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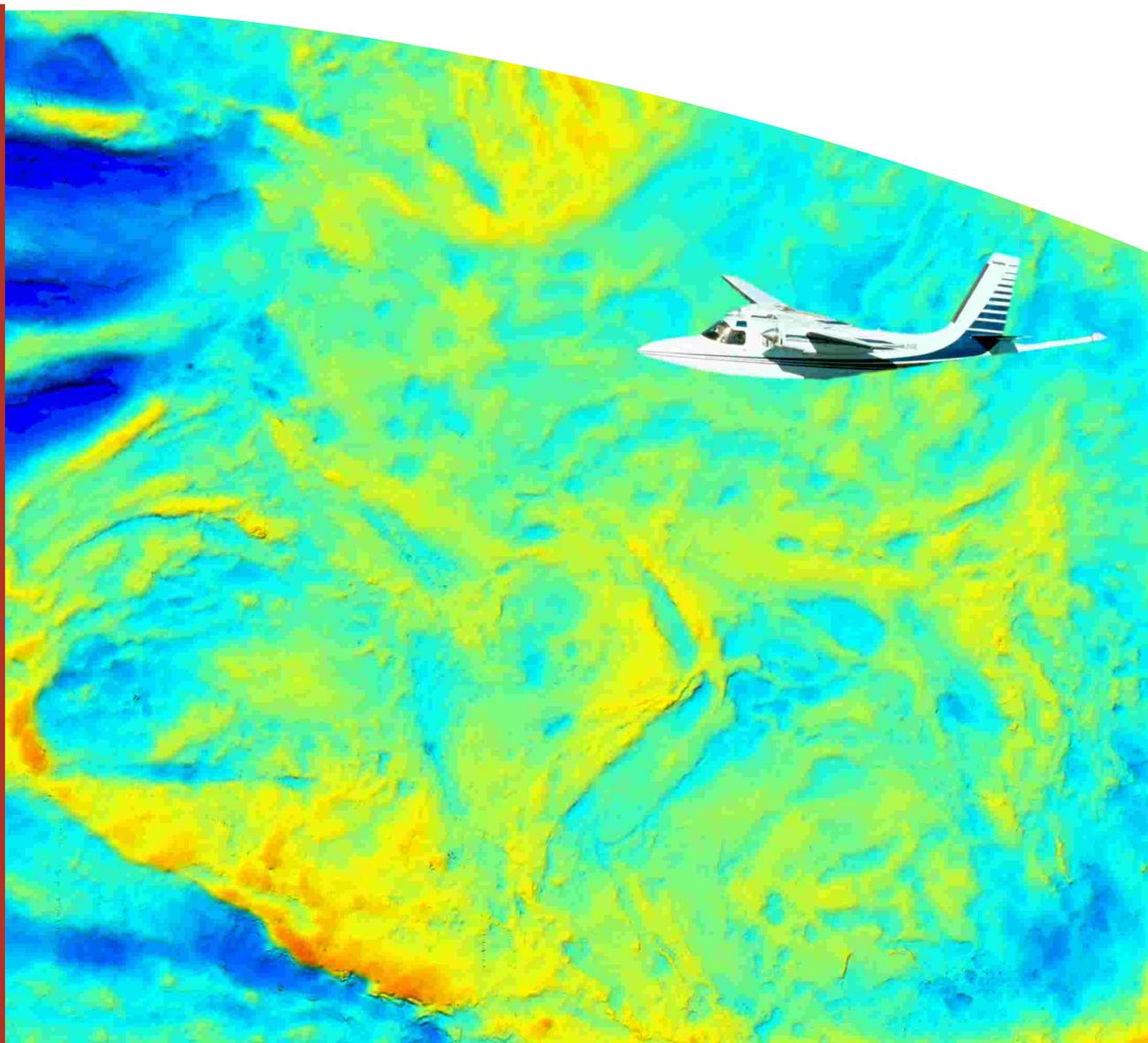
Airborne Gravity 2004

Abstracts from the ASEG-PESA
Airborne Gravity 2004 Workshop

Edited by Richard Lane

Record

2004/18



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Preface

The "Airborne Gravity 2004 Workshop" was held in Sydney on August 15, in conjunction with ASEG-PESA Sydney 2004 (the ASEG's 17th Geophysical Conference and Exhibition). The aims of the workshop were to provide participants with a review of the current state of the art in airborne gravity instrumentation, to present case histories of the use of these methods in minerals and petroleum applications, and to distribute sample data sets. "Airborne gravity" is used in this context to include both airborne gravimeter and airborne gravity gradiometer methods.

The program was split into 2 sessions. The morning session provided a review of the systems, with presentations covering a number of systems currently in operation as well as some that are still under development. The focus shifted in the afternoon session to case histories, with examples from surveys spanning the globe; from Antarctica to the tropics of Papua New Guinea, from Africa through Australia to Canada.

