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Air-FTG™: Bell Geospace's Airborne Gravity Gradiometer – A Description and Case Study

Introduction

In 1998, Bell Geospace took an underwater technology from the military and brought it to the surface for use in marine petroleum applications. Last year we took to the air! The technology we refer to is 3D-Full Tensor Gravity Gradiometry (3D-FTG) and although it has been measured for more than a century, it was only done from stationary measurements which meant slow surveys and limited coverage. As airborne methods have improved in the last 20 years, explorationists have looked for a density tool to complement airborne magnetics and EM. Recent attempts to fly gravimeters have met with limited success due to their high sensitivity to aircraft turbulence and their long spatial resolution.

The recent introduction by Bell Geospace of an airborne 3D-FTG ('Air-FTG™') has provided the technology to fill that gap and allow petroleum and mineral exploration companies to cover large areas with a true prospect level density sensing device in a short amount of time.

Method

The 3D-FTG uses a technology that was developed for the US Navy by Bell Aerospace (currently Lockheed Martin Corp.) for use aboard Trident Class nuclear submarines. Full Tensor Gradiometry utilises a set of three rotating disks (Gravity Gradient Instruments, GGIs), each containing two pairs of orthogonally mounted accelerometers (Figure 1). Each GGI is spun to a set frequency in order to avoid bias in measurement in the direction of the primary components. By taking the difference of the gravity field sensed by each pair of accelerometers, the Air-FTG™ is able to compensate for most of the turbulence experienced by

the aircraft and retain the high frequency signal that is critical to prospect level geophysical surveying. The only other working airborne gravity gradiometer in the world is configured differently and as a result has to settle for a partial tensor measurement.

The gravity field is composed of three vectors, G_x, G_y and G_z. Each vector contains three gradients. A gradient describes the rate of change of that vector as you move in the three orthogonal directions. This means that T_{xy} describes how the G_x vector changes as you move in the y direction. There are nine gradients that can be described in this manner but only five represent independent gradients (Figure 2), i.e. T_{xx}, T_{xy}, T_{xz}, T_{yy} and T_{yz}. T_{zz} is the negative sum of T_{xx} and T_{yy} satisfying Laplace's equation.

Air-FTG™ is currently acquired onboard a Cessna Grand Caravan 208B, which has been modified to house the instrument, all support electronics, differential global positioning systems, a magnetometer, and appropriate terrain measuring hardware. By positioning the FTG near to the centre of pitch, roll and yaw, rotational accelerations can be held to a minimum. Any accelerations that remain are measured by dedicated accelerometers and their effects are removed during post mission compensation. This design allows Air-FTG™ to fly in much rougher conditions and also eliminates the need for long lead-in or lead-out lines.

Air-FTG™ surveys can be flown at constant barometric elevation or in a gentle drape. As the Air-FTG™ is measuring the gradient field directly, and its signal strength falls off with the cube of the distance:

$$T_{ij} \propto 1/R^3$$

it is usually desirable to survey as close to bodies as possible. Therefore, a gentle drape is normally used. Special software is used to factor in terrain, aircraft climb performance, and cross tie matching so that the survey crew can obtain the best possible survey results. Surveys can be flown as low as 80 m and line spacing is usually in the range of 50 to 2000 m depending on the target and scope of survey. Resolutions of less than 5 Eötvös (0.5 mgals/km) over 400 m spatial wavelengths have been recorded on our recent African surveying program.

Data acquired is stored on disks during flight operations. Immediately following each flight, the data is downloaded to a processing computer where processing algorithms are applied to compensate for the aircraft turbulence, mass shifts, and the self gradient of the aircraft and instrument itself. At this stage a very strict quality control check is applied to the data which looks for excessive accelerations, calibration errors, repeat differences and a series of other predetermined benchmarks.

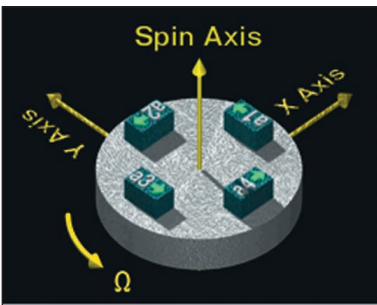


Fig. 1. (Above) Schematic of accelerometer arrangement on one of three Gravity Gradient Instruments (GGIs) in the Full Tensor Gravity Gradiometer.

