Airborne Full Tensor Gradiometery: A technology whose time has come

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Abstract:

Gravity Gradients are the first spatial derivative of the 3 Gravity vectors that describe the acceleration felt on a body at the earth's surface in the 3 orthogonal components of Cartesian space (North, East, Down or x,y and z). The gradients, or tensors, are defined by 2 subscripts Gij, where I and j are replaced by x,y or z. There are 9 possible gradients that can be described thusly, 5 of which are independent (Figure 1).

3D-Full Tensor Gradiometer ("3D-FTG") is the only instrument in the world that is capable of measuring all 5 of these tensors on a moving platform. The 3D-FTG has recently flown successful airborne surveys which allow it to service the mineral and onshore petroleum industry in addition to the existing offshore market.

The five (5) gradients can be used to determine subsurface anomaly location, edges and shapes of bodies as well as refining density models and overall geologic models.

Introduction

Gravity gradients have been measured for more than a century, but only 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 airplane turbulence and their long spatial resolution.

The recent introduction 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 by the US Navy for use aboard Trident Class nuclear submarines. This technology utilizes a set of three (3) rotating disks, each containing two (2) pairs of orthogonally mounted accelerometers. By taking the difference of the gravity sensed by each pair of accelerometers, the Air-FTG™ is able to compensate for most of the turbulence experienced by the airplane and retain the high frequency signal that is critical to prospect level geophysical surveying.

Air-FTG™ is acquired onboard a Cessna Grand Caravan 208B which has been modified to house the instrument, all support electronics, regular and differential global positioning systems, a magnetometer, and appropriate terrain measuring hardware. By positioning the FTG near to the center of pitch, roll and yaw, rotational accelerations can be held to a minimum. Any accelerations that remain are measured by dedicated accelerometers and removed during post mission compensation. This design allows Air-FTG™ to fly in much rougher conditions than a standard gravimeter 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. Since the Air-FTG™ is measuring the gradient directly, and it falls off with the cube of the distance:

$$G_{ij} \alpha 1/R^3$$

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, airplane climb performance, and cross tie matching so that the survey crew can obtain the best possible survey results. Altitudes can be flown as low as 80 meters and line spacing is usually in the range of 50 to 250 meters depending on the target.

Data is acquired and 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. 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.

Once the field crew has determined that the survey data is of the highest quality, that data is sent electronically to the processing center 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.

Once the entire survey is complete, overall analysis 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 (Selman, et al., 2001). This is the stage where individual tensors are calculated.

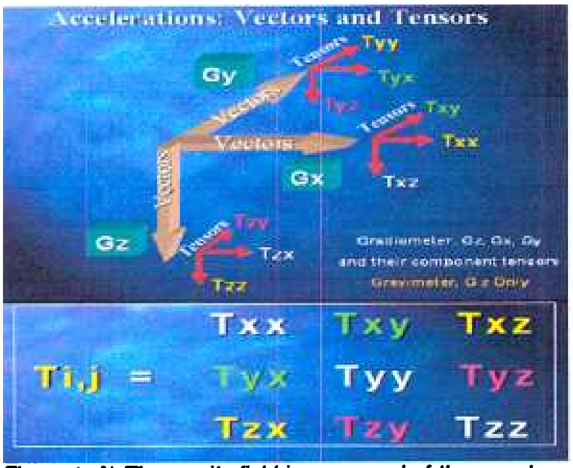


Figure 1: A) The gravity field is composed of three vectors, Gy, Gx and Gz. Each vector contains three gradients. B) Nine gradients are shown. Five represent independently measured gradients. Gradients that are measured but are redundant are shown in like colors. Tzz is not independent, as it is the negative sum of Txx and Tyy.

The final step involves more typical potential field processing methods such as filtering and line leveling. One technique that is unique to FTG data is harmonic fit in which the Laplacian nature of the independent tensors is used. Harmonic fit checks the signals to make sure that all of the tensors 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 5 independent tensors T_{xx}, T_{xy}, T_{xz}, T_{yy}, and T_{yz} as well as the vertical tensor T_{zz}. T_{zz} is not independent because $T_{xx}+T_{yy}+T_{zz}=0$ (Another Laplacian must) but it is presented because it puts the density anomalies in their appropriate spatial perspective.