To capture the essence of the day and to promote the ongoing development of airborne geophysical methods, speakers were invited to submit papers for inclusion in a workshop volume. The papers were reviewed prior to publication in this Geoscience Australia Record. Participants received a copy at the workshop, and additional copies of the Record are available on an ongoing basis from Geoscience Australia (www.ga.gov.au).

Units

Physical quantities should be expressed in SI units. The Bureau International des Poids et Mesures (BIPM) is the custodian of this system. To quote from their website (www.bipm.fr): "Its mandate is to provide the basis for a single, coherent system of measurements throughout the world, traceable to the International System of Units (SI)".

The SI unit for acceleration is "metre per second squared" (m/s^2). The signals encountered in gravity surveys for exploration are small, and the prefix "micro" is commonly used (micrometre per second squared, $\mu\text{m/s}^2$). The gal (or Gal), equal to 1 cm/s^2 , is a derived unit for acceleration in the CGS system of units. A prefix of "milli" is commonly used (milligal, mGal). In rare cases in the literature, a "gravity unit" (gu) may be encountered. In this publication, the $\mu\text{m/s}^2$ has been the preferred unit for gravity measurements, but mGal has been accepted.

$$\begin{aligned}1 \mu\text{m/s}^2 &= 10^{-6} \text{ m/s}^2 \\1 \text{ mGal} &= 10 \mu\text{m/s}^2 \\1 \text{ gu} &= 1 \mu\text{m/s}^2\end{aligned}$$

The gravity gradient is a gradient of acceleration and so the appropriate units are acceleration units divided by distance units. Thus, "per second squared" (s^{-2}) is appropriate in the SI system. Typical gravity gradients measured in exploration are extremely small, and the prefix "nano" is appropriate in most circumstances (per

nanosecond squared, ns⁻²). The eotvos unit (Eo), although not recognised in either the SI or CGS systems, is used almost universally in geophysics as the unit for gravity gradient measurements. It is equal to 1 ns⁻². In this publication, the ns⁻² and Eo have both been accepted as units for gravity gradient measurements.

$$1 \text{ ns}^{-2} = 10^{-9} \text{ s}^{-2}$$

$$1 \text{ Eo} = 1 \text{ ns}^{-2}$$

Acknowledgments

The Airborne Gravity 2004 Workshop Organising Committee would like to acknowledge the support of the ASEG-PESA 2004 Conference Organizing Committee and the Conference Secretariat. Support from Geoscience Australia, BHP Billiton and the NSW Department of Primary Industries - Mineral Resources helped to make the workshop a success. The diligence of Mario Bacchin, Katharine Hagan, Angie Jaensch, Jim Mason, Peter Milligan, Ian Hone and Roger Clifton enabled this Record to be produced in time for the Workshop, despite a tight deadline. Finally, a vote of thanks goes to the speakers who committed their time and energy to deliver presentations on the day and to compose this permanent record of the event.

The Air-FTG™ airborne gravity gradiometer system

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Abstract

Air-FTG™ is a multiple accelerometer moving platform technology that measures the full gravity gradient tensor. Full tensor gradient measurements provide more information about the gravity field from each measurement location than partial tensor gradient or single vector field measurements. This facilitates interpretation of sub-surface features exhibiting a lateral density contrast to their surrounds.

Surveys are flown for both detailed and regional applications; with line spacings from 50 to 2000 m. Processing and interpretation techniques utilise all components of the data to enhance signal to noise ratios. The standard deviation of noise in the vertical gravity gradient component is typically 5 to 6 Eo after low-pass filtering to remove wavelengths less than 400 to 600 m.

Introduction

The gradiometer instrument at the heart of the Air-FTG™ system was developed by Bell Aerospace (now Lockheed Martin) during the 1970's and 80's for the US Navy (Brzezowski and Heller, 1988; Jekeli, 1993). The full tensor gradiometer (FTG) instrument represents a significant advance in gradiometer instrumentation and is the only operational moving platform full tensor gravity gradiometer.

Gravity gradiometers measure the spatial rate of change in the gravity field. This form of measurement captures the high frequency signal associated with near-surface lateral density variations more clearly than conventional vertical gravity field instruments. This is possible because the gradiometer signal strength falls off with the cube of the distance to the target (Hammond and Murphy, 2003), in contrast to the conventional vertical gravity signal which decays with the square of the distance. Given typical accuracy levels for gravity gradiometer and vertical gravity measurements, the gradiometer enjoys an advantage for identification and mapping of certain near-surface mineral or hydrocarbon occurrences (Li, 2001).

Air-FTG™ was launched in 2002 on the strength of its marine counterpart's success. Two marine FTG instruments were previously deployed; one each in the Gulf of Mexico and offshore NW Europe from 1998 to 2002. These instruments were then modified for use on an aircraft and are currently operational in North America and Africa. More than 60 000 line km of data have been acquired to date. Both systems can be deployed on either marine or airborne platforms, thus offering a flexible service to the exploration industry.