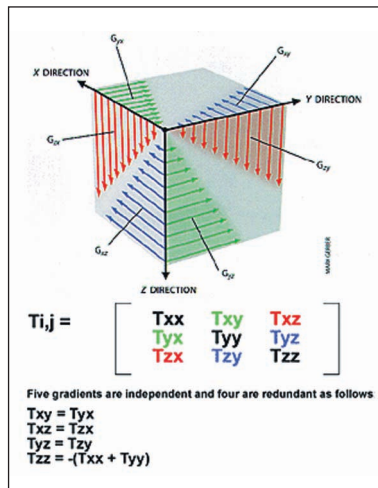


Fig. 2. (Right) Description of the relationship between gravity vectors and their tensor components and the matrix description showing redundancies.

Once the field crew has determined that the survey data is of the highest quality, that data is sent electronically to the processing centre where another set of eyes performs even more rigorous QC checks on the data. If, at any stage, the data does not meet these strict quality standards, those lines are re-flown and merged into the survey.

When the entire survey is complete, overall analysis and processing of the survey can begin. The data from the spinning disks has to be deconvolved and slowly varying changes need to be compensated for. This is all done on the data as a network of lines rather than on individual lines. This is the stage where individual tensor components are calculated. The gradient value recorded in the field on each of the GGLs is dependent on the distance between the accelerometers, frequency of spin on each disc and spatial configuration of each GGL. It is only then that we are able to extract all independent components, i.e. T_{xx} , T_{xy} , T_{xz} , T_{yy} and T_{yz} from the recorded data.

The final step involves more typical potential field processing methods such as filtering and line levelling. One technique that is unique to FTG data is harmonic fit in which the Laplacian nature of the independent tensor components is used. Harmonic fit checks the signals to make sure that all of the components are solutions of Laplace's Equation. Any signal which does not meet this test can be considered noise and discarded.

Final tensor maps are then created for the five independent tensor components T_{xx} , T_{xy} , T_{xz} , T_{yy} and T_{yz} as well as the vertical component T_{zz} . T_{zz} is not independent because $T_{xx} + T_{yy} + T_{zz} = 0$ (another Laplace must) but it is presented because it puts the density anomalies in their appropriate spatial perspective, i.e. it is the one that is most easily related directly to subsurface geology.

Air-FTG™ case studies

To date, Bell Geospace has acquired 1,202 km of Air-FTG™ surveys in North America during initial testing and has acquired over 12,000 line km of commercial surveys in

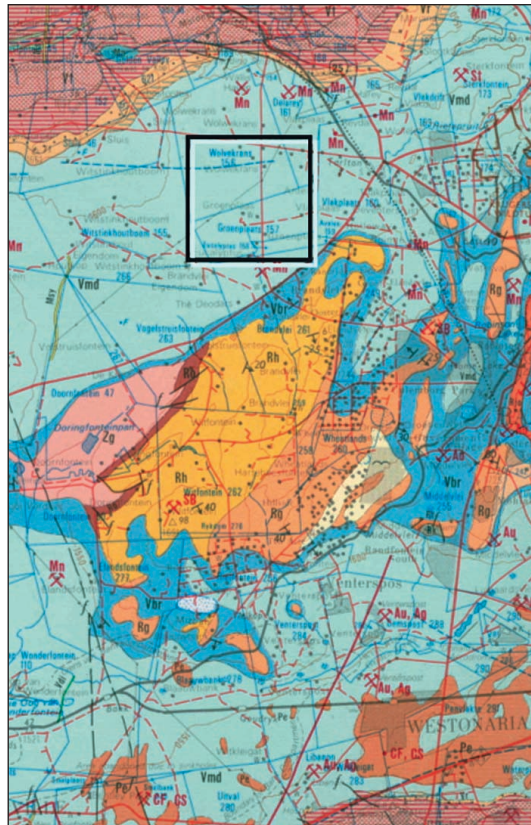


Fig. 3. Geological map for the survey area (survey boundary shown in black is ~6 x 6 km). The geology is dominated by the Malmani Dolomite (light blue colour) of the Transvaal Sequence and the local area exhibits a NE-SW regional trend that is faulted by a series of NW and ENE oriented transfer structures.

