraft induced noise.

INTRODUCTION

Poseidon Geophysics and their associate company Geodass have operated a commercially successful triaxial aeromagnetic gradiometry system for more than eight years. The triaxial system overcomes some of the limitations of single sensor systems, with marked improvement in defining the individual magnetic field components.

The nomenclature in this paper uses ΔHx for the transverse horizontal gradient, ΔHy for the in-line horizontal gradient, and ΔHz for the vertical gradient. Gradients are those measured directly, derivatives are those calculated from the total field data. The aircraft frame of reference (AFR) is distinguished from the source frame of reference (SFR).

TRIAXIAL GRADIOMETER INSTALLATION

Data presented in this paper were acquired using instruments installed in a Cessna 404 Titan fixed wing aircraft. Four Scintrex CS-2 cesium vapour magnetometers are mounted in fibreglass nacelles on each wingtip and at the top and bottom of the tail (Figure 1). The separation between the wingtip sensors (ΔHx) is 16.46 m, the wingtip and tail sensors (ΔHy) is 8.68 m, and the tail sensors (ΔHz) is 1.92 m.

The magnetic effect of the aircraft has been reduced by replacing ferrous magnetic components with stainless steel or aluminium equivalents. The residual magnetic effect was corrected with an RMS Instruments AADC compensator, which uses a 27-term real-time software compensation algorithm derived from the output of a three-component fluxgate magnetometer.

THREE VS. FOUR SENSORS

Total magnetic field measurements using optically pumped magnetometers are scalar measurements. The objective of gradient measurements or derivative calculations is to resolve the individual vector components. In a three sensor configuration, the vector normal to the plane of the sensors cannot be uniquely resolved, hence the necessity of defining the total field vector with a four sensor array.

In a three sensor configuration such as the NRC Convair 580 (Hardwick 1996) only the ΔHx and ΔHy gradients in the plane of the three sensors is measured, and the ΔHz is calculated. Shallow sources with anomaly wavelengths shorter than the baseline distance between the fore and aft sensors would be measured at different time intervals, and would create spurious vertical gradient anomalies.

The magnitude of the horizontal gradient from a compact magnetic source off to one side of the flight path is perhaps several orders of magnitude larger than the vertical gradient. If there is any roll in the aircraft, part of the signal from the horizontal field contributes to the AFR vertical gradient. Unless All three gradients are measured you cannot resolve the three components of the total field uniquely. This again demonstrates the necessity of measuring all three components of the magnetic field.

MEASURED VS. CALCULATED

If assumptions about the source body geometry are made (i.e., two-dimensional), it has been demonstrated that calculated derivatives closely match the exact gradients (e.g., Paine 1986). Noise in the input

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Figure 1: *Cessna 404 Titan aircraft with triaxial aeromagnetic gradiometer installation. The separation between the wingtip sensors (DHx) is 16.46 m, the wingtip and tail sensors (DHy) is 8.68 m, and the tail sensors (DHz) is 1.92 m.*

data or introduced in the data processing may be magnified by the calculations of the derivatives and yield unacceptable results. By measuring the gradients directly, no *a priori* assumptions about the source body geometry need be made, and calculated derivatives such as Euler deconvolution or magnetic modelling are more precise and are not biased by any fundamental assumptions.

Derivatives in any direction can be calculated from the total field using either space domain or frequency domain operators. These calculations are limited by the sampling bias inherent from the original data and the gridding process. Generally the high frequency components of the gradients are lost in the derivative calculations. Measured gradients retain the fidelity of the high frequency components, which are caused by either narrow/shallow magnetic sources and micropulsations in the earth's magnetic field.

Another approach is to measure the total field and the transverse horizontal gradient (ΔHx) and use a Hilbert transform to calculate the unknown gradients. The gradients (or derivatives) must satisfy the Laplace equation so that the sum of the second partial derivatives equal zero outside of the source. If one or more of the gradients is not measured, it must be assumed that the second partial derivative is zero. This approach suffers from the *a priori* assumptions about the source body geometry. If less than three gradients are measured, the vectors are not true gradients but are components of the total field in the plane of measurement.