In this paper, the nature of the Air-FTG™ measurements will be described, an analysis of the accuracy of these measurements will be provided, and then the key parameters that need to be considered for successful application of the technology in exploration programmes will be discussed.

Air-FTG™

Air-FTG™ accurately measures small changes in the gravity field caused by subsurface densities at prospect level resolution. The system works by taking ultra sensitive real-time measurements of the differences in the gravity gradient field in all directions. Gradient data can be directly related to geological structures and discrete bodies that have a density contrast relative to their surroundings, such as kimberlites or massive sulphides.

What is measured?

Gravitational potential is a scalar quantity that represents the energy associated with a unit mass in a gravitational or 'gravity' field. The gravity field is a vector field that describes the spatial variations in potential (i.e., the potential gradients). It can be decomposed into three mutually perpendicular components, shown schematically in [Figure 1](#). In this paper, a coordinate system with the x-axis aligned east-west, the y-axis aligned north-south, and the z-axis aligned vertically is used. Conventional ground or marine gravity methods entail measurements of the vertical component of gravity (Gz). Gravity gradiometry involves measurement of the spatial variations (gradients) of the gravity field. Each of the three vector components of the gravity field has a gradient parallel to each of the three mutually perpendicular coordinate axes. Thus, a FTG instrument

must measure or derive nine components of the gravity gradient tensor, T_{ij} , where i and j are one of x , y or z (Figure 1).

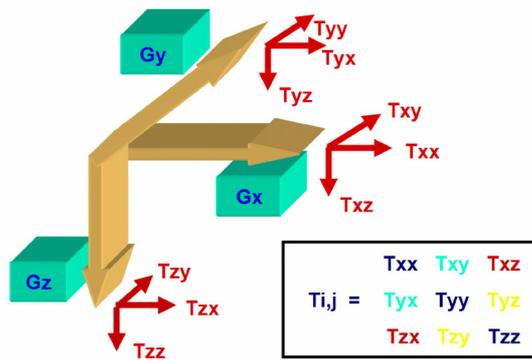


Figure 1. Schematic diagram showing the gravity field vector elements in gold and the tensor components in red. The nine tensor components, T_{ij} , are summarised in matrix form, with colours used to identify the five independent tensor components. Any two of T_{xx} , T_{yy} and T_{zz} are independent.

Although the full tensor consists of nine components, only five are truly independent. Gravity is a conservative field, which means that the amount of work required to move from A to B is independent of the path taken between the two points. From this, it can be shown (e.g., Blakely, 1995) that the gravity gradient tensor is symmetric about the leading diagonal (i.e., T_{ij} equals T_{ji}) (Figure 1). For measurements made above the surface of the Earth and ignoring the mass of the atmosphere, gravitational potential obeys the Laplace Equation and the diagonal element T_{zz} equals the negative sum of the other two elements of the leading diagonal, T_{xx} and T_{yy} (e.g., Blakely, 1995). Therefore, the five independent components of the full gradient tensor are T_{xy} , T_{xz} , T_{yz} , and any two of T_{xx} , T_{yy} and T_{zz} . In practice, the vertical gravity gradient or T_{zz} term is given even if T_{xx} and T_{yy} are also given because T_{zz} is the gradient that is most easily related to subsurface geology.

Gradients are measured in units of eotvos, with 1 Eo equal to 0.1 mGal/km.

Spatial images of the individual tensor components reflect different attributes of target geology. Figure 2a shows a tensor component display for an Air-FTG™ survey acquired onshore Louisiana, USA. The target was a salt cap rock which yielded the prominent positive anomaly in the centre of the T_{zz} image. The location of this feature is highlighted in white in all of the data images. The salt cap rock response can be compared with the synthetic tensor component display for a buried discrete positive density feature shown in Figure 2b. Images of the individual tensor components provide information about geological setting. T_{xx} and T_{xz} identify the north-south edges of the target, revealing in this example those lineaments relevant to the body's emplacement. Similarly, T_{yy} and T_{yz} map the east-west trending lineaments and east-west edges of the target. The T_{xy} cap rock anomaly has the characteristic quadrupole anomaly form with 2 highs and 2 lows that is associated with a discrete target. T_{xx} and T_{yy} anomaly magnitudes can be used to investigate body thickness.