Interpretation Methodology

Interpretation can range from simple target detection, to sophisticated model building. In many mineral cases, targets are being identified for further study with E-M, magnetics, surface geophysics or drill holes. In these cases the Tzz is a good first indicator of position but the other tensors can refine edge definition. Each tensor has its own directional "expertise" as is shown in this table:

Tensor	"Expertise"
T_{xx}	N-S Features
T_{xy}	Corners (NW, SE, etc.)
T_{xz}	Center of Mass (E-W)
T_{yy}	E-W Features
T_{yz}	Center of Mass (N-S)
T_{zz}	Proper shape information

If simple target detection is not enough, the next step is to use the 3D-FTG information for model building or more precisely to improve your geologic model. This can be done by using forward iterative modeling or with inversion.

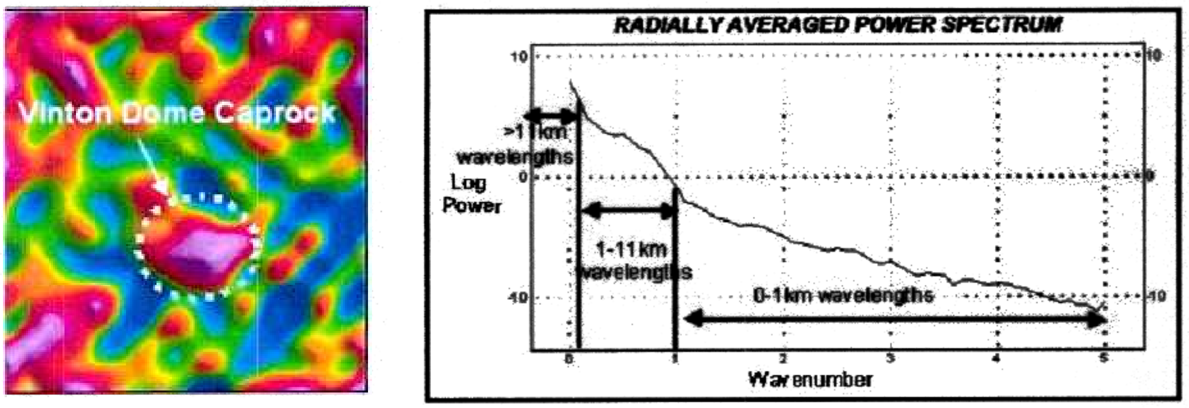
The first step in forward iterative modeling is to construct an initial model, which reflects as accurately as possible, the current interpretation of the subsurface. Top and base of target (ore body, salt, basalt, etc) and horizons are converted to xyz ASCII files and imported into the modeling program from the 3-D interpretation. A basement layer is created utilizing a regional depth to basement map and modifying it as required by the gravity long wavelengths. Constant depth layers are created and clipped to the top and/or base of target as needed. These depth layers are used to apply stacked laterally and vertically varying density grids building a density cube that surrounds the target bodies.

Lateral density data are derived from seismic velocities whenever seismic data is available. While density grids may be constructed without seismic data, it is a less accurate process. Since the apparent densities are calculated using a generalized form of the Gardner equation, only appropriate when dealing with relatively flat, unconsolidated sediments, deviations will cause false density halos around the target bodies. A statistical analysis of the density grid will reveal the abnormally high and low densities for the grid. Care must be taken not to edit out anomalous densities that are not related to the effect of the Gardner equation (Coburn et. al., 2002).

Density grids are typically created on 609 meter (2000 foot) intervals from surface down to 3048 meters (15000 feet) below surface. Density grids are extracted from 3048 meters (15000 feet) to as deep as possible which is typically around 12192 meters (40000 feet), at 1524 meter (5000 foot) intervals. Constant density layers are used for the deeper horizons.

