FINAL REPORT

Processing and Acquisition of Air-FTG® Data

Decorah, Iowa

for United States Geological Survey

BellGeospace

January 2013

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Introduction

Since 1999 Bell Geospace Inc. (BGI) has specialized in the acquisition, processing and interpretation of 3-D Full Tensor Gravity Gradiometry (FTG) data. For the majority of this time BGI was the sole provider of FTG data to the hydrocarbon exploration industry. Marine FTG data has been collected in the Gulf of Mexico, the North Sea , East Asia and offshore the Shetland and Faroe Islands.

In 2001 Bell Geospace successfully converted the FTG platform for use in an aircraft. Air-FTG® surveys have been completed in Africa, New Zealand, Australia, North America, South America, and Europe.

BGI flew a survey for the USGS in December 2012 and January 2013 over the town of Decorah in North East Iowa.

The main body of this report provides general information on Air-FTG® instrumentation, gradient data acquisition, processing and operational methods. Appendices 1 and 2 give a general overview of background information on tensors, and 3 and 4 give final product descriptions for FTG data.

Addendum A presents the results of the Decorah Air-FTG® Survey flown for the USGS.

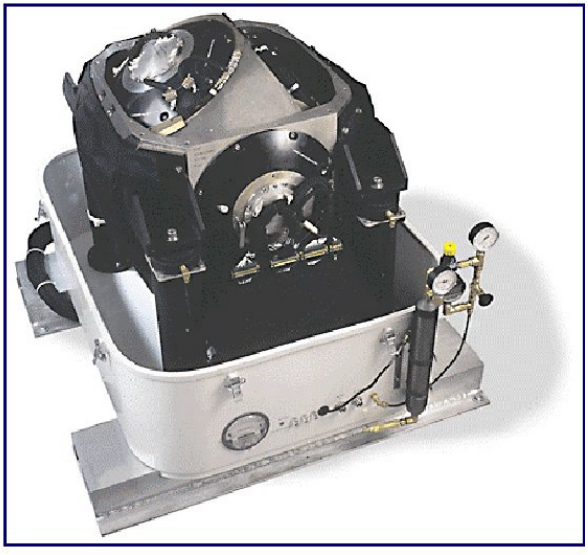


Figure 1. Bell Geospace's FTG-003. Support equipment not shown

Equipment Description

Full Tensor Gradiometer (FTG)

The Full Tensor Gradiometry (FTG) system is a high-precision, high-resolution, multiple accelerometer rotating platform that measures the gradient of the gravity field. The FTG system contains three Gravity Gradient Instruments (GGIs), each consisting of two opposing pairs of accelerometers arranged on a rotating disc.

The FTG system used by Bell Geospace (see Figure 1) is one of the few operational FTGs available for a moving vehicle. The gradiometer is installed in the aircraft along with all the required support equipment, including control electronics, computers, monitors, printers, air conditioning, and other peripheral devices needed to support FTG data acquisition.

The FTG is contained in an airtight case while in operation. The case is approximately 1 cubic meter and weighs 227 kg with the GGIs installed. The electronics cabinet is approximately the same size and weighs 160 kg. The case provides a temperature, pressure, and humidity controlled environment for the FTG during data acquisition.

Magnetometer
(When present)

MODEL G-822A CESIUM MAGNETOMETER SENSOR SPECIFICATIONS

OPERATING PRINCIPLE: Self-oscillating split-beam Cesium Vapor (non-radioactive)

OPERATING RANGE: 20,000 to 100,000 nT

OPERATING ZONES: The earth's field vector should be at an angle greater than 6° from the sensor's equator and greater than 6° away from the sensor's long axis.

Automatic hemisphere switching.

SENSITIVITY: <0.0005 nT/%Hz rms. Typically 0.003 nT P-P at a 0.1 second sample rate using 822A Supercounter, 0.02nT P-P for CM-221

HEADING ERROR: ±0.15 nT (over entire 360° polar and equatorial spin)

ABSOLUTE ACCURACY: <3 nT throughout range

OUTPUT: Cycle of Larmor frequency = 3.498572 Hz/nT,

2V P-P coupled through the sensor power input

MECHANICAL:

Sensor: 2.375" (60.32 mm) dia., 5.75" (146 mm) long, 12 oz (339 g) - any orientation in 7" dia. stinger

Sensor Electronics: 2.5" (63.5 mm) dia., 11" (279.4 mm) long, 22 oz (623 g)

Cables:

Sensor to electronics: Standard 162 in. (13 ft 6 inch or4.1 m). Other lengths available from 2.4ft (0.75m) at 40 inch (1m) increments with connector on electronics end. Note: Cable lengths are approximate due to cable dielectric variations

Sensor Electronics to Counter: Standard 10m, up to 165 ft (50 m) (Coax with signal superimposed on power, requires decoupler board or box.)

OPERATING TEMPERATURE: -30°F to +122°F (-35°C to +50°C)

STORAGE TEMPERATURE: -48°F to +158°F (-45°C to +70°C)

ALTITUDE: Up to 30,000 ft (9,000 m)

WEATHERPROOF: O-Ring sealed for operation in rain or 100% humidity

POWER: 24 to 32 VDC, 1 amp at turn-on and 0.5 amp thereafter

Acessories

Signal/Power Decoupler, board or multichannel

box:

Separates the Larmor signal from the power (28 V) to enable

connection to RMS Instruments' AADCII A utomatic Aeromagnetic

Compensator or Customer supplied counter

Internal Decoupler: P/N 27504 - up to two sensor installation

External Decoupler: P/N 27560 - three and four sensor installation

Internal CM-221 Counter See G-823 A Data Sheet

Stinger, Wingtip, Bird Contact Factory for complete system integration information

Base Station Accessories Non-magnetic Tripod, clamps cables

Base Magnetometer (When present)

Manufacturer	Geometrics
Type	Proton precession
Model	G-856AX
Dynamic Range (nT)	20,000 – 90,000
Accuracy (nT)	± 0.5
Precision (nT)	0.1
Resolution (nT)	0.1
Sampling Rate per second	1.5

Airborne Gradient Data Acquisition

Gradiometer data is initially acquired in an internal coordinate system that is referenced to the axes of the three GGIs which are the primary measurement components of the FTG. This data is later transformed into a "left handed-down" coordinate system with x and y in the plane of the earth's surface and z perpendicular to that plane downward towards the Earth.

Prior to acquisition, a self-calibration procedure is performed with the aircraft on the ground. This creates a table of calibration factors that will be used during data processing to remove the gradient effects of the variations in pitch, roll, and yaw experienced by the aircraft in flight. Data is acquired continuously throughout the flight, usually at ground speeds of around 215 km/hr. The system generates approximately 400 megabytes of data per hour including the navigation data and data on the plane's accelerations. The data is stored on a computer hard drive and backed up to AIT tape cartridges. Two sets of backup tapes are made which are sent to Bell Geospace's processing office in separate shipments. One set is used for final processing and engineering analysis while the other is stored offsite as backup.

Operations

The gradiometry data was collected with FTG-001 onboard a Basler Turbo owned by BGI (Figure 2). The FTG is installed in the main cabin as near as possible to the center of pitch, roll and yaw of the plane. Both GPS and DGPS systems are used for positioning with latitude and longitude coordinates acquired on the WGS-84 ellipsoid. During processing the data is locally projected in x and y in the appropriate Universal Transverse Mercator (UTM) zone.

A radar altimeter system is deployed to measure the distance between the airplane and the ground. Along with the plane's altitude acquired via GPS, radar altimetry data can be used to produce a digital elevation model (DEM) which may be useful in terrain corrections.

Global Positioning System (GPS)

The Global Positioning System consists of a constellation of 24 active satellites orbiting the earth. Each satellite has a period of approximately 12 hours and an altitude of approximately 20,000 km. Each satellite contains a very accurate cesium

Figure 2. Bell Geospace's BT-67, #C-FTGX

clock that is synchronized to a common clock by the ground control stations usually operated by the Military.

Each satellite transmits individually coded radio signals that are received by the user's GPS receiver. Along with timing information, each satellite transmits ephemeredes (astronomical almanac or table) information that enables the receiver to compute the satellite's precise spatial position. The receiver decodes the timing signals from the satellites in view (4 satellites or more for a 3-dimensional fix) and, knowing their respective locations from the ephemeredes information, the GPS system computes a latitude, longitude, and altitude for the user.

A Novatel Propak LB airborne differential GPS Systems (dual-frequency) was used on the aircraft. It provides an accuracy of ±5 meters and positions were real-time differentially corrected with the Omni-Star system. The GPS systems were used in conjunction with a PNAV-2001 Navigation System. The main features of this system are:

- Real-time graphical and numerical display of flight path with survey-area and grid-line overlay
- Distance-from-line and distance-to-go indicators
- Operation in survey-grid or waypoint navigation mode
- Recording of raw range-data for all satellites from both the aircraft-borne and base-station GPS receivers, for post-flight refinement of GPS position

Quality Assurance

Quality Control Program

Accelerations measured by the instrument during data acquisition are closely monitored along with many other indicators of instrument performance. On the main FTG screen, the operators visually inspect the inline sums and cross gradients, position and temperature of the gyros, GGI case and block temperatures and the north, east, and vertical accelerations being measured. Any variances beyond the norm are closely watched and if an error is detected the acquisition is interrupted and appropriate action is taken. Duplicate sets of spares are available in case of suspected hardware failure. Many other factors are also monitored that will help alert the operator to any unusual performance of the FTG. These include strip charts, coefficient tables and onsite offline analysis of the data. In addition to the onboard QC checks, final survey data is sent to a Bell Geospace processing office electronically for preliminary processing. Any substandard data will be identified by cross tie analysis and other methods. As soon as the source of the data degradation is identified and corrected, substandard lines are re-acquired and again transmitted into the office for approval before the vessel leaves the survey area.