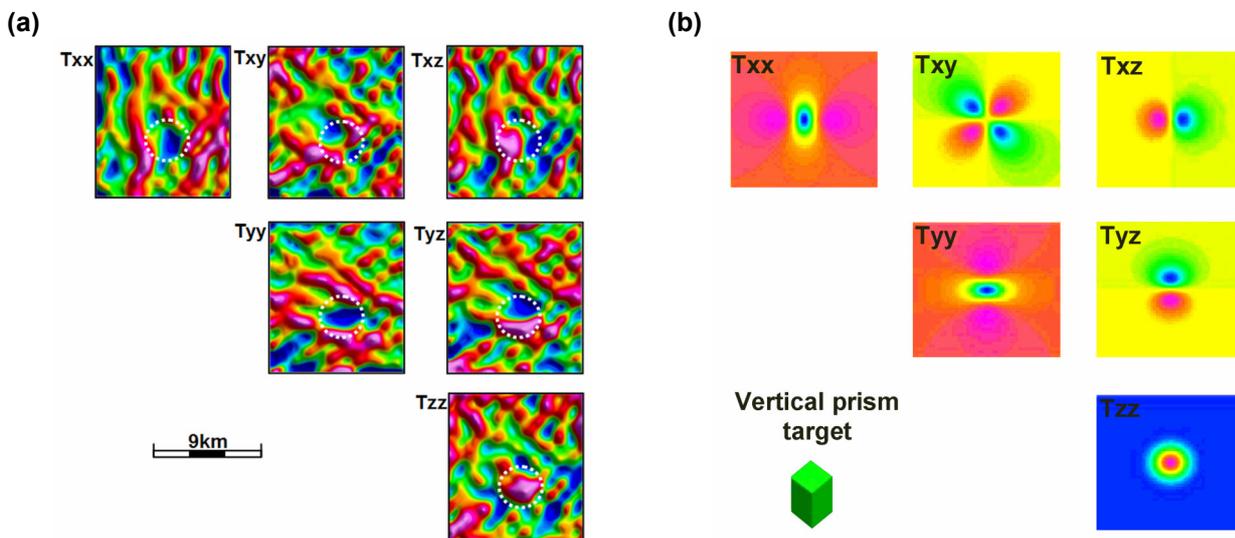


Figure 2. Tensor display for (a) an Air-FTG™ survey acquired over a known salt caprock feature onshore USA, and (b) a theoretical response for an idealised target. The white polygon helps to locate the response of the caprock in each component.

How do we measure the tensor components?

The instrument contains three Gravity Gradient Instruments (GGIs) each consisting of two opposing pairs of accelerometers arranged on a disc (Figure 3). The gradient of the gravity field is measured as the difference in readings between the opposing pairs of accelerometers on each disc. The three GGIs are mounted such that their axes are mutually perpendicular and each make the same angle with the vertical. Viewed from above, the projections of the three axes are 120 degrees apart. To minimise any bias related to the orientation or movement direction of the instrument, the assembly of GGIs is rotated at constant speed about a vertical axis. Brett (2000) gives a more detailed account on the workings of the system.

The measurements from each GGI can be resolved into two gradients in the plane of the rotating disc by taking into account the distance between each accelerometer and the frequency of spin of the disc. The tensor components measured in the external coordinate axis directions are obtained by forming the appropriate linear combination of the six GGI outputs. A three-GGI configuration is required to obtain the five independent tensor components that constitute the basis of the full tensor.