MEASURED GRADIENTS

Measurements of ΔHz over a short baseline (approximately 2 m) in a small aircraft with noise levels on the order of 5 pT/m after compensation (McMullan and McLellan, 1994) are possible with the improved sensitivity of commercially available nuclear resonance-type magnetometers. Below the noise level, calculated derivatives are blended with the measured gradients. This hybrid approach provides a consistent image over the full dynamic range of the data.

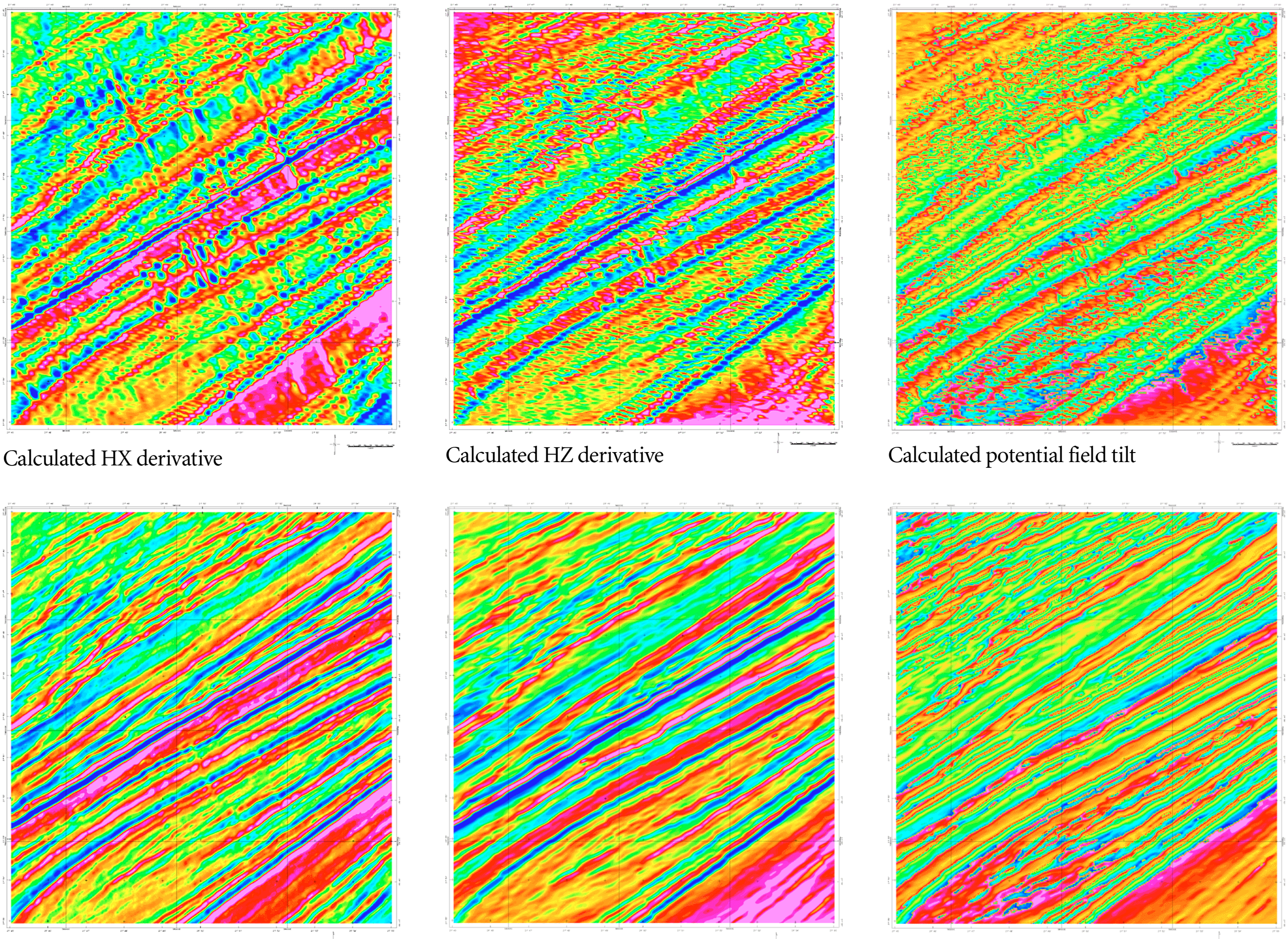
The transverse horizontal gradient is perhaps the most important, as the measurement of ΔHx partially compensates for the spatial aliasing caused by the sampling bias along the flight lines. The ΔHx replaces the terms in the interpolation algorithm commonly used for gridding.