Field Quality Control

The first stage of QC is in the field. It is important that we catch instrument problems as soon as we can so they can be addressed and survey time is not wasted. Our crews are highly trained and have many years of experience (average 7 years) with FTG Acquisition. Much of the software used in the field is proprietary and comes from Lockheed Martin, the equipment manufacturer. This software allows our crews to monitor key parameters that are crucial to the correct operation of the FTG and in many cases provides flags

or pop ups when components are not operating up to spec. Besides monitoring physical characteristics such as temperature, humidity and power draws, the operator watches instrument position, rotation rates and other parameters that could indicate data problems. Individual GGI signals are watched on the scope for tell tale signs.

Once the crew returns to base, they run a first pass processing run and from that they get a set of tensor components that can be plotted and evaluated. They can look for navigation errors and poor signal quality which will indicate a need for reflights. At this point they also send the data to the office where it is further evaluated.

Office Quality Control

Preliminary

The first step is to have another set of eyes perform the same steps that are described in the field QC section. Once we run the processing steps the data is plotted on a map. At this point we review the data, specifically looking at the following indicators:

Quantitative Quality Control

Noise content cannot be measured directly so we have developed several methods over the 15 years that we have been acquiring FTG data which allow us to estimate the noise. Our first indication that we may have noise comes from monitoring the vertical acceleration or Vacc. We monitor accelerations from stand alone accelerometers that are in the system but are not used to measure the gradient. These give us indication of the induced (non-gravity related) accelerations that the system is being exposed to which may add noise to the signal.

The next thing we do is apply a numerical analysis using 3 criteria.

Energy in inline sum (EILS) – By definition the in line energy of the data should sum to zero since it is a Laplacian Tensor. While this is what we would see from perfect accelerometers, it is never really achievable. We have determined limits of EILS that indicate that there is too much noise. This is evaluated in step 1 and compared to a threshold to get a pass/fail rating. Note that this evaluates noise along the entire line.

Local Inline Sum – After field processing we can look for energy bursts along the line that are indicative of high frequency noise. Again this gives us a pass/fail indication.

Line to Line QC – During processing the lines are compared to their neighbors. Since 3D-FTG is a truly 3 dimensional measurement, it is being affected by density variations in all directions. Therefore, signals on one line will be evident (perhaps larger or smaller) on neighboring lines. By gridding neighboring lines and comparing we can get an indication of noise. Bell Geospace has a patented system that does this automatically and provides a numerical analysis of the results which we compare to a determined threshold.

These 3 analyses give us a very good indication of where we should focus our qualitative evaluation effort. If we pass 2 or more of these tests we have a high confidence in the data. If, however, the line only passes one or none of these tests, this can be an indication that the noise is unacceptable and the line will be reacquired.

Qualitative Quality Control

While we look at all lines, we pay special attention to those ranked high for noise content in the quantitative phase. At this point our data processing experts evaluate the data using commercial packages such as Geosoft to look at every line that has been acquired for indications of noise. Other geophysical methods such as cross tie analysis are used here and data that still

appears too noisy to their experienced eyes are flagged for re-acquisition.

Once new lines are acquired the process is repeated until all lines pass the QC and are included in the final database.

Quality Assurance & Quality Control Organization for Bell Geospace Crew

Bell Geospace has an organization of experts that have been acquiring, QC'ing, processing and interpreting Full Tensor Gravity Gradiometry data in the geophysical environment for more than 12 years, the longest of any other company in the industry. The first line of quality comes from our field organization, which averages 7 years with Bell Geospace. Many of our supervisors have more than 10 years with Bell Geospace doing Full Tensor Gravity Gradiometry and 20 to 30 years of experience in various methods of geophysical data acquisition.

Bell's field crew consists of one Operations Supervisor and one Operator. The Operations Supervisor has full authority for all decisions in the field (not withstanding safety which is under the authority of the Pilot) including quality of our data and when to stop surveying due to quality or other survey issues or concerns. The Field QC which is described in another section of this proposal is overseen by the Operations Supervisor who is in 24 hour contact via mobile phone or sat phone with all of the experts in the organization for assistance as needed

An overview of this process is shown in the chart on page 10.

FTG Data Processing

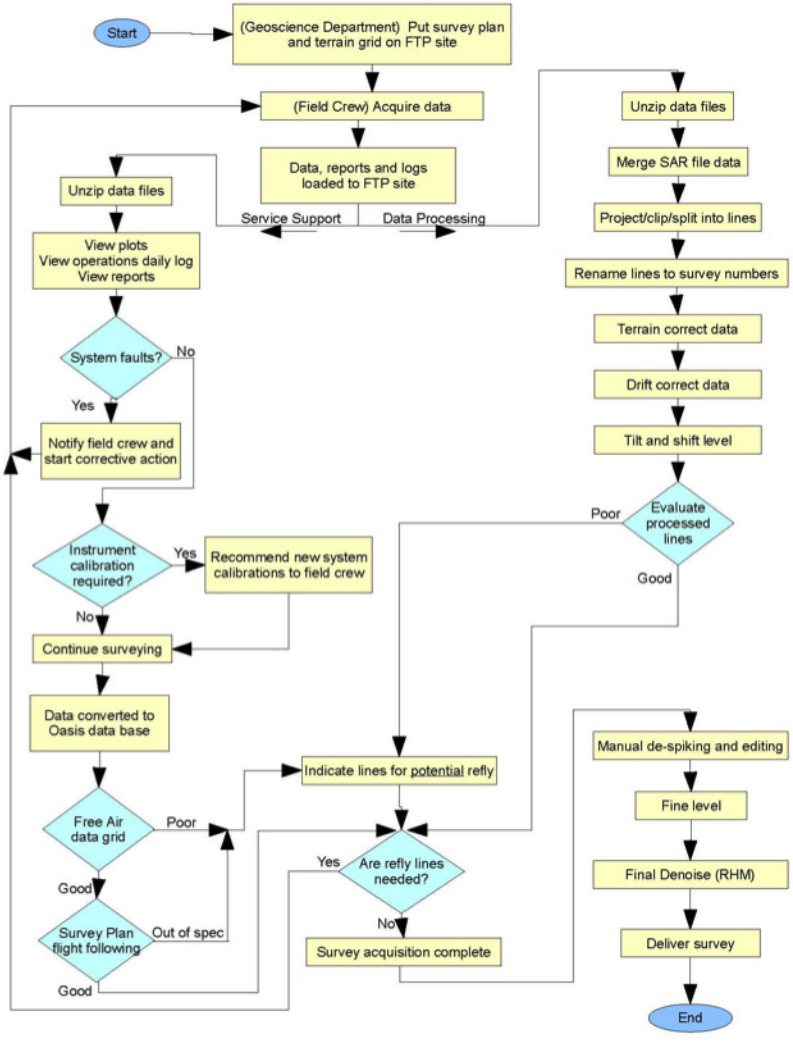
The acquired FTG survey undergoes a series of processing steps to obtain the final measured gravity gradient data used for interpretation. Specific processing methods may vary slightly depending upon survey layout, weather conditions, and other factors affecting the data. A generalized FTG data processing schematic is provided in Appendix 1.

High Rate Post Mission Compensation

Raw data recorded by the instrument consists of two signals from each of three Gravity Gradient Instruments (GGI). These are referred to as the Cross and Inline signals. The three sets of signal data are run through proprietary software, High-Rate Post Mission Compensation, or HRPMC. This step operates on the most highly sampled data, using the gyro outputs at 1024 hertz and GGI outputs at 128 hertz. HRPMC compensates the data for most of the physical conditions that affect the data during signal acquisition. This includes corrections for the gradients of the aircraft and the gradients of the instrument itself. Files monitoring GGI platform status are logged in real time and used to create tables of coefficients that are subsequently used in processing. A series of complex algorithms within the program use these files to generate coefficients for each 2 hour segment of acquisition. These coefficients are necessary to calculate corrections for aircraft motion and position relative to the instrument during the survey. Another set of corrections are made to remove gradients due to the centripetal accelerations that result from the rotation of each of the three GGIs.

Upon completion of HRPMC, the data are subject to another step referred to as SAR, which strips out the necessary elements, averages the values and reformats it into a 24-column binary file. The averaging process in SAR allows the processor to

BGI Quality Assurance and Processing



choose the data sample rate for all subsequent processing and final data. The final sample rate is currently limited to 1 second or greater. The SAR files are comprised of daily blocks of data and are combined to create one file containing all the data for the entire survey. Since FTG data is recorded continuously, this file also contains data recorded during traverses, turns, and on lines that were later re-acquired for various reasons. The data recorded in these instances are removed from the data file before final processing. It is during the SAR procedure that navigation and aircraft attitude data are merged with the gradient data. Gravity is also merged in at this point if a gravimeter is installed.

Terrain Correction Method

The terrain corrections are computed with a 3-D prism based modelling package. The program uses grids and prisms to compute the gravity effect of each defined layer. The computation assumes a density of 1.0 gm/cc and calculates the gravity tensor response of a model that represents the mass of the Earth between the terrain surface and the ellipsoid.

The correction can be scaled and applied for any density using the formula:

Tzz_TC_d_FLM = Tzz_FA_FLM – TC_Tzz_100*d where d represents the desired density

Tzz_TC_d_FLM is the terrain corrected de-noised Tzz component at a density of d gm/cc

Tzz_FA_FLM is the de-noised, levelled Free Air Tzz component

TC_Tzz_100_FLM is the de-noised terrain correction for Tzz at a density of 1.00 gm/cc

Equivalent equations hold for the other components. "FLM" indicates that de-noising through Fourier Layer Modeling was performed. (see page 13)

In most cases the terrain corrections must also undergo FLM with the same parameters as the tensor data. This is because FLM computes the data on a smoothed altitude surface and this surface must be common to both datasets to properly match the frequencies from the terrain that are present in the FTG data.