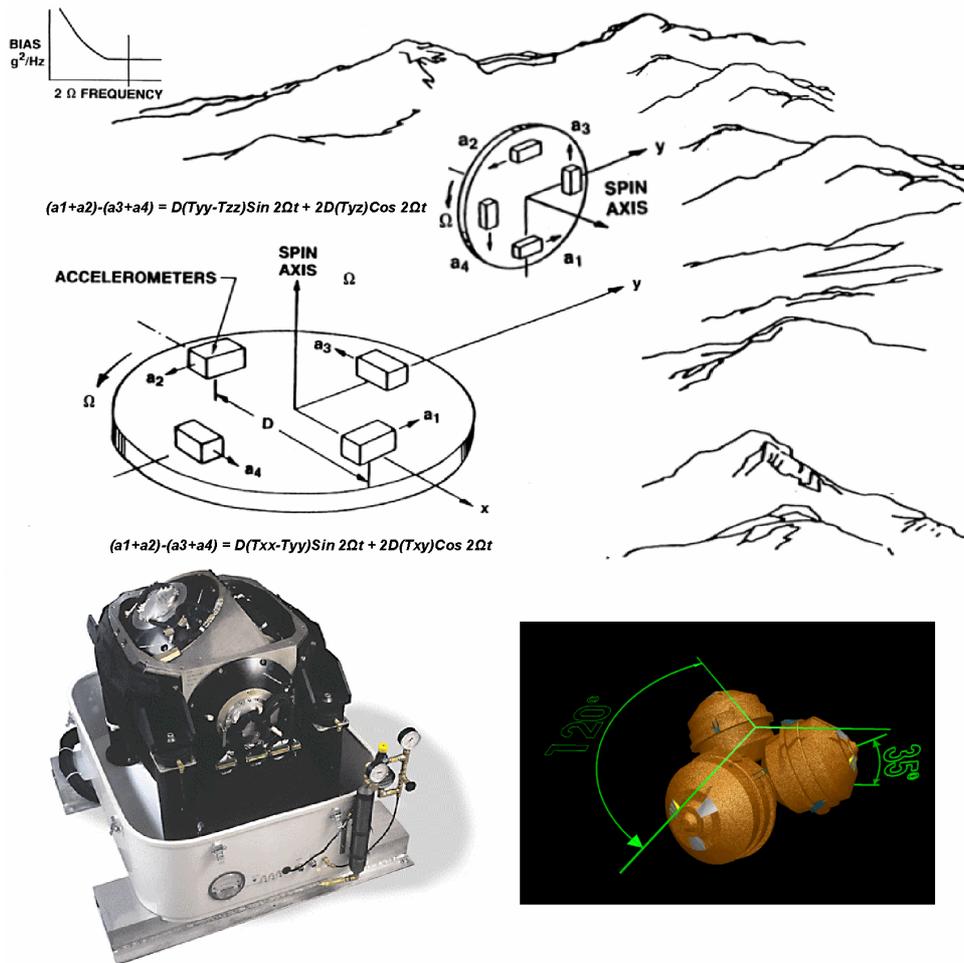


Figure 3. Photograph of the Air-FTG™ instrument with schematic diagram of accelerometer arrangement within each GGI. The darkened inset illustrates the umbrella configuration of the GGIs within the instrument.

Accuracy

The most effective means of evaluating Air-FTG™ data is via comparison with ground gravity data. This can be done by either spatial integration of Air-FTG™ tensor component data to estimate vertical gravity data or spatial transformation of the ground vertical gravity data to estimate a tensor quantity. The rms value for the difference between ground and airborne datasets provides an estimate of the combined errors in the ground and airborne data. This procedure does not allow these errors to be separated, nor does it account for errors that arise because the airborne datasets are acquired over survey areas of finite extent. Provided the ground data are adequately sampled and sufficiently accurate, the contribution of the ground data errors to the differences can be assumed to be small. The rms value can then be taken as an estimate of the upper bound for the noise in the airborne data.

An Air-FTG™ survey was carried out in the Ventersdorp region, South Africa, to assist in the identification and mapping of diamondiferous palaeochannel sequences. A total of 7500 line km of data were acquired with an in-line spacing of 400 m oriented east-west and tie-line spacing of 1600 m oriented north-south. A smaller orientation survey was flown prior to the main survey at 200 m in-line spacing and was merged with the larger data set. The survey was flown on a gentle drape surface at 80 m terrain clearance. The data indicate the presence of a series of north-south and east-north-east trending low density features. These follow the known palaeochannels in the area and confirmed the interpretation based on a series of gravity lows outlined with previously acquired ground gravity measurements. The ground gravity data were acquired at 50 m station spacing along north-east oriented lines spaced at 100 m intervals. A subset covering the same area was extracted from the airborne and ground datasets (Figure 4). The area of the subset lies within the boundary of the orientation survey where data were acquired at 200 m line spacing.

The ground gravity data were first upward continued to a mean height of 1649 m above sea level to align these data with the airborne drape surface (i.e., an 80 m drape above ground) and then a Tzz response was computed by taking the first vertical derivative of the vertical gravity data (Figure 4c). The consistency between the airborne and ground datasets can be judged qualitatively using the three prominent Tzz lows for reference. Quantitatively, the difference between the Tzz data derived from airborne and ground measurements (Figure 4d) has a standard deviation of approximately 5.5 Eo. The yellow-green areas in Figure 4d indicate where both data sets are closely in agreement and testify to the accuracy of the Air-FTG™ system. Many of the areas shown in red, where the differences are larger in magnitude, are where the ground data indicate rapid spatial changes in value. The airborne data are low-pass filtered to remove wavelengths less than 400 m, and this limits the accuracy in areas of rapid spatial changes.