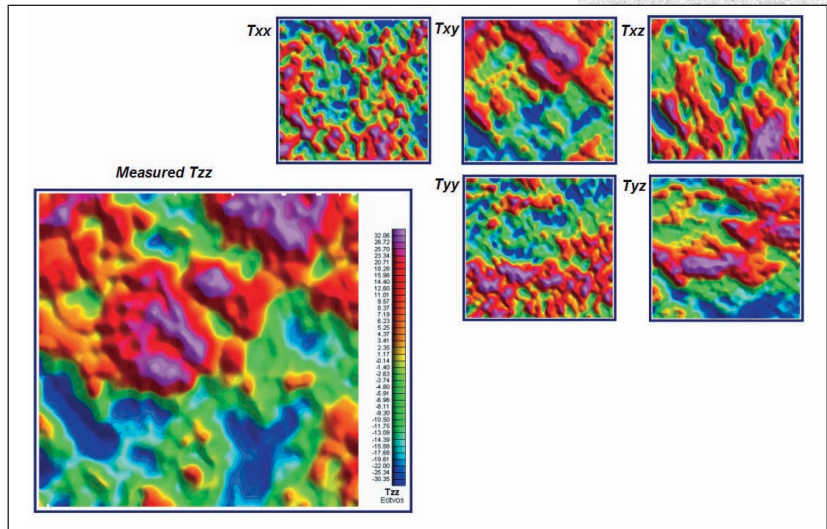


Fig. 4. (Below) The measured Air-FTG™ Tensor Component display. The five independent components, T_{xx} , T_{yy} , T_{xy} , T_{xz} and T_{yz} resolve the dominant structural trends. T_{zz} identifies a series of low density anomalies (blue) attributed to subsurface cavities.

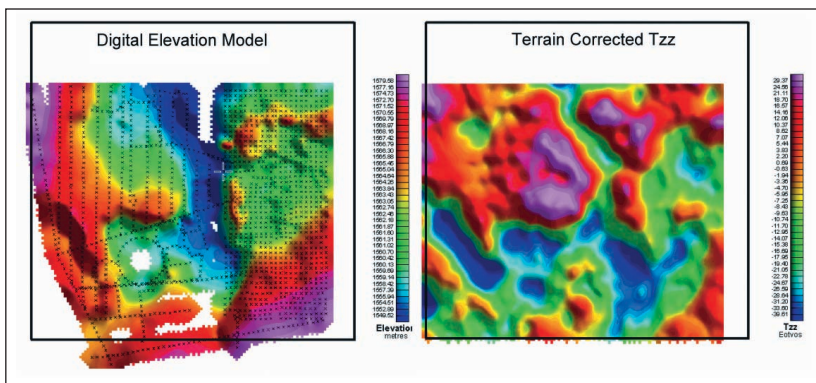


Fig. 5. Released elevation data (on left) and resultant Terrain Corrected T_{zz} for area of overlap between Air-FTG™ and elevation data. The Air-FTG™ survey boundary outlined in black, elevation measurement stations shown by black 'x's in elevation map.

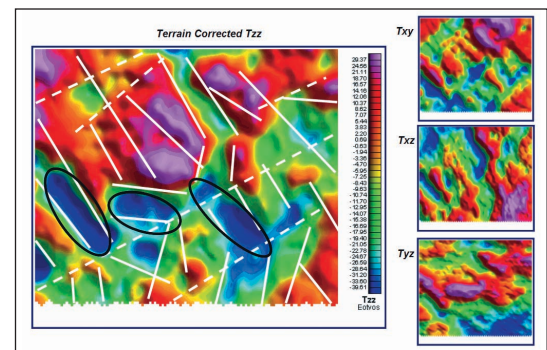


Fig. 6. Terrain corrected Air-FTG™ T_{zz} and horizontal component data, T_{xx} , T_{yz} and T_{xy} , for area of overlap with elevation data. Sub-surface solution cavities are identified in T_{zz} and appear offset via lineaments identified in the horizontal components. The cavities are outlined in black and interpreted lineaments in white.