FTG-Specific Line Corrections

The next process is another proprietary method referred to as FTG-Specific Line Correction. This step calculates the tensor components from the measured inline and cross signals and removes bulk low frequency errors through time based line levelling and correlated GGI output. This process assumes that there is no correlation between the error we want to remove and the signal that we want to keep.

The DGPS provides highly accurate aircraft position, heading, and speed measurements. The exact position of each GGI relative to the umbrella frame is provided from the servomotors that induce the rotations, and from the gyros on the stabilized platform. From this information the measured accelerations in the inline and cross signals from each GGI can be converted to directional gradients and provides the tensor elements Txx, Txy, Txz, Tyy, Tyz and Tzz. In this survey the carousel was not rotating so only the rotation of the GGI's must be compensated for. The carousel rotation rate is normally 360 degrees per hour, so on lines that are only a few minutes long a complete rotation would not occur while online and so would not assist in noise compensation. Feed back from the gyros and GPS data allows the servomotors to keep each GGI in the same horizontal and vertical

orientation relative to the ground throughout the survey.

The FTG data record is synchronized and time stamped with the GMT time at one second intervals. The differentially corrected GPS data is also GMT time stamped. Based on a match in GMT time, the umbrella frame coordinates in the FTG data are replaced with real world coordinates in the WGS-84 ellipsoid. Coordinates in other ellipsoids, local datum's and various projection methods can be produced later in the processing as requested by the client.

The GGI drift poses a special problem because it is not linear, so traditional line levelling techniques are inadequate to correct for this error, and, since GGI drift is time dependent, levelling must occur in the time domain. Because of the nature of gradient data and the Laplace equation (Txx +Tyy +Tzz = 0), complicated levelling procedures must be used to keep all components levelled both to themselves and to each of the other components so that this relationship is not disrupted during correction. This process is generally executed as follows:

First, the data on the turns and traverses outside the survey area are deleted. Secondly, time-varying heading and roll corrections are applied. Using the position and attitude of the aircraft relative to the carousel, line groups with the same heading and carousel angle are used to compute corrections that are linear over small sections of lines.

After this procedure, the data is free of most DC shift and most of the low frequency error and can be mapped with a very little line error evident.

Final Line Levelling

After the data is FTG levelled and bulk corrected, some small misties at intersections still remain due to random noise content and subtle non-linear errors. At this point a more traditional approach to line levelling can be taken to produce final data suitable for mapping. To best evaluate the remaining misties and noise, a Butterworth filter usually between 0.5 and 1 kilometer in length is applied and misties are calculated at every line intersection. The misties in the filtered data are analyzed on a line-by-line basis. Each GGI component is shown in profile form with intersection mistie information from crossing lines displayed as well. In most cases the largest misties are due to a random noise spike near an intersection or from remnant effects from turning on to or off of a line. Usually spikes occur over very few data points but still may affect the filtered trace enough to indicate a mistie. The erroneous unfiltered data is either interpolated across or manually edited for a better fit with the intersecting lines. After each GGI component has been edited by this method on every line, the filter is reapplied and misties are calculated and analyzed again. This procedure is repeated until virtually all errors are removed. After a thorough edit, the data can be levelled by the application of low order polynomials or tensioned spline adjustments.

The corrections calculated from the filtered trace are also applied to the unfiltered data. This process is completed in several passes, each time re-calculating misties, and applying a successively higher order fit to the data until the misties are very near zero, and well within the noise envelope.

After each polynomial adjustment, the data are gridded and mapped to monitor the effectiveness of the adjustments. Intersections that cannot be tied with the polynomial fit are re-examined in profile and map form to determine which line best fits the shape of the surrounding data and is then manually adjusted as necessary. This procedure finally produces mistie adjusted, unfiltered data. The unfiltered data can then be mapped without

any apparent line oriented error. Tensors are computed from the levelled GGI signals and gridded and examined for remnant errors. Often another pass through the GGI signals is needed to produce the best tensor data possible.

Although this dataset produces quite reasonable maps, additional improvements can sometimes be achieved through Micro-levelling. This is a process in which tie lines are excluded, and the correlation between parallel lines is analyzed. The user can specify various filter lengths, tolerances, and other parameters to fine-tune the process to better address the characteristics of the non-correlated frequencies. This process attempts to remove or reduce various frequencies in each line that are not present in neighboring lines. This includes high frequency noise and lower frequency errors between intersections that cannot be removed in the tie line based adjustments. This technique is less effective where line spacing varies or is too great. Generally, lines more than 500 meters apart show only marginal improvement, primarily in the lowest frequencies. All filtering, levelling and mapping is done in Geosoft's Oasis Montaj data analysis package.

In surveys where no tie lines are flown, BGI has developed proprietary methods of line adjustment.

Computed Gravity - Tz

The gravity field can be calculated from the gradient tensor by means of integration. This can readily be done by one of two methods: along-line integration or Fourier-domain vertical integration. The output of any integration process lacks an unknown constant of integration, therefore, the absolute value of the gravity field can not be calculated from the gradient tensor. This is remedied by mixing the calculated gravity with gravimeter measurements. If gravimeter data is available over a wide area this mixing is best achieved using a pair of complementary filters: a low pass filter is applied to the gravimeter output and a high pass filter applied to the gradiometer output. The two filtered signals are then added to yield computed enhanced Tze in which the low frequency values are tied to the gravimeter readings and the high frequency information originates from the gradiometer.

When suitable gravity data is not available, vertical integration of the Tzz component will approximate the gravity signal. However, some of the regional frequencies may not be present.

Fourier Layer Modeling (FLM)

The nature of the 3-D Full Tensor Gradiometer allows for some distinct advantages in noise reduction over other systems. The FTG records five independent measurements of the geology from different perspectives. These measurements are related by the fact that they are recording data from the same geological source. If a signal in one tensor is not supported in the other tensors, that signal is removed from the data. This process produces a greatly improved dataset with a much better signal to noise ratio. The final tensor products contain very little erroneous noise and allows for high confidence in the mapped anomalies throughout the frequency range.

One of the primary control parameters within FLM is the wave length cut-off frequency. This is the minimum wave length that FLM will attempt to correlate between the tensors. In general this is set to the minimum line spacing in the survey. However, in some cases multiple FLM runs may be performed with various cut off frequencies. When this is the case, the results of each run will be indicated by adding the cut off frequency used in meters to the FLM suffix in the channel name. For example, data processed with a 250 meter cut off frequency will retain the suffix "FLM250",

and data run with a 500 meter cut off frequency will be indicated as "FLM500". This holds true for subsequent products such as maps, grids and other derivative processes.

Magnetic Data Processing

Magnetic data acquired with the cesium vapor sensor is typically of very high quality and requires only a few processing steps to produce final data. The majority of erroneous data is removed by the compensation process that corrects the data for the effects of the aircraft as heading and position changes relative to the magnetic field. A base magnetometer was not used to record and remove the daily variations in the magnetic field due to regional factors. A lag correction is also applied to correct for the distance between the mag sensor and the GPS antennae. The lag correction is computed based on speed and distance to accurately shift the mag data to the GPS reference point and ensure that lines flown in opposite directions are not biased by the distance between the sensor and antennae. The Earth's Field is calculated and removed, although it is typically a gentle slope and provides a very linear correction. At this point only minor line adjustments are required to remove any remnant errors that are apparent at line intersections. The data is then ready for Reduction to the Magnetic Pole or Equator to approximate the anomaly directly over the causative body. Various derivative calculations to accentuate the anomalies can also be provided.

Comments

Bell Geospace continuously fine-tunes the acquisition and processing parameters for Air-FTG® data. The process described here produces valuable and dependable data that is suitable for the intended purposes. As we progress it is important to note that many procedures described herein continue to improve as we continue to learn more about the performance of the instrument in dynamic airborne environments. Air-FTG® data can consistently detect shallow bodies spanning 300 meters or less, with amplitudes repeatedly and accurately measured at less than 7 Eötvös. Third party analyses have recently put resolution at 4.7 to 7 Eötvös. As we further refine processing and acquisition methods, even higher resolution can be expected.

Final Maps and Digital Data

The final step in the data processing is the application of gridding and contouring to the flight line data. Typically a minimum curvature grid with an increment of 1/3 to 1/2 the closest line spacing is used. Air-FTG® gradient component maps may be contoured at an appropriate interval and displayed using a color filled shaded relief grid. Measured free air and terrain corrected maps for each of the six-tensor components are provided. Computed gravity, the result of the vertical integration of the measured free air Tzz component, can be produced and made available for comparison and reference purposes. Maps are provided in digital form with several formats available. Typically Geosoft Oasis packed maps are provided.

The final digital flight line data are generally provided on CD-ROM in a Geosoft Oasis database and also in Geosoft grid format. Other export formats are available. Measured free air and terrain corrected tensor components are included along with the terrain corrections at 1.00 gm/cc to facilitate re-computation at various densities.

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Appendix 1: Background Information on Tensors

Gradiometer data differs in many aspects from conventional high-resolution gravity data. One important difference is in bandwidth which is 500m or less for gradient data versus approximately 3,000m for conventional gravity. The greatly increased bandwidth allows the retention of the short wavelength signal generated by shallow to intermediate geologic features which are not retained in gravity data. The increased sensitivity allows for much greater resolution and is the reason gradiometer data can be successfully incorporated into the subsequent interpretation at a prospect level.

Just as the gradient of a scalar field such as gravitational potential is a 3 x 1 matrix of numbers commonly called a vector, the gradient of a vector field is a 3 x 3 matrix of numbers commonly called a tensor. Each element of the tensor is the rate of change of one of the components of the vector in one of the coordinate directions. Thus, when T is a scalar field,

$$\text{grad } T = [\, \partial T/\partial x \;\; \partial T/\partial y \;\; \partial T/\partial z \,] \text{ or } [Tx \; Ty \; Tz]$$

$$\text{Then, grad(grad } T) = \begin{bmatrix} Txx & Tyx & Tzx \\ Txy & Tyy & Tzy \\ Txz & Tyz & Tzz \end{bmatrix}$$

In the expressions above, Tx, Ty, and Tz represent the familiar acceleration of gravity in the three coordinate directions. Txx, Tyx, ... represent the rate of change of each component of gravity as one's position changes in the three coordinate directions.