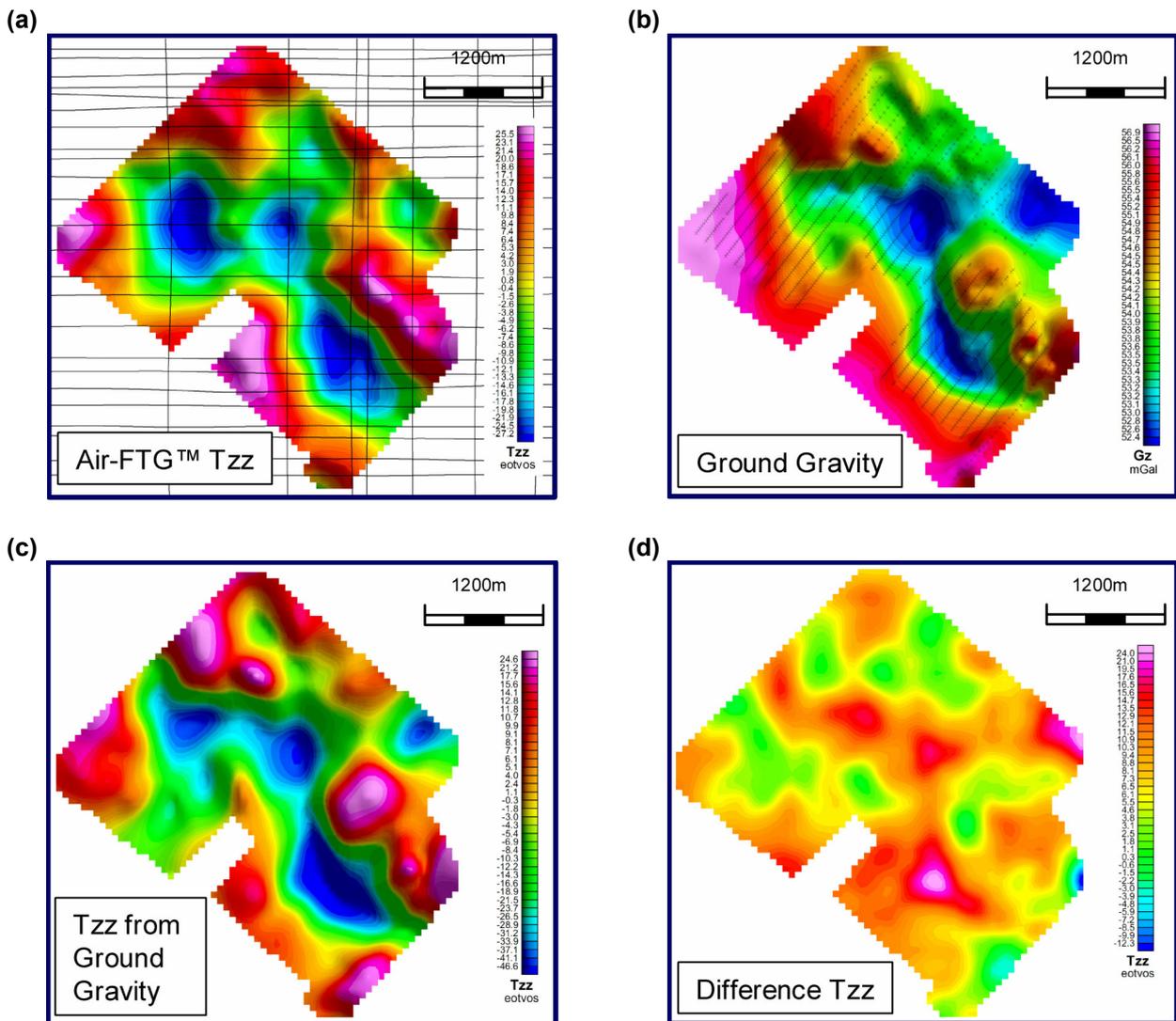


Figure 4. Comparison of Air-FTG™ Tzz data with ground gravity data from the Ventersdorp area, South Africa. Both data sets are terrain corrected. (a) Air-FTG™ Tzz response with flight lines shown as an overlay. (b) Ground gravity Gz image with stations shown as an overlay. (c) Tzz image derived from upward continued ground gravity data. (d) A difference image for the Tzz values derived from Air-FTG™ and the ground gravity data.

Acquisition issues

The two key issues affecting FTG surveys are choice of platform (i.e., aircraft in the case of Air-FTG™) and survey design.

Platform

Air-FTG™ is a highly sensitive instrument requiring a noise free and stable environment to operate to maximum efficiency. This is clearly not possible in the real world, so that issues such as engine activity and propeller speeds that contribute to platform vibrations must be managed. Furthermore, it must be possible for the instrument to be installed close to the centre of gravity of the vessel. This last point, together with the fact that the instrument and data acquisition system together have a mass in excess of 450 kg limits the choice of airborne platform. A Cessna Grand Caravan is currently the preferred platform as it can adequately meet the above requirements. The aircraft is of sufficient size to host the technology and its single engine induces a manageable vibration noise level on the system. The propeller speeds, engine noise and vibrations acting on the system are monitored throughout each flight and the data are compensated for residual noise effects using these auxiliary measurements.

Since the strength of signal in an Air-FTG™ survey falls off with the cube of the distance to the target, it is important to fly at low terrain clearance to capture the small amplitudes associated with subtle targets. Air-FTG™ surveys are typically flown using drape methods at 80 m above ground. This is the lowest flying height that is considered safe given the aircraft performance levels.