The measured in-line gradient ΔHy is a space derivative of the field whereas the derivative calculated from the difference between successive total field measurements is a time derivative of the field. The measurements of ΔHy includes signal from variations in the Earth's magnetic field such as micropulsations. The difference between the measured and calculated gradients can therefore be used to reconstruct a diurnal record Coggon (1996).

It has been previously demonstrated that direct subtraction of readings from a magnetic base station is not effective in removing the diurnal variations of the magnetic field (e.g., Pendock 1993) because of local conductivity anomalies and phase differences in the field between the base station and the survey area. However, diurnal variations in the earth's field, particularly in the micropulsation frequency range are a significant contribution to levelling errors (Wanliss and Antoine, 1995).

DERIVATIVES

It has been demonstrated previously (McMullan *et.al.*, 1995) that derivatives calculated with the measured gradients compared to the calculated equivalents are superior, particularly those which utilise all three gradients, such as analytic signal, potential field tilt, or Euler deconvolution (Figure 2).



Calculated HX derivative

Calculated HZ derivative

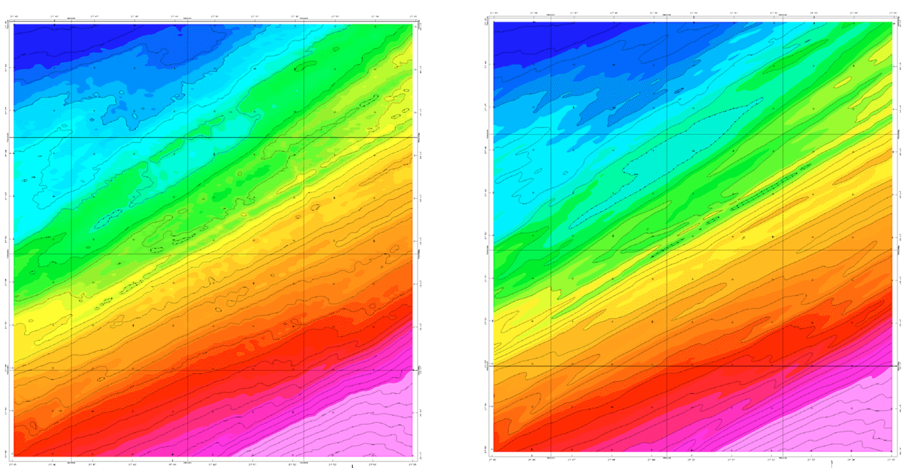
Calculated potential field tilt

Measured HX gradient

Measured HZ gradient

Potential field tilt from measured gradients

Figure 2: *Comparison of calculated derivatives vs. measured gradients, Ghantzi-Chobe Fold Belt, northwestern Botswana.*



TMI bi-directional spline gridding

TMI horizontal gradient enhanced

Figure 3: *Comparison of bi-directional gridding vs. horizontal gradient enhanced total magnetic intensity (TMI), Ghantzi-Chobe Fold Belt, northwestern Botswana.*

LEVELLING

The most common method of levelling aeromagnetic surveys uses the flight line-tie line intersections. As tie lines usually account for 10 to 20% of surveys, reducing or eliminating the need for tie lines is an important economic consideration.