For a potential field, the sum of the diagonal components is zero, i.e., Txx+Tyy+Tzz = 0. This is the definition of a potential field and is the famous Laplace's Equation. Perhaps as importantly, one can show that the matrix is symmetrical about this diagonal, so Tyx = Txy, Tyz = Tzy, and Txz = Tzx.

As a consequence of these two facts, only five components of the gradient tensor are independent. For example, if one knows Txx, Tyy, Txz, Txz, and Tyz, the remaining four components are uniquely determined by the relationships given above. (Figure 1.1)

Each of the gravity gradient tensor components responds uniquely to the size, shape and thickness of density anomalies, providing extensive constraint during the interpretation process. All 5 independent tensors are used in the interpretation process to determine the center of mass (Txz and Tyz), edges (Tyy and Txx) and corners (Txy) of the anomaly. The expression of Tzz (the vertical component) more closely resembles the conventional gravity in that the anomaly is shown in the correct position spatially, over center of geologic mass, and is thus more easily related to sub-surface geology.

For more information, please see Potential Theory in Gravity & Magnetic Applications by Richard J. Blakely (Cambridge University Press, 1996).

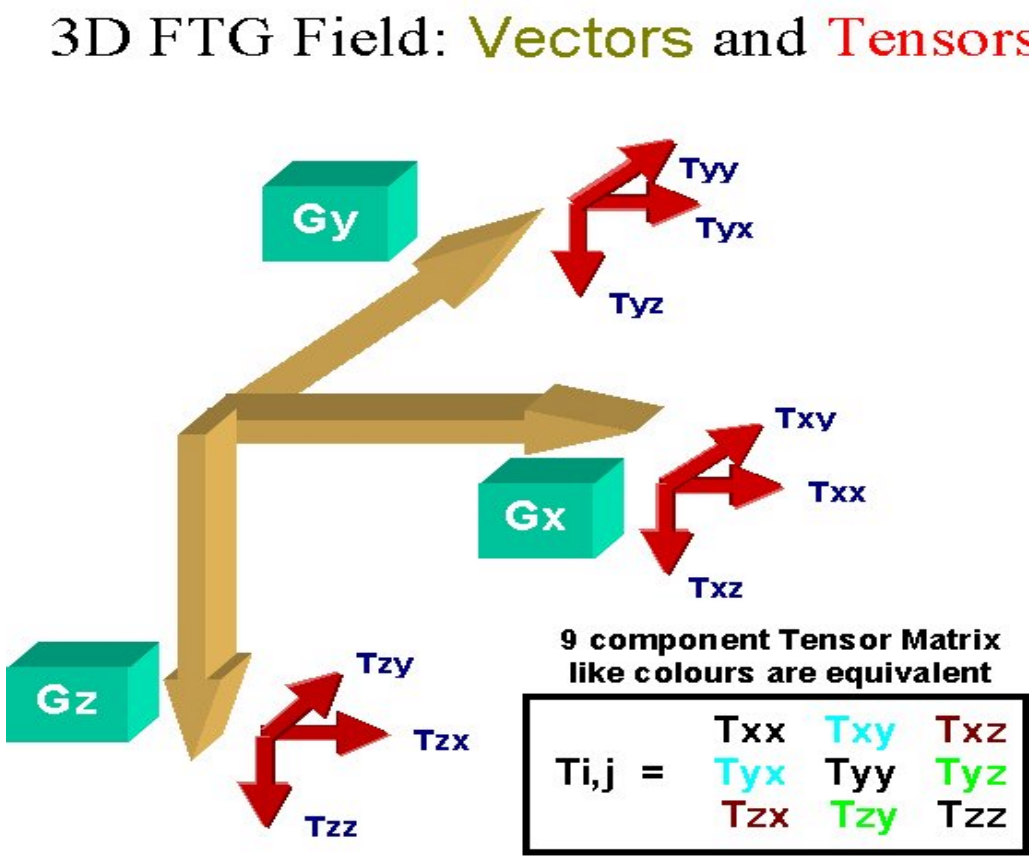


Figure 1.1: Vector and Tensor Relationships

Appendix 2: FTG Data Processing

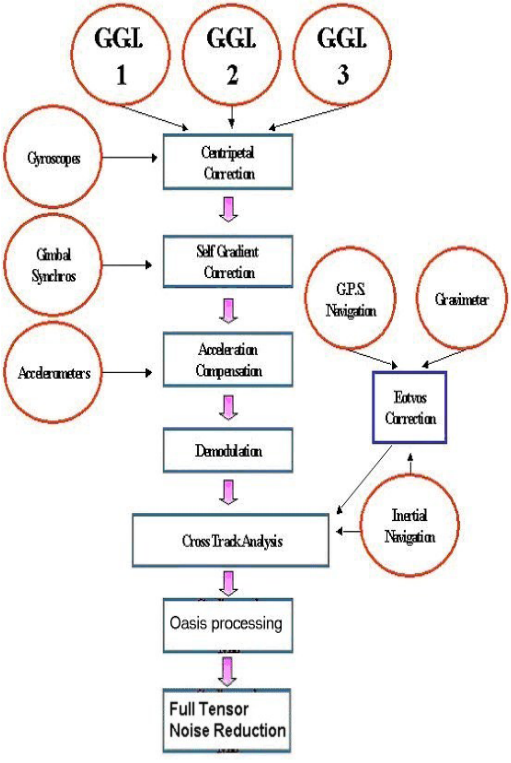


Figure 2.1: A Schematic diagram showing different stages of FTG Data Processing

The box "Oasis processing" consists of several steps that may be summarized as

- Editing of erroneous spikes and data with a poor signal to noise ratio
- Line levelling, Micro levelling in some cases
- Reduction to the Pole for Magnetics, Filtering and all other derivative and residual products
- Gridding and map production
- Application of terrain corrections
- Production of Deliverables

Appendix 3. Contents of the Distribution CD or FTP File Contents

The deliverable products reside in separate directories on the CD. The digital flightline data is provided in a Geosoft Oasis database and/or other formats (if requested) at a one second sample rate. Each database channel is described in Appendix 4, and the maps are named for the channels they originate from. Below are examples of typical filenames:

Description	File Name
Flight Line Tensor Data	Survey_Name_Air-FTG.gdb
Flight Lines Map	Flight_Lines.map
Terrain Map	Topography.map
Free Air Tzz Map	Tzz_fa_FLM.map
Terrain Corrected Tzz	Tzz_TC_220_FLM.map

(Files related to the remaining tensors follow the same naming convention.)

Notes: All final FTG data were de-noised with the Fourier Layer Model process. The FLM wavelength cut off frequency used will be indicated by the FLM suffix if a cutoff frequency other than the line spacing is used. Small surveys may not be suitable for FLM. In this survey the cut off frequency was 400 meters.

Appendix 4: Oasis Database Channel Descriptions

The final digital Air-FTG® flight line data is provided in a Geosoft Oasis Montage database at a one second sample rate.

Following is a list of channel names and a short description of the channel contents. If not all channel names are listed, the contents of those not listed here can be inferred from the examples given.

FTG Database contents

Channel Name	Description
Line	Flight Line Number
Fiducial	Fiducial Number
YYMMDD	Date of acquisition
HHMMSS	Time of acquisition
Lat	Latitude in WGS84
Lon	Longitude in WGS84
X	Easting in Meters, WGS84, UTM Zone 15 North
Y	Northing in Meters, WGS84, UTM Zone 15 North
Altitude	GPS Altitude referenced to WGS84
RA_Clr	Radar Altimeter Clearance
LA_Clr	Laser Altimeter Clearance
Terrain_SRTM	SRTM Terrain Model sampled from grid
Tzz_FA	Raw Free Air Tzz
Tzz_fa_lev	Free Air Tzz, Leveled
Tzz_fa_FLM	Free Air Tzz, Leveled, de-noised
Tzz_TC_267_lev	Terrain Corrected Leveled Tzz, Density 2.67 gm/cc
Tzz_TC_267_FL	Terrain Corrected Tzz, Density 2.67 gm/cc, de-noised
TC_Tzz_100	Terrain Correction for Tzz at Density 1.00 gm/cc
TC_Tzz_100_FLM	Terrain Correction for Tzz at Density 1.00 gm/cc, de-noised

(The remaining tensors follow the same convention)

Terrain corrections computed at density 1.00 gm/cc

TC_Txx_100

TC_Tyx_100

TC_Txz_100

TC_Tyy_100

TC_Tyz_100

TC_Tzz_100

TC_Tz_100

Bathymetry corrections computed at density 1.00 gm/cc (when necessary)

TCW_Txx_100

TCW_Tyx_100

TCW_Txz_100

TCW_Tyy_100

TCW_Tyz_100

TCW_Tzz_100

TCW_Tz_100

Leveled Free Air components

Txx_FA_lev

Tyx_FA_lev

Txz_FA_lev

Tyy_FA_lev

Tyz_FA_lev

Tzz_FA_lev

Tz_FA_lev

Terrain Corrected Tensors at density 2.67 gm/cc

Txx_TC_267_lev

Tyx_TC_267_lev

Txz_TC_267_lev

Tyy_TC_267_lev

Tyz_TC_267_lev

Tzz_TC_267_lev

Tz_TC_267_lev

Levelled, de-noised Free Air components

Txx_FA_FLM

Tyx_FA_FLM

Txz_FA_FLM

Tyy_FA_FLM

Tyz_FA_FLM

Tzz_FA_FLM

Tz_FA_FLM

De-noised Bathymetry corrections computed at density 1.00 gm/cc

TCW_Txx_100_FLM

TCW_Tyx_100_FLM

TCW_Txz_100_FLM

TCW_Tyy_100_FLM

TCW_Tyz_100_FLM

TCW_Tzz_100_FLM

TCW_Tz_100_FLM

Levelled, de-noised Tensors terrain corrected at density 2.67 gm/cc

Txx_TC_267_FLM

Tyx_TC_267_FLM

Txz_TC_267_FLM

Tyy_TC_267_FLM

Tyz_TC_267_FLM

Tzz_TC_267_FLM

Tz_TC_267_FLM

(Tz gravity data is derived from the vertical integration of the Tzz data.)