Once the geologic model is constructed, the gradients calculated from the model are compared to the actual measured gradients. The resulting difference maps show residual anomalies; areas where mass needs to be increased or decreased within the geologic model. These errors may be corrected by modifying density grids, structure, or a combination of density and structure. If a well-imaged target is present in a portion of the model it can be used to calibrate the density grids. Since the thickness of target in that portion of the model is a known quantity, all of the anomalies at that location can be attributed to the density grids. The wavelength of the anomaly is used to determine which density grid is incorrect. Once the density grids have been adjusted, the difference (between the measured and the calculated gradients) will be close to zero in the area of the known target thickness. Spatial wavelength filtering techniques are routinely applied to extract causative signal from source targets. The method extracts the signal for specific wavelength intervals. A Tensor cube results that serves to separate the high from low frequency content (Fig. 2). Figure 3 shows a profile, or Frequency Section, extracted from the Tzz cube over Vinton Dome, LA.

Figure 2: Vinton Dome, LA airborne gradiometry data. Power spectrum points where the data can be broken up into its spatial frequency or wavelength. Long wavelengths indicate deep anomaly sources while short wavelengths indicate shallow anomaly sources.



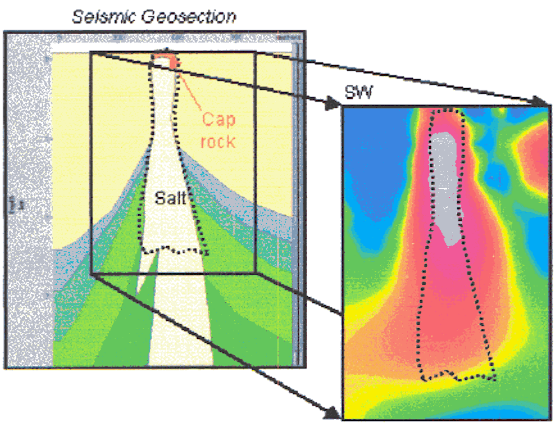


Figure 3: Profile extracted from 11 frequency slices and stacked generating a Frequency or Pseudo-depth Section. Note that the wavelength increases downwards. Negative anomalies are shown in blue while positive anomalies are shown in red. The pseudo-section compares favorably with the seismic generated profile

After the density grids are calibrated, it is reasonable to assume that the remaining errors displayed on the difference maps are the result of target bodies of indeterminate thickness. It is therefore necessary to modify the geologic model. In areas where the target is less dense than the surrounding sediment, the negative anomalies indicate areas where mass needs to be decreased, meaning that target thickness needs to be increased. The positive anomalies indicate where mass needs to be increased, meaning that target "volume" needs to be decreased (Coburn, 2002). These anomalies will be reversed in the case of a target body that is higher in density than the sediments surrounding it. The interpreter must take into consideration the depth of the target body and relate that to the size of the anomaly that needs to be corrected. Combining the information from all of the gradients helps to define whether the source of an anomaly is shallow or deep and its geometry. In many cases, a long wavelength anomaly dominates the gravity difference map. Since gravity is more sensitive to deep (greater than 9144 meters (30,000 feet)) sources, this long wavelength feature is often used to approximate the basement when no other data is available. By modifying the structure and density grids at various depths, the differences can be minimized to an acceptable limit (usually + / - 8 Eötvös for airborne FTG data).

In cases where seismic is available, this iterative manner should give a reasonable model which fits the constraints of both the seismic data and the FTG data. It is essential to go back and forth between the seismic data and the FTG data during the iterative phase of the modeling. The final modified density grids can then be converted into velocities and used in both the processing and interpretation of the seismic data.

Ground Gravity VS Airborne Gradient Data

A recent Air-FTG™ survey was acquired for The South African Council for Geoscience to look for subsurface caverns. A comparison of the Air-FTG™ data to conventional ground collected gravity data is shown in Figure 4. The airborne FTG data compares very favorably with the ground data. The airborne data (B) shows detail in areas the ground data (A) does not. This is due to the limitations in the collection of ground data due to terrain and morphological features. The Air-FTG™ data exhibit a varying response from definitive density lows to more localized and trended highs.

