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Getting the best value from gravity gradiometry

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Summary:

The critically important steps to get best value from your gravity gradiometry data, assuming your contractor has done his job well in designing and acquiring the data, is the preparation of the representation of the potential field gradients. The ~200m resolving power of existing gradiometer systems approaches what is necessary for minerals applications. In particular, beyond the aircraft, the topographic surface represents the largest and most proximal density contrast encountered in an airborne survey. Hence terrain effects can have significant impact on AGG data. The critical steps are:

- Terrain correction and determining 'best' terrain density
- Gridding, using all the measured gradients to constrain the interpolation
- Smoothing/de-noising by using the 3rd order tensor constraints
- Anti-alias filtering of the gradient signals so that wave lengths are properly represented in all directions
- Transformation of the gradients by integration to estimate the gravity or magnetic field

Terrain corrections are a necessary step in the processing of observed AGG data in rugged terrain, in order to highlight subsurface density variations with a minimal overprint from the terrain. We propose a simple and rapid AGG tensor-based method to estimate an optimum bulk terrain density for subsequent terrain-correction.
Each of the currently deployed systems for acquiring gradiometry is evolving driven by competition and the users' needs. Mining applications of the technology to directly detect ore-bodies that show up as anomalies can now be successful provided the dimensions are of the order of 200m or more. High resolution 3D geology models of operating mines can be used to calibrate gradiometry surveys

Key words: tensor, gravity, terrain-correction, integration, gridding.

Introduction:

Low-flying draped airborne gravity gradiometry (AGG) surveys, measuring lateral density variations in the Earth's gravitational field are being used in rugged terrain for detection of anomalously dense near-surface ore-bodies, such as Iron Oxide Copper Gold deposits (IOCG) and volcanogenic massive sulphide ore deposits (VMS) (eg Brazil 2012) as well as for the definition of geological structure in oil exploration (eg Kenya 2012).

The critically important step to get best value from your gravity gradiometry data, assuming your contractor has done his job well in designing and acquiring the data, is the preparation of the potential field gradients in an optimum form for interpretation.
In particular, beyond the aircraft, the topographic surface represents the largest and most proximal density contrast encountered in an airborne survey, followed by any local weathering profiles in the near sub-soils. Hence terrain effects and weathering do have significant impact on AGG data. Then there are the issues of gridding, filtering and integration to negotiate. It is after all these processes and adjustments have been applied, post-mission, that most interpretation work starts.

Methods and Results:

The critical steps are:

- Terrain correction and determining 'best' terrain density
- Gridding, using all the measured gradients to constrain the interpolation
- Smoothing/de-noising while honouring the 3rd order tensor constraints
- Anti-alias filtering of the gradient signals so that wave lengths are properly represented in all directions and no distortions exist along line
- Transformation of the gradients by integration to estimate the gravity or magnetic field

Tensor Terrain Corrections

Terrain corrections are routinely applied as part of post-survey processing: for every point of observation, the theoretical gravity tensor response from the terrain alone is computed using a Digital Elevation Model (DEM) and a suitable bulk terrain density value. The theoretical gravity tensor response from the terrain is subtracted from the observed AGG data, yielding a terrain-corrected AGG highlighting subsurface density variation with a minimal overprint from terrain effects (FitzGerald, 2011).
The advent of satellite-derived regional DEM and survey-scale "LIght Detection And Range" (LIDAR) derived DEM's has improved the quality of AGG terrain correction considerably.

With modern software the theoretical gravity tensor response for the terrain model can be readily computed for all operational AGG systems (Falcon and FTG), as well as for systems currently under development. However, this does require full insight and understanding of the reference coordinate systems used by the various instrument designers and survey operators.

Tensor Gridding

After terrain correction, gridding is the next most important step prior to any interpretation or inversion.
Algorithms to rapidly grid full tensors and the horizontal curvature components of the tensor have an immediate benefit for a very low increment on the cost of acquiring the data. Intrepid have one such technique (FitzGerald, 2006, 2008) and this is available commercially. During 2011, a second variation specifically for FALCON has been implemented. Note, this does not mean 6 separate grids, but one multi-band grid that treats the tensor curvature gradients as the signal, and not each component individually.