Free Air data that has had FLM applied should be terrain corrected with the terrain corrections that have also had FLM applied. Similarly, the Free Air data without FLM should be corrected using the non-FLM terrain corrections. This is necessary due to the fact that FLM computes the data on a smoothed altitude surface, and the terrain corrections must also be computed on this surface to be precise. However, in areas where the terrain effect is minimal, FLM on the terrain corrections may not be necessary.

For example, for terrain corrected Tzz at density 2.1 use:

Tzz_FA_LEV – TC_Tzz_100 * 2.1

Or for de-noised Tzz use:

Tzz_FA_FLM – TC_Tzz_100_FLM * 2.1

When a bathymetry layer is present, TCW_Tzz_100*d must be added to the equation, where d is the density contrast between the sediment density and 1.03

for example with a two layer model:

Tzz_TC_220_FLM = Tzz_FA_FLM-TCT_Tzz_100_FLM*2.2-(TCW_Tzz_100_FLM*1.17)

Note: The cut off wavelength frequency is generally set equal to the line spacing in the survey. When line spacing varies, multiple runs may be performed and the best results selected as final. For further explanation, see the FLM description on page 15. FLM may not be effective on surveys with very few lines. FLM was performed with a cut off frequency of 400 meters on this survey.

Magnetics Products

(When Present)

TMI is the Total Magnetic Intensity, leveled, with base mag and Earth's Field removed

TMI_RTP is the above reduced to the magnetic pole

TMI_RTP_FVD is the first vertical derivative of the above

The information contained in this report is for the use of Bell Geospace and other authorized individuals only. All information contained herein is by all intent a true and accurate representation of the facts and results as they pertain to this Air-FTG® survey.

Addendum A: Decorah, Iowa

Database name: Decorah_Iowa_Air-FTG.gdb

This survey is located in North Eastern Iowa. (Figure A1). The survey area lies between Latitudes 43.21° and 43.55° North and Longitudes -92.02° and -91.58° West. The Air-FTG® survey was flown over this project between December 25, 2012 and January 2, 2013.

Weather

The weather during this survey was typical for this region this time of year. High winds prevented flights on many days. Often line keeping was problematic, but lines outside spec were repeated. Fog and low clouds were also quite often an issue. Snow and ice also caused cancellation of flights. But on days that the weather cooperated acquisition went quickly and allowed for %100 coverage of good quality data. Day by day weather conditions can be found in the flight logs.

Safety is always the first priority so when visibility is diminished or if wind conditions become unstable, flights are halted. This is especially true when terrain and the presence of towers in the survey area complicate navigation.

Data taken at high accelerations must be examined in the office to determine quality, and often times it is quite acceptable data. Lines that are deemed too noisy are repeated until the data passes QC parameters and visual analysis. Daily weather and acceleration information can be found in the flight logs.

Gradient data does not degrade as quickly as gravity data in rough weather, but gradient data quality is affected by extreme weather and turbulent conditions. Data acquisition is generally halted when vertical accelerations were sustained above

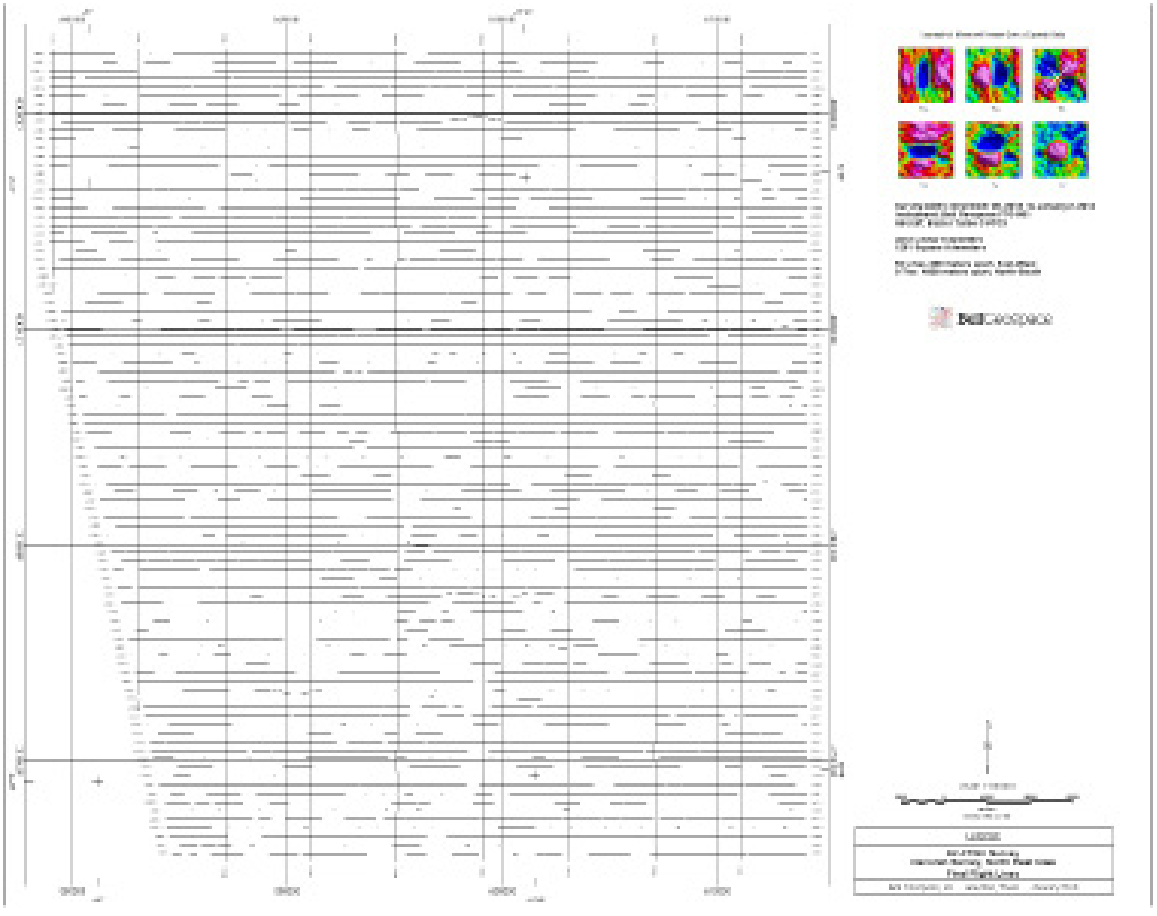


Figure A2. Final Flight Lines

80 milli-g's. Lines acquired in the most turbulent conditions are examined and re-acquired if the data quality is substandard. Vertical acceleration is not the only indicator of data quality, and in many cases lines with higher acceleration numbers exhibit data superior to lines with lower accelerations. Other factors must be considered to effectively evaluate data quality. More information on these parameters can be found in the QA section of this report.

Operations Summary

The crew and equipment were stationed in Decorah, Iowa for the duration of this survey. BGI Personnel involved in this survey were Julius Vale, Ali Vaughton and Brett Unmack. The data were acquired with Bell Geospace's FTG-001 onboard a Basler Turbo, Registration #FTG-X (Figure 2). The aircraft is owned by BGI and operated and maintained by Enterprise and ALCI Aviation, LTD. The pilots were Brian, Keith, Chris and Ross. The

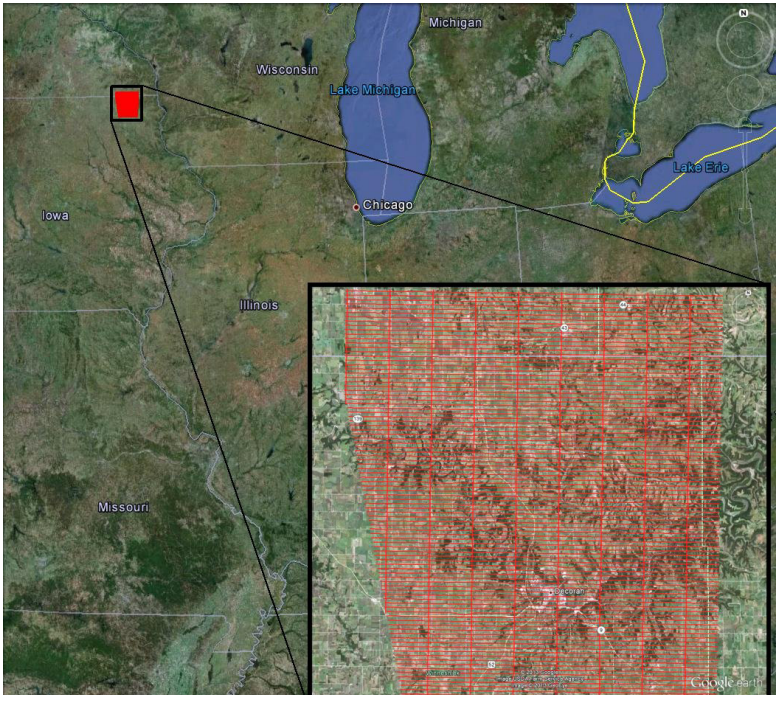


Figure A1. Survey Location.

Terrain clearance was a not a serious concern in this survey, but on windy days line keeping became more difficult, especially over valleys.

Table A1 includes information about the flight altitude, and ground clearance. The terrain model shown here (Figure A3) was produced from SRTM data .