Survey design optimising signal

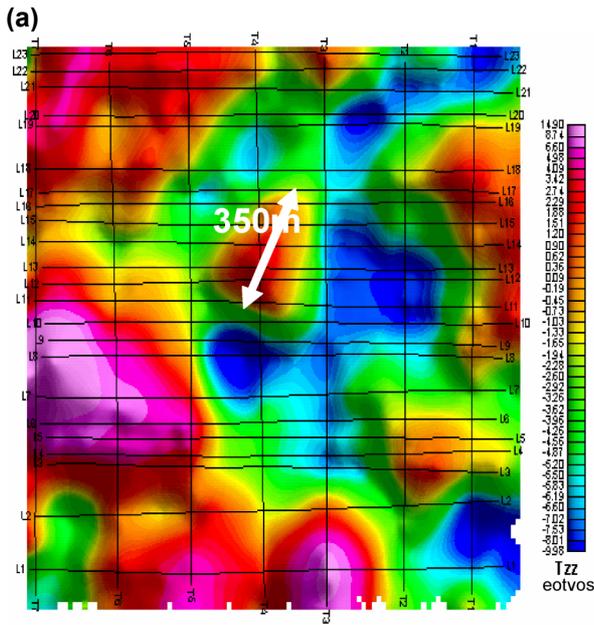
As with any geophysical technique, the choice of line spacing, orientation and survey size for an Air-FTG™ survey is critical to effective surveying. Target size, orientation, density contrast and depth of burial are key factors in determining survey parameters. These issues are always analysed prior to a survey.

As an example, a subset of Air-FTG™ Tzz data from a recent survey acquired in Africa is shown in [Figure 5](#). An anomaly that is a 350 m in length is present in the centre of the image. This feature is well defined when surveyed with 50 m line spacing ([Figure 5a](#)). By selecting groups of lines in the database, it is possible to simulate surveys flown with 150 or 250 m line spacing ([Figure 5b and c](#)). The results indicate that 150 m line spacing would allow the feature to be mapped with adequate detail. The optimum line orientation in this particular case would be east-west, perpendicular to the long axis of the anomaly.

Air-FTG™ surveys are typically flown with line spacings from 50 to 2000 m. Tight line spacings are required for small scale geological targets such as kimberlites, whilst wider line spacings can be used for regional mapping applications on large surveys. Such wide line spaced surveys are possible with Air-FTG™ because the system measures the horizontal components Txz and Tyz in addition to Txx, Tyy and Txy, thus increasing confidence when interpolating from line to line. This is a well-known benefit of gradient measurements (Schmidt and Clark, 2000).

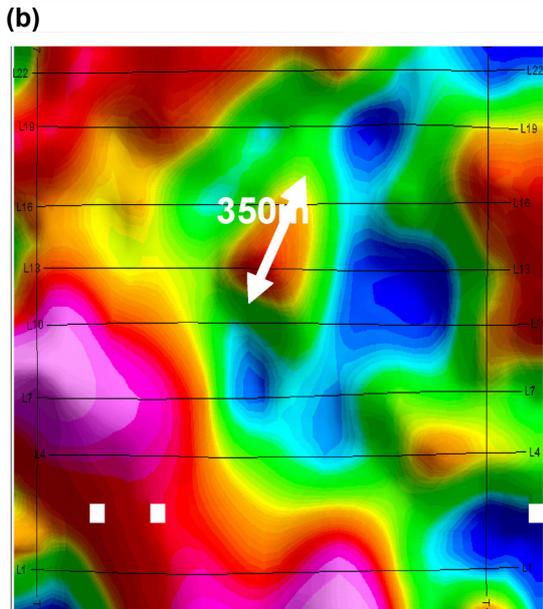
Geographic coverage

The technology, although declassified, is still governed by the US State Department's International Trade in Arms Regulatory (ITAR) Licensing Restrictions (22.CFR121.1). This in effect means that there are a number of embargoed countries where it would be difficult to obtain a license to perform a survey. Fortunately, the number of embargoed countries is small. Air-FTG™ surveys have been acquired in the USA, Canada, South Africa, Botswana, Zambia, and Mali.

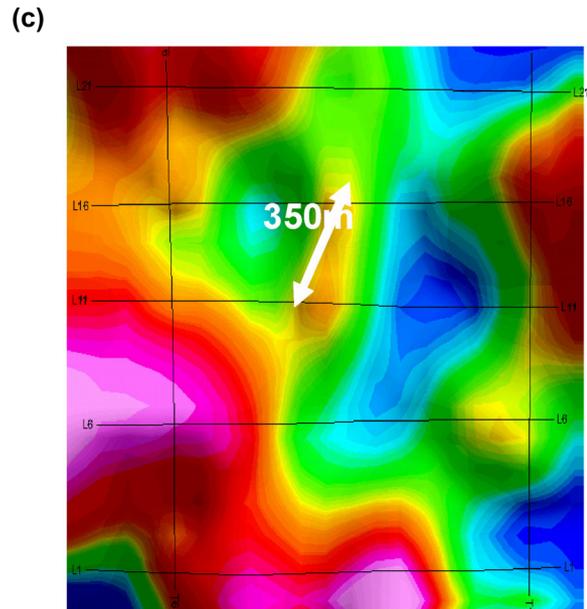


Inline spacing 50 m

Figure 5. Images illustrating line spacing issues. A survey flown with 50 m lines spacing shown in (a) was reprocessed for line spacing of 150 m (b) and 250 m (c). The central 350 m wide target is resolved best with 50 to 150 m line spacings.