Traditional potential fields practice (Reid, 1980), dictates a gridding cell size one quarter the line spacing. This has become the industry norm. For tensor data, the new methods demonstrate good coherence to one sixth the line spacing. This is not surprising as gradient information constrains the interpolation better than component by component interpolation. In support of this, Brewster, 2011, also shows a method to quantify the benefits of using all the tensor components during gridding. He shows a 2/3 reduction in cell size while still being able to discriminate twin target bodies successfully. Barnes, 2013 takes the equivalent layer option to also explore how to exploit the full tensor signal during the gridding process, keeping the signal to noise ratio high than 1.

Tensor De-Noising Techniques

A grid of observed tensor estimates on the drape surface of an airborne survey can be further improved by using fundamental physics relationships involving 3rd order tensor components (Pajot, 2007). In this paper, a 5 x 5 convolution kernel for a finite difference operator to smooth and denoise a full tensor is described. An improved implementation specifically adapted for gridding and termed MITRE, is now available.
This is logically equivalent to the improvements of a gridded scalar potential using Minimum Curvature (Briggs, 1974).
The most important difference from "Minimum Curvature" is the progression to 3rd order tensor arithmetic to honour the tensor component relations. The implementation required the following:

a) respect for tensor measurement frame (East North Down, East North Up, North East Down)
b) new definition of a residual error couched in 3rd order tensor terms – see Equation 1.
c) a move away from a Gauss-Seidel solver to a Jacobi scheme.
d) a 7 x 7 x 6 convolution window to operate and produce a least squares best fit of the full tensor field.
e) The larger operator size (7 x 7) also helps support the interpolated tensor field when the cell size is reduced.

Further discussion is given in FitzGerald, 2012.

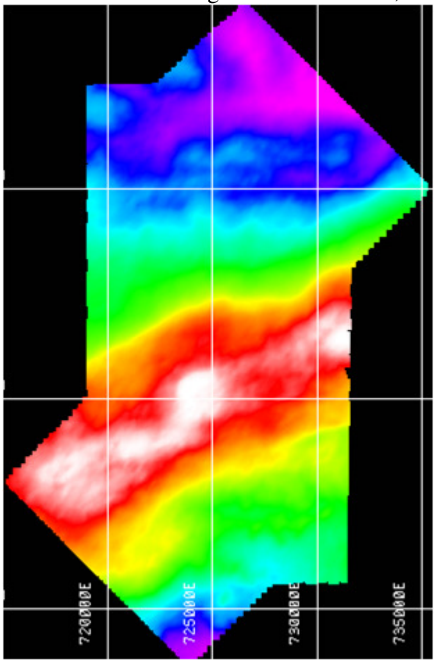

Figure 1. T_z integrated from T_{zz} only

The tensor noise residual can be reasonably measured in a grid by the following function

Noise=

$$\left\{\left(U_{xx,y}-U_{xy,x}\right)^2+\left(U_{xy,y}-U_{yy,x}\right)^2+\left(U_{xz,y}-U_{yz,x}\right)^2\right\}4\Delta x\Delta y$$

Equation 1a.

where U is the potential and Δx,=Δy are the grid spacing intervals. When expressed as central finite differences, this becomes

Noise =

$$\left\{\left(U_{xx}(i,j+1)-U_{xx}(i,j-1)-U_{xy}(i+1,j)+U_{xy}(i-1,j)\right)^2+\ldots\right\}$$

Equation 1b.

Alternatively, a least squares best fit of the underlying potential for each tensor estimate can also achieve the same outcome (Barnes 2011). This can take the form of a) an equivalent layer style framework b) a discrete Fast Fourier transformation of each component back to the potential along profiles c) a 3D truncated Fourier series (T3DFS). From experience, the equivalent layer techniques tend to smooth the signal more than local convolution filtering methods such as MITRE.

Anti-alias Filtering of Gradiometry Data

Using Falcon data as the example, the important point here is to recognise that the useful along line gradient frequency content is around 2 samples/second or every 30 metres and the across line frequency content is the line spacing, usually greater than 250m. Airborne contractors who use Fourier filtering of the tensor gradients, do this component wise, rather than by a 'whole of tensor' method. At a further stage before the integration of the tensor to estimate gravity, another anti-alias step maybe applied for Falcon. This is usually a 7th power Butterworth low pass filter to all the measured gradients.

In contrast to this, a whole of tensor approach can be applied to filtering. This is done by using an Invariant transform, and recasting every reading into its EigenValues, and a rotational matrix, expressed in a compact quaternion form. When using all the tensor as the signal, we have sometimes found the Gibbs phenomena can occur, as phase jumps can be introduced by the filtering. A novel method to unwrap any phase busts and thus avoid this, is a current project within Intrepid Geophysics. The problem arises in an ambiguity in expressing rotations.