This DEM was also used to compute terrain corrections.

mechanic was Miro Budinsky .

Survey Design and Data Acquisition

Figure A2 shows the location of the final flightlines. The survey contains 94 lines 400 meters apart, with variable lengths. Nine tie lines were acquired 4000 meters apart. The lines are flown East-West with perpendicular tie lines. The survey contains 3412 linear kilometers and encompasses an area of about 1281 square kilometers. There are 57,721 data points at a one second interval.

The survey was designed as a constant 80 meter altitude. The survey plan defines a flight path that will maintain a constant distance from the water for the entire length of each survey line. However, it is not always possible to maintain a constant altitude due to weather and pilot's abilities.

	Min	Max	Std Dev	Mean
Terrain	226	426	32	349
Altitude	368	511	24	448
Clearance	60	185	14	98

Table A 1. Flight Altitude Statistics (Meters)

Final Maps

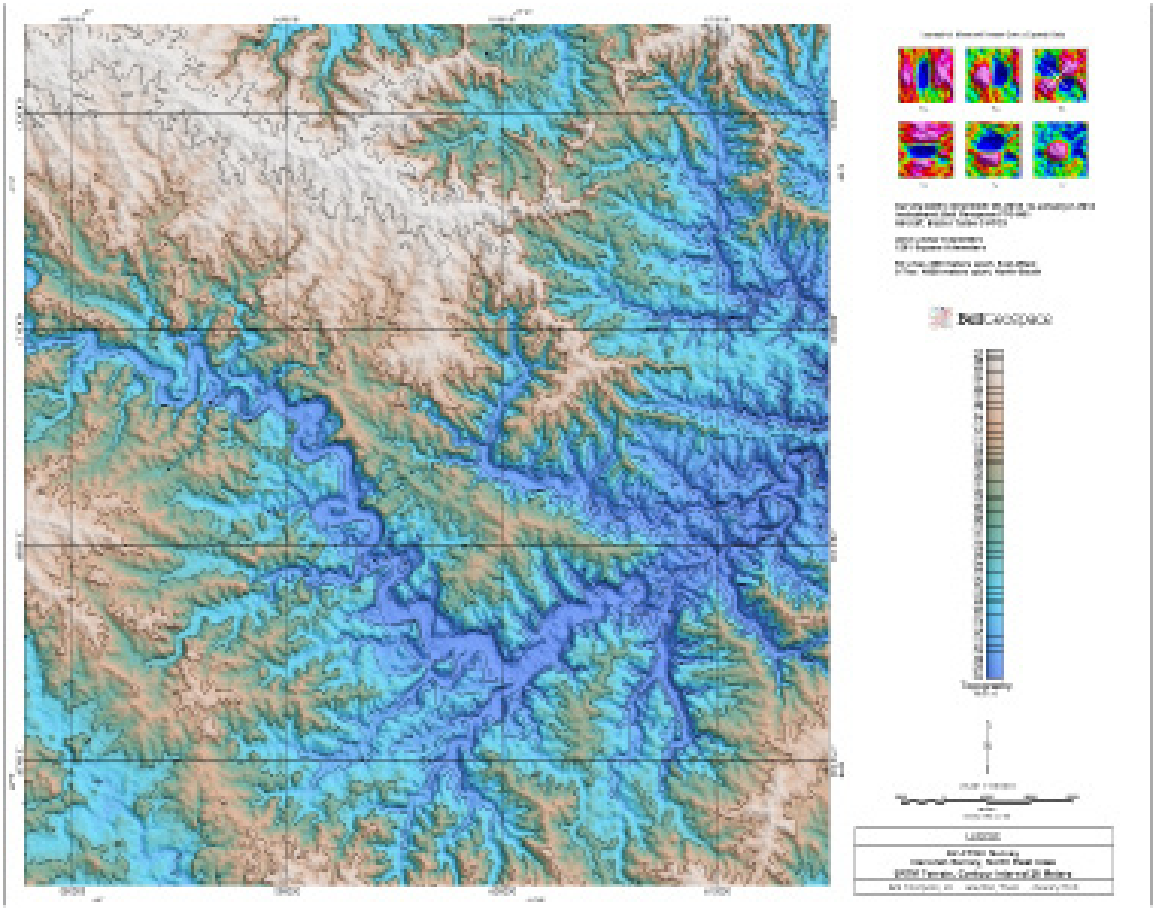
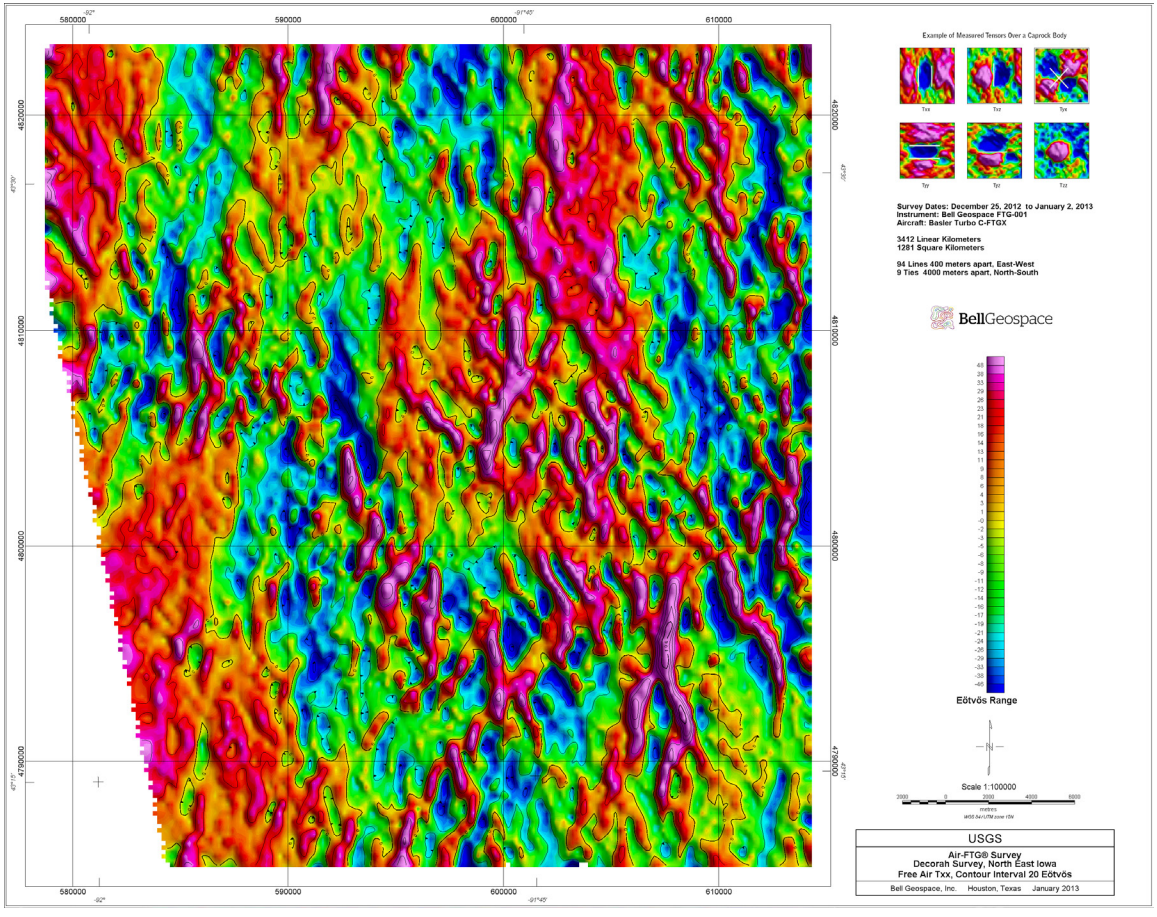


Figure A 3. Terrain.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Example of Measured Tensors Over a Caprock Body
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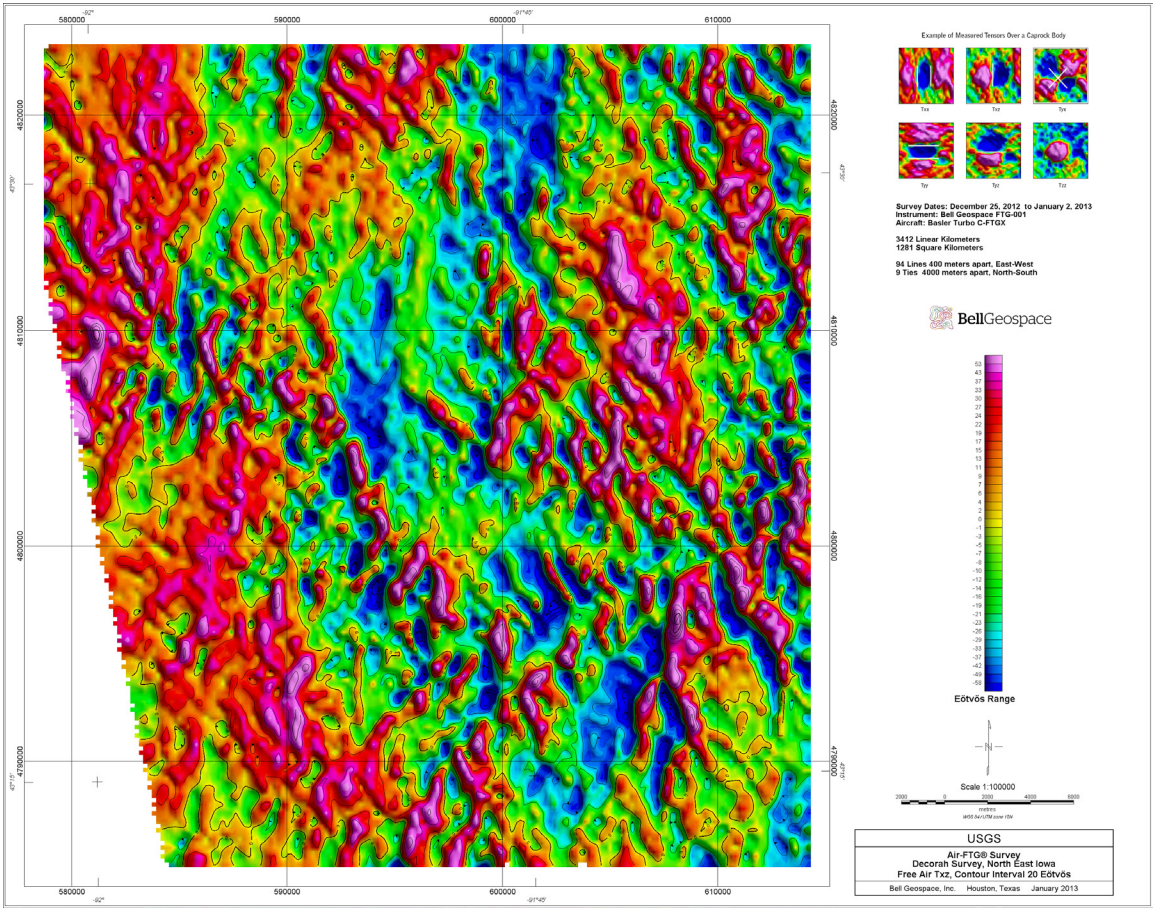
Tyz
Tzz
Survey Dates: December 25, 2012 to January 2, 2013
Instrument: Bell Geospace FTG-001
Aircraft: Basler Turbo C-FTGX
3412 Linear Kilometers
1281 Square Kilometers
94 Lines 400 meters apart, East-West
9 Ties 4000 meters apart, North-South
BellGeospace
Eötvös Range
Scale 1:100000
meters
USGS
Air-FTG® Survey
Decorah Survey, North East Iowa
Free Air Txx, Contour Interval 20 Eötvös
Bell Geospace, Inc. Houston, Texas January 2013