Elevation data partially overlapping the survey area, were released by the Council for Geoscience for analysis of the data. Terrain corrections were applied to a subset of the data and a background density of 2.67 g/cc was assumed. The terrain corrected Air-FTG™ Tzz response confirms the density lows imaged in the free air data and indicate these as sub-surface cavities (Blue "lows" in figure 4-A). Their wavelength indicates a maximum

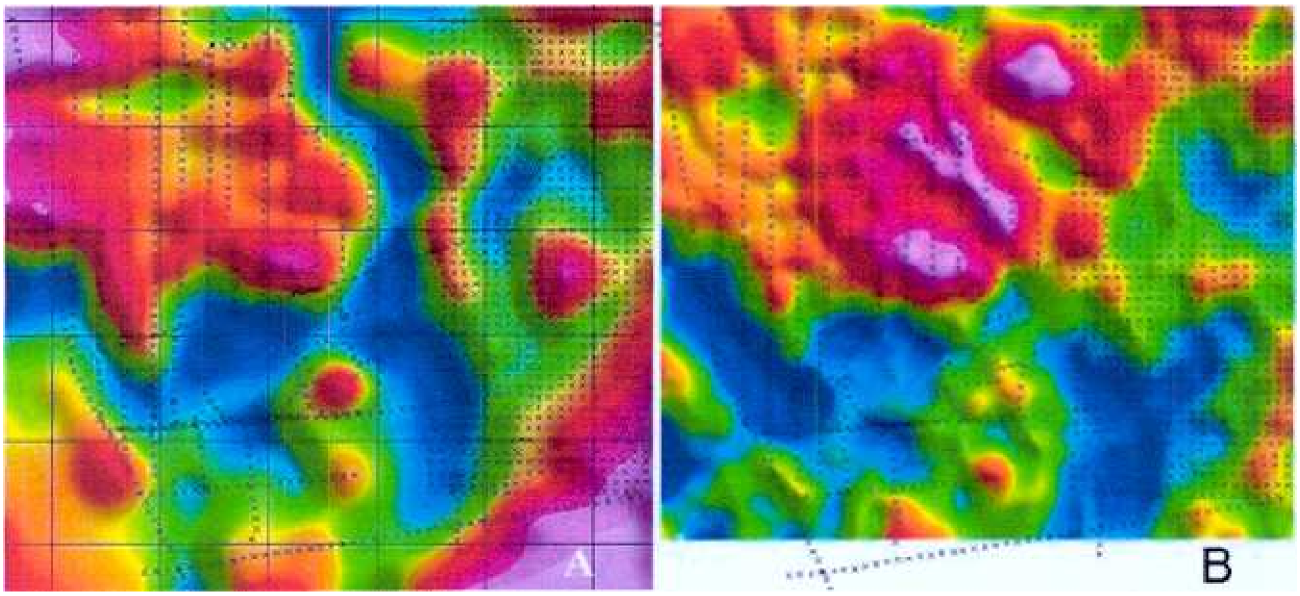


Figure 4: Ground Gravity, calculated vertical gradient (A) vs. Air-FTG measured vertical gradient (B). Note the improved character from Air-FTG where ground stations (marked by x) are missing or spread apart

pseudo depth of 150 - 200 m below the surface for these caverns.

Conclusions

Airborne Full Tensor Gravity Gradient (Air-FTG™) data compares very favorably with conventional land gravity data. Air-FTG™ data can fill in gaps in land gravity surveys and be incorporated into the overall analysis very quickly. Air-FTG™ data can be collected, especially in areas with terrain issues, much faster and more cost efficiently than conventional land gravity data. Air-FTG™ data, when properly processed and interpreted can Air-FTG™ interpretation can be done quickly for target identification and can also be done in detail to substantially improve the density/geologic model in areas where other technologies (seismic, E-M, magnetics) have trouble and it can do so on a prospect level. An improved geologic/density model can be used to identify targets for subsequent survey methods or it can be incorporated into both the seismic interpretation as well as the seismic processing workflow. Incorporating the density model derived from this process improves the interval velocity model. This type of density analysis can successfully define the target body even when it can not be resolved by seismic imaging alone.

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Acknowledgements

We would to thank The Council for Geosciences in South Africa, for allowing us to use and publish the Bouguer corrected ground gravity data included in this paper. We would like to thank Bell Geospace, Inc. for allowing us to use and present the Airborne Full Tensor Gradient Data used in this paper. We would like to thank Colm Murphy and Dean Selman for their help in the processing of the data and preparation of figures.