So the number of FFT transforms for AGG data can vary from

A. 5, if each component is treated separately
B. 4, if the Eigen Value/Quaternion approach is used
C. 3, if the Hilbert Pair relations are available in the geometry of the instrument

The more compact the FFT used, arguably the better the physics is being honoured.

Further FALCON Discussion

All Lockheed Martin designed Gravity Gradient Instruments (G.G.I.) measure a Hilbert pair signal. The spinning circular disk generally would indicate this possibility. In the FALCON case, the G.G.I is being deployed horizontally and the measured components are T_{uv} and T_{NE} where T_{uv} is defined to be $(T_{NN}-T_{EE})$ *0.5. The signal has special properties that are a little different to what is considered normal. For one thing, the components can be packed into a single complex number. When this is done, the standard convolution theorem filter weights have to be re-thought to include directional factors (Kschischang, 2006). A very simple and efficient formulation results. Currently, for the Butterworth filtering of FALCON data, we are using 4 FFT operations (Kschischang, 2006).

Tensor Gradient Integration

There has been little written on this subject in recent years. The original work at the University of Calgary by (Vassiliou, 1985) is mostly forgotten. This is a shame because this was the first time a transfer function was designed to maximise the signal recovery from all of the partial derivatives. Work in the last couple of years consistently shows that about 30% of the vertical component of gravity is coherently tied up in the XZ and YZ gradients. The example presented here is but one of many. The 3 partial derivatives or curvature gradients each contain parts of the vertical component. No one curvature gradient contains all the phase or rotational part. The current efforts of contractors to recover T_z from T_{zz} or the FALCON measurements are missing this contribution. By way of example, figure 1 shows the T_z derived by integrating just T_{zz} and figure 2 shows the T_z derived from using T_{xz} T_{yz} T_{zz}. The difference between the two estimates is shown in figure 3. As the FALCON system doesn't measure these cross gradient terms, they cannot be used to contribute to the T_z estimate.

Recent work on estimating the TMI from a magnetic tensor measurement, also raises similar issues. Does the TMI signal, as currently measured, carry all the curvature information in the magnetic field?

Recovery of Non-Measured Tensor Components

Many people have sought answers on just what can be calculated. The FALCON design is cleverly targeted at using the 2D horizontal tensor measure to recover the vertical component of gravity, exploiting a variation on the LaPlace trace condition. Several new instruments are in development where it is hoped a partial tensor gradient will also prove to be sufficient. These are notably the GEDEX and Rio VK designs (Tzz - Txx). The new designs hope to achieve noise levels around 1 Eotvos, and so be able to resolve subtle density anomalies with a small footprint. In theory, all components can be recovered from any potential field component. However, when it comes to real situations, even Full Tensor measures along profiles can exhibit increased noise levels for even small processing steps. The reason lies in signal sample aliasing. Any component that has a gradient well constrained along profile behaves as one would hope, however cross gradients almost immediately deteriorate with unacceptable noise if they are not matched to cross line gradient measures from other lines. This leads us to the conclusion that most practioners tacitly follow, you cannot practically work on tensor gradient drape corrections, or estimate non-measured components, except from a 2D grid. It is only in the context of the fully constrained drape grid, which has therefore already been strongly low-passed, that one can compute any other component. In practice, the issues of padding and other data conditioning requirements, also conspire to thwart this as a viable technique to recover the full tensor.

A novel development in 2012 saw the use of spatial indexing for levelling the tensor signal. The k-d tree methods (Wikipedia) are now used commonly in GIS and image processing. This efficient method of finding nearest neighbours, preserves all the profile tensor signal content, while allowing practical and stable continuation to an arbitrary surface. This spatial indexing method promises to improve the efficiency of several geophysical processes, and perhaps offer something for the single component measuring camp.

Interpretation

Most interpretation of AGG data ignores the true nature of the measured signal and falls back to inversion of the vertical component of gravity, using a "checkerboard" of point sources. Holstein (2009) shows a novel method for finding 2D sheet like bodies directly from AGG data. The further development of this work exploits inherent dimensionality of most geology bodies, as this is also reflected in the full set of curvature gradients and its local Eigen System (eg you can tell reasonably easily that you have a dyke).