Inline spacing 150 m



Inline spacing 250 m

Products

Processing

There are 2 stages in processing Air-FTG™ data: “High Rate” and “Post-mission Processing”. During the High Rate stage, the accelerometer output is compensated for the effects of external forces. This initial stage uses Lockheed Martin proprietary software to correct for centripetal forces resulting from spinning of discs, to apply a self-gradient correction relating to aircraft motion and drainage of fuel, and to correct for accelerations acting on the instrument. At the end of the stage, the data are demodulated in preparation for input to the second stage. During demodulation, the data are re-sampled to 0.5 Hz (2 second intervals), and individual tensor components are extracted and transformed from an internal coordinate system to an external real-world coordinate system.

Post-mission Processing employs a combination of Bell Geospace proprietary and industry-standard techniques. The first is a “Line Correction” procedure that accounts for GGI drift and uses both differentially-

corrected GPS and inertial navigation data to correct for heading errors. Industry-standard techniques such as levelling and micro-levelling are then applied.

The final phase of Post-mission Processing is the application of a “Denoising” routine. This proprietary technique makes use of the properties of full tensor measurements to identify and remove residual noise in the data. A subsurface body with a density contrast will yield characteristic responses in each tensor component such as those shown in [Figure 2](#). The Denoising routine works by identifying an anomaly in one of the components and then looking systematically for the corresponding response in each of the other components. It uses multiple lines and makes no assumptions about density and source geometry in its computations. If the expected response is not found, then the anomaly is considered to arise from noise and is eliminated from the dataset.

Topography represents the single largest density contrast encountered with airborne gravity gradient data. A detailed Digital Terrain Model is required to calculate terrain corrections that remove the effect of this interface prior to interpretation. Terrain corrections are routinely applied to Air-FTG™ data during the processing sequence.

The processing steps described here are continuously refined and upgraded and have led to improvements in Air-FTG™ noise levels from 12-15 Eo to 5 Eo in the past 18 months.

Interpretation

Interpreting Air-FTG™ data is a challenge to the uninitiated! The volume of information often makes it difficult to find a starting point. However, it is useful to start with the Tzz component as this is the tensor component that best images the subsurface geology. The individual tensor components may then be used to help resolve particular attributes of the target, i.e., locating edges and assisting to estimate thickness and / or density contrast of specific geological features. As with many other geophysical data types, anomalies from different sources overlap, and the different anomalies must be separated before target signatures can be identified.

A number of techniques are routinely applied to interpret gradient data such as Fourier filtering (i.e., separating signals according to wavelength), lineament analysis (i.e., using the horizontal component data to identify geological structure and target boundaries), use of 3D display techniques to allow the interpreter to view the dataset from all angles thus aiding identification of targets, and 3D density modelling to investigate the geometry and density contrasts of geological features.

An enabling technology

Air-FTG™ is generally considered as an enabling technology. It can be used to advantage when identifying or screening targets, or when making a quick assessment of acreage at the early stages in an exploration program. It can also be used to ease land access issues by enabling surveying to be carried out in terrain that would be difficult to access on the ground due to cultural sensitivities, rugged topography, desert conditions or vegetation. This allows key areas for detailed follow up to be identified before direct ground access is required.

In summary, Air-FTG™ is a tool that can be used to enhance an exploration portfolio and reduce risk when making exploration decisions.

Summary

The following points summarise the key issues addressed in this paper:

- Air-FTG™ is a multiple accelerometer moving platform technology acquiring the full gravity gradient tensor;
- Full tensor measurements provide more information than partial tensor measurements, and this increases confidence when interpreting lateral density contrasts in the subsurface;
- The system currently achieves resolution of approximately 5 Eo when low-pass filtered to remove wavelengths less than 400 to 600 m;
- The preferred platform is currently a Cessna Grand Caravan, a single engine fixed wing aircraft;
- Surveys for smaller targets are flown in drape mode at 80 m terrain clearance;
- Line spacings from 50 to 2000 m can be used
 - i.e., both local and regional surveying techniques are possible;

- The processing sequence includes an innovative noise reduction routine that makes use of all five independent tensor components;
- Additional interpretation techniques are available for use with the multi-component output
 - Fourier filtering, 3D display techniques and 3D modelling; and
- Air-FTG™ is an enabling technology facilitating rapid decision-making and reducing risk in exploration programmes.

Acknowledgements

Etruscan Resources Inc. are greatly thanked for releasing the ground gravity data and for granting permission to publish the Air-FTG™ data in the comparison analysis. Bell Geospace are acknowledged for granting permission to publish examples of airborne data and their constructive review of this paper at all stages. Richard Lane of Geoscience Australia is also thanked greatly for his critical review and in making this a better paper.

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