Free Air Txx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BellGeospace
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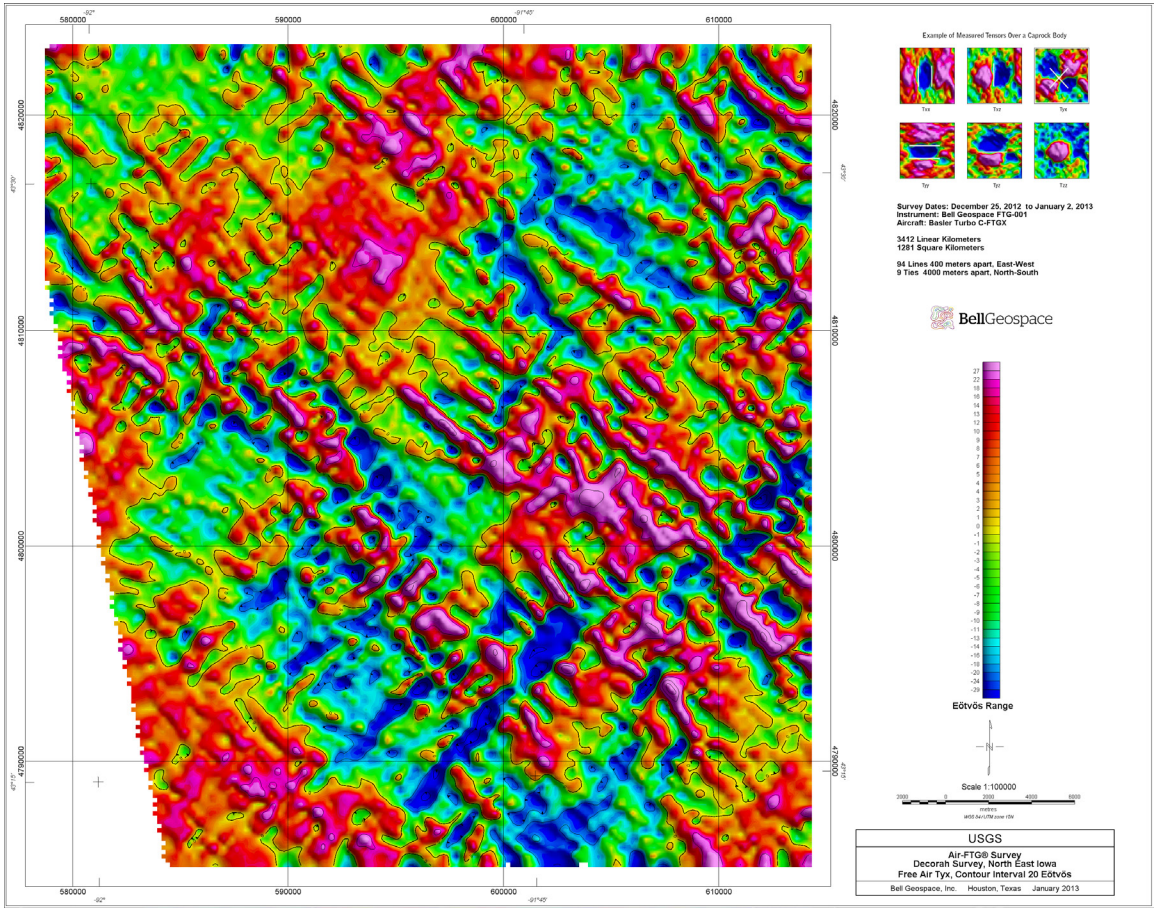
Air-FTG® Survey
Decorah Survey, North East Iowa
Free Air Txz, Contour Interval 20 Eötvös
Bell Geospace, Inc. Houston, Texas January 2013

Free Air Txz.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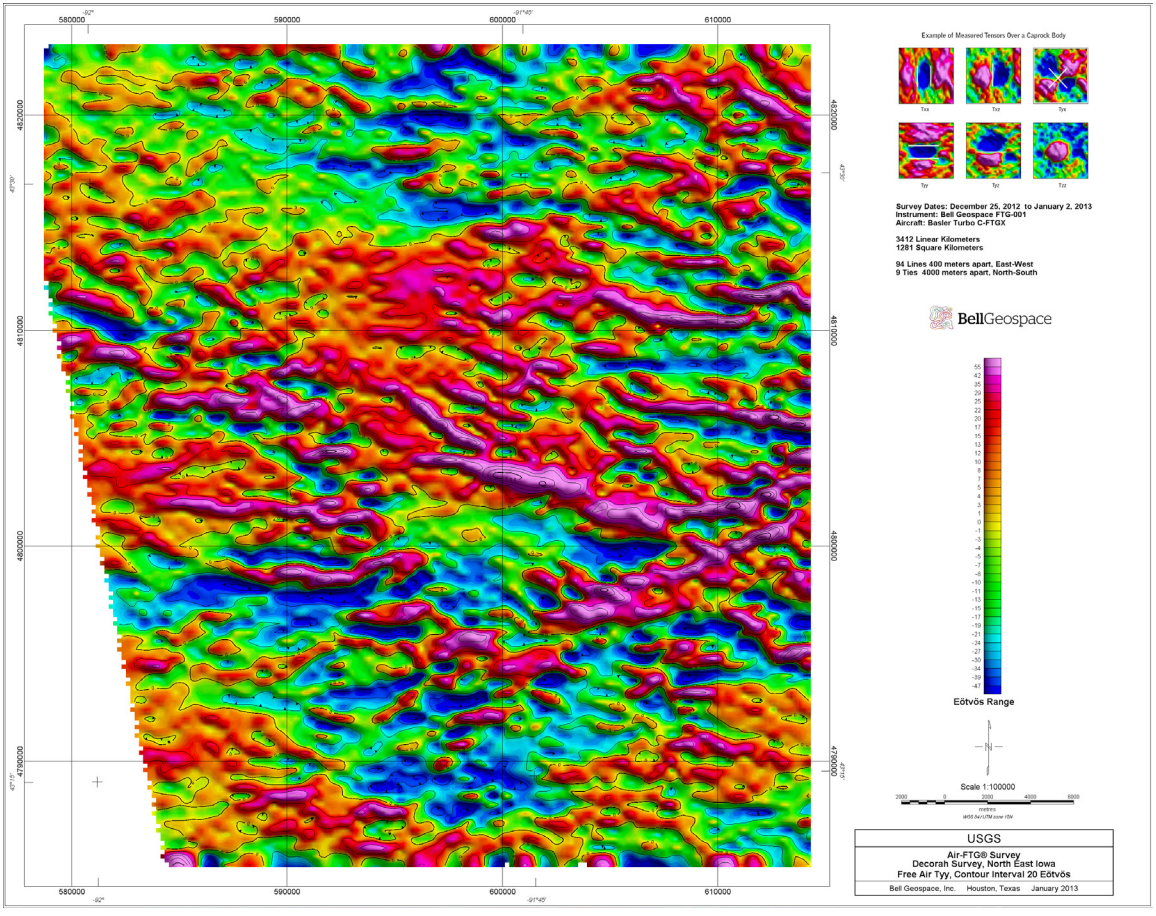
Free Air Tyx, Contour Interval 20 Eötvös
Bell Geospace, Inc. Houston, Texas January 2013