Although Nelson (1994) argues that measured horizontal gradients can be used to reduce or eliminate the necessity of tie lines for levelling aeromagnetic data, there are other components that create line-based noise in grids which cannot be accounted for in the measured gradients. For example the difference in altitude variations, aircraft positioning errors, and uncompensated aircraft effects cannot be eliminated by using the horizontal gradient in the gridding algorithm. It is therefore necessary to include tie lines, although the frequency may be reduced.

The consequence of using ΔHx in the gridding is a much improved total field grid (Figure 3). The logical consequence of this would be to widen the flight line spacing to reduce the overall survey cost. However, the improvement in the continuity of features sub-parallel to the flight lines which are strongly aliased, and the identification of small targets between the flight lines advocates measuring the gradients at conventional line spacing, leading to an improved geological map.

RECONSTITUTION OF TOTAL FIELD FROM GRADIENTS

The reconstitution of the total field from the measured gradients provides the possibility of total magnetic intensity measurements which are free of diurnal noise. The total field can be reconstituted from the measured gradients using the simple vector sum of the components.

However, the long wavelength components of the field are not retained in gradient measurements, but can be added back to restore the full fidelity of the signal (Hardwick and Boustead, 1997). Alternatively long wavelength information can be obtained by measuring along a few tie lines.

CONCLUSION

The overall objective of magnetic surveys is to improve geological mapping, which is greatly enhanced by measuring the magnetic gradients directly. Other advantages of the measured gradients are seen as follows:

- removal of diurnal variations of the earth's magnetic field
- improved resolution of closely spaced/shallow sources
- improvement in gridding algorithms and calculated derivatives
- reduction or elimination of tie lines used for levelling
- direct indication of the strike extent and direction of magnetic bodies
- indicate off-profile magnetic sources

The limiting factor in the precision of measured gradients is the compensation for the magnetic effects of the aircraft. With better recording of the aircraft movement, particularly in turbulent flying conditions, and measurement of the static magnetic response of the aircraft, the compensation can be improved by post processing to remove the system response.

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REFERENCES

Coggon, J.H., 1976. Magnetic and gravity anomalies of polyhedra, *Geoexploration*, 14, pp 93-105.

Coggon, J.H., 1996. Gradient magnetic processing, internal memorandum, Poseidon Geophysics (Pty) Limited, Gaborone.

Hardwick, C.D., 1996. Aeromagnetic gradiometry in 1995, *Exploration Geophysics*, Vol 27, p1-11.

Hardwick, C.D. and Boustead, G., 1997. *Total field levelling using measured horizontal gradient in place of tie lines*, paper presented at High Resolution Geophysics workshop, Tucson.

McMullan, S.R., McLellan, W.H. and Koosimile, D.I., 1995. Three dimensional aeromagnetics, *Preview*, No. 57, p83-91.

McMullan, S.R. and McLellan, W.H., 1994. *Final Report—Geophysical exploration of the Ghanzi-Chobe Fold Belt, Ghanzi and Chinamba Hills areas*, by Poseidon Geophysics (Pty) Limited, Geological Survey of Botswana, Open File report, unpublished.

Nelson, J.B., 1994. Levelling of total-field aeromagnetic data with measured horizontal gradients, *Geophysics*, Vol. 59, No. 8, pp1166-1170.

Paine, 1986. A comparison of methods for approximating the vertical gradient of one-dimensional magnetic field data, *Geophysics*, Vol. 51, No. 9, pp1725–1735.

Pendock, N., 1993. *Preliminary analysis of magnetic measurements from six base stations*, Department of Computation al and Applied Mathematics, University of the Witwatersrand, unpublished.

Wanliss, J.A. and Antoine, L.A.G., 1995. Geomagnetic micropulsations: Implications for high resolution aeromagnetic surveys, *Exploration Geophysics*, Vol 26, p535-538.