Rather than a blind inversion, case studies of high resolution surveys over existing mine sites can be made. Detailed 3D geology models are constructed, with high precision terrain, lots of drilling and detailed knowledge of the near surface. This then presents an ideal framework for calibrating the AGG survey data to test for spoil dumps, tailings dams, open pits, and significant orebodies, known and unknown. Forward modelling the AGG response of the known situation is compared to what was observed. In 2012/2013, the heliFalcon and Bell FTG systems have received such detailed study, to verify and differentiate exactly what can be achieved, and what is still beyond reach. It is from this work that we conclude a best resolution of 200m is achievable, with careful processing.

AGG is starting to gain more favour in on-shore oil exploration due to its superior short wave length signal and therefore better definition of horst/graben structures. Recent Kenya AGG surveys are a striking example of this capability.

Direct use of all the measured tensor components to help find buried sources and delineate sub-surface faulting has also progressed, finding expression in new developments in "worming" and the Euler Deconvolution methods.

Conclusion:

Terrain corrections are a necessary step in the processing of observed AGG data in rugged terrain, in order to highlight subsurface density variations with a minimal overprint from the terrain. We propose a simple and rapid AGG tensor-based method to estimate an optimum bulk terrain density for subsequent terrain-correction.

The method produced predicted average surface density maps, the quality of which is improved as the number of recorded tensor components increases, and the method is well suited for rugged terrain, where terrain corrections are ever more pronounced and important.

Each of the currently deployed systems for acquiring gradiometry is evolving and being driven by competition and users' needs. Mining applications of the technology to directly detect ore-bodies that produce at least moderate density contrasts can now be successful, provided the dimensions are of the order of 200m or more. Examples showing both Falcon and FTG data being prepared to the high standard required for quantitative interpretation are shown in the presentation. More care is needed within our industry, in preparing grids of the vertical component of gravity from gradiometry.

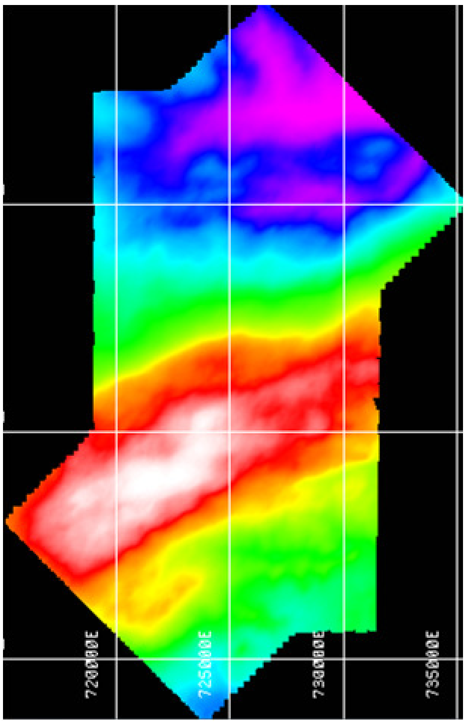

Figure 2. T_z integrated from T_{xz} T_{yz} T_{zz}

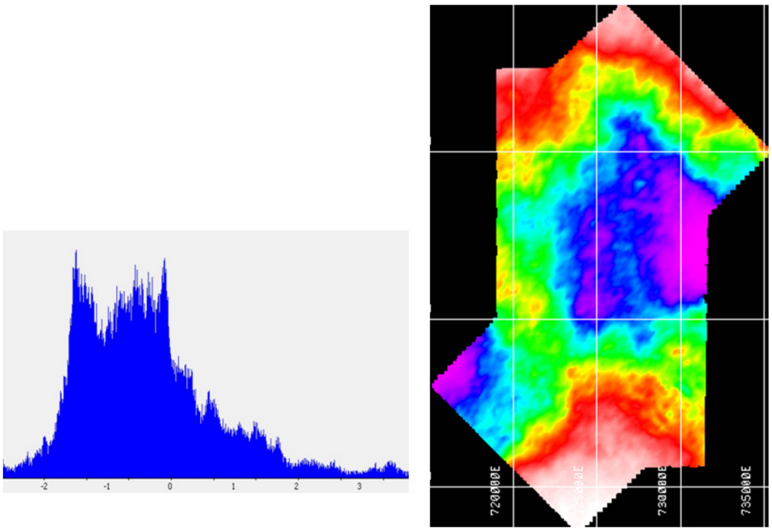

Figure 3. Difference grid, showing +/-3 mGal coherent signal estimated differences. This radically alters any quantitative outcomes in terms of underlying density anomaly and volume of material involved.

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