Africa. Targets covered include a salt dome, base metals, precious metals, kimberlite and potential ground water storage. While results have been excellent, our clients have been using Air-FTG™ over active target areas and have not released many of these examples yet. One exception is a survey that was acquired for ground water storage identification.

Council for Geoscience, South Africa

The first Air-FTG™ survey outside the Americas was acquired for the South African Council for Geoscience in late 2002. The survey area is located west of Johannesburg over an area comprising Malmani Dolomite of the Chuniespoort Group, part of the Transvaal Sequence. Regional structure (Figure 3) shows a dominant NE-SW trend with NW and ENE oriented transfer faults. The dolomite sequences display a typical leached karstic environment with localised development of sinkholes and dolines. They are overlain by a manganese and iron rich soil that varies in thickness from a few centimetres to 30 m. The purpose of the survey was to determine the technology's suitability for locating and mapping sub-surface cavities for ground water storage, and the results indicate that it is indeed an excellent tool for this application.

550 line-km of data were acquired on a 6 x 6 km survey grid at a constant barometric height of 1745 m above mean sea level. In-lines are spaced 100 m with a N-S orientation; tie lines have 400 m line spacing and oriented E-W. The gradient data (Figure 4) exhibit a varying response from definitive density lows to more localised and trended highs. The horizontal components, T_{xz} , T_{yz} , and T_{xy} , identify a number of lineaments that follow the regional structure. They may also be indicative of fracture/joint development within the dolomitised limestone. Some of these lineaments partially display a positive response and are interpreted as a series of dykes.

Terrain Corrections confirm sub-surface cavity presence

Elevation data (Figure 5), partially overlapping the survey area, were released by the Council for Geoscience for our analysis of the data. Terrain corrections were therefore only applied to a subset of the data and a background density of 2.67 t/m³ was assumed. However, the wide spacing between stations in the western half of the survey area prohibits analysis of the high frequency lineaments observed in the free air Air-FTG™ response. Nevertheless, these are interpreted as geological events as they are oriented obliquely to the flight path. Therefore, the terrain correction procedure is rather incomplete. On the other hand, the terrain corrections do confirm the longer wavelength low density anomalies observed in the free-air data. We interpret these as sub-surface cavities. Their wavelength indicates a maximum depth of 150 – 200 m below the surface for these caverns.

Horizontal Components reveal structural control on distribution of cavities

The horizontal components, T_{xz} and T_{yz} , typically map the central axes of mass bodies. However, their maxima and minima also allow mapping of structural or lithological contacts. In this survey (Figure 4 and 6), they identify the regional structural trends in the area. Additionally, T_{xy} , allows mapping of the NW oriented structures in this survey. T_{yz} , to a lesser extent, maps WNW trending structures. This suggests that the dominant structural trend affecting the area is NW oriented. However, subtle ENE oriented offsets are observed in T_{xz} and T_{xy} .

Figure 6 shows the terrain corrected T_{xz} , T_{yz} , and T_{xy} . The interpreted structures are summarised on the Tzz plot (also Figure 6). It is clear from the interpretation that the sub-surface cavities are not 'stand-alone' features, but show continuity. The impact of these for ground water storage is significant due to potential leakage from one cavity to the other.

Conclusions

Air-FTG™ offers an exciting opportunity to the exploration and surveying industries. The technology records all components of the gravity field allowing for a more precise determination of the gravity field. Important information relating to geological setting (structural and / or lithological) and target shape and size are readily determined.

The Air-FTG™ data acquired for the Council for Geoscience demonstrate the added value the technology brings to subsurface mapping of solution cavities within a karstic environment. Detailed information on the location and shape of the cavities is resolved. Furthermore, the identification and mapping of the geological structure from the horizontal components, T_{xz} , T_{yz} , and T_{xy} , helps to understand the potential subsurface continuity of these caverns and their significance in terms of leakage to each other for ground water storage issues.

Acknowledgements

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