Free Air Tyx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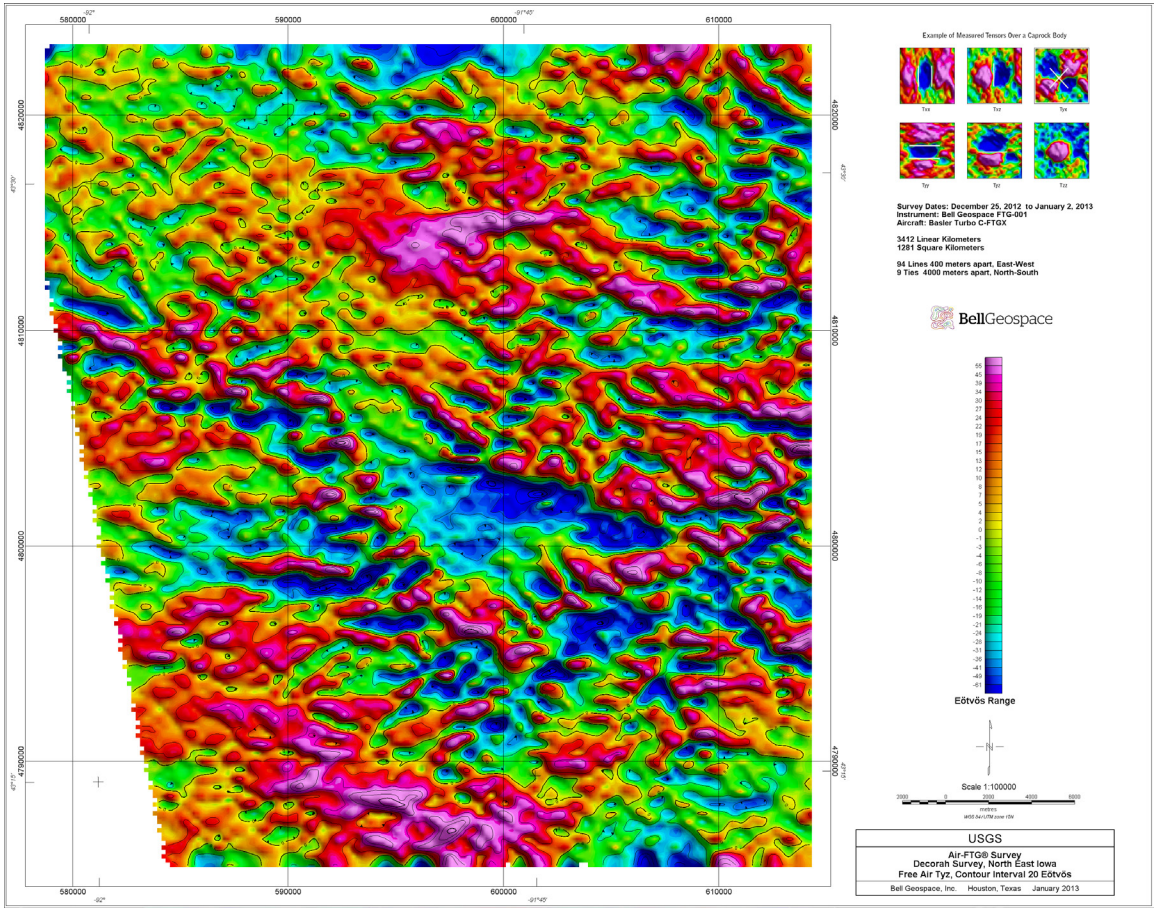
Free Air Tyy, Contour Interval 20 Eötvös
Bell Geospace, Inc. Houston, Texas January 2013

Free Air Tyy.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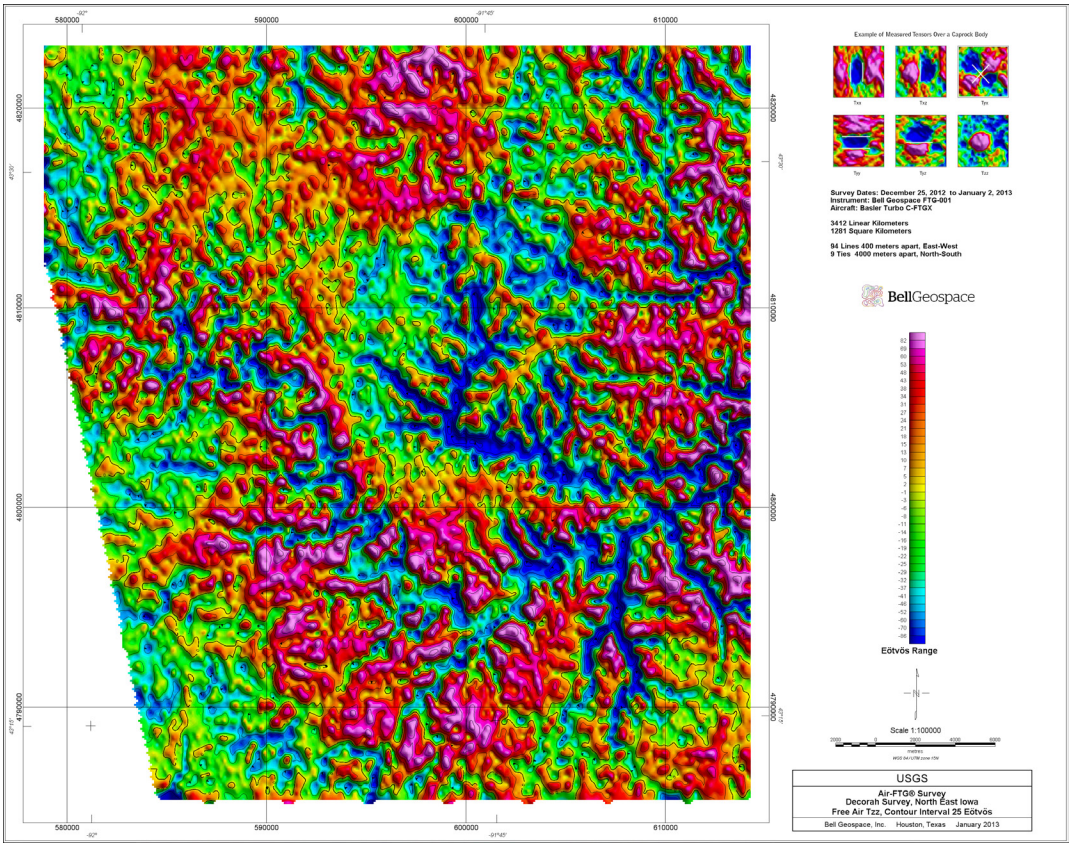
Bell Geospace, Inc. Houston, Texas January 2013

Free Air Tyz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BellGeospace
Eötvös Range
Scale 1:100000
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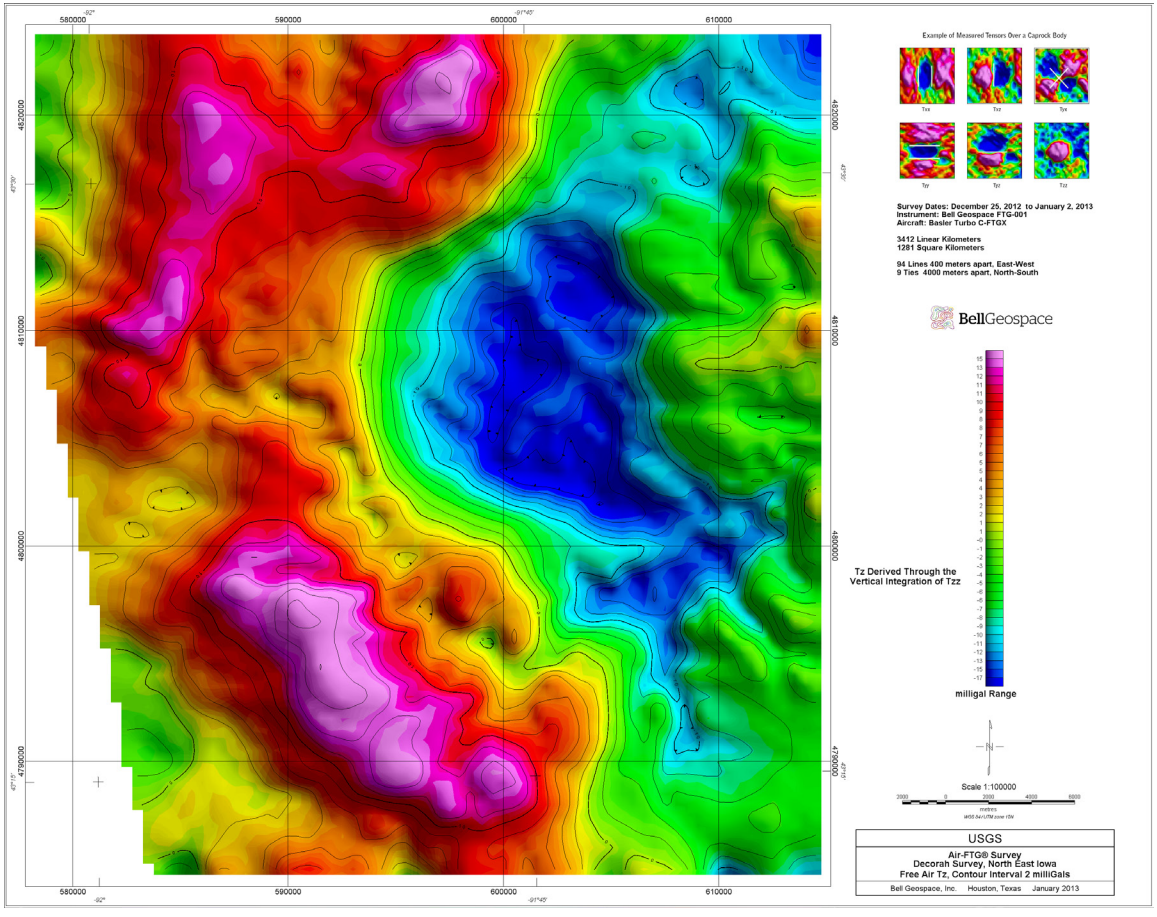
Decorah Survey, North East Iowa
Free Air Tzz, Contour Interval 25 Eötvös
Bell Geospace, Inc. Houston, Texas January 2013

Free Air Tzz.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3412 Linear Kilometers
1281 Square Kilometers
94 Lines 400 meters apart, East-West
9 Ties 4000 meters apart, North-South
BellGeospace
Tz Derived Through the Vertical Integration of Tzz
milligal Range
Scale 1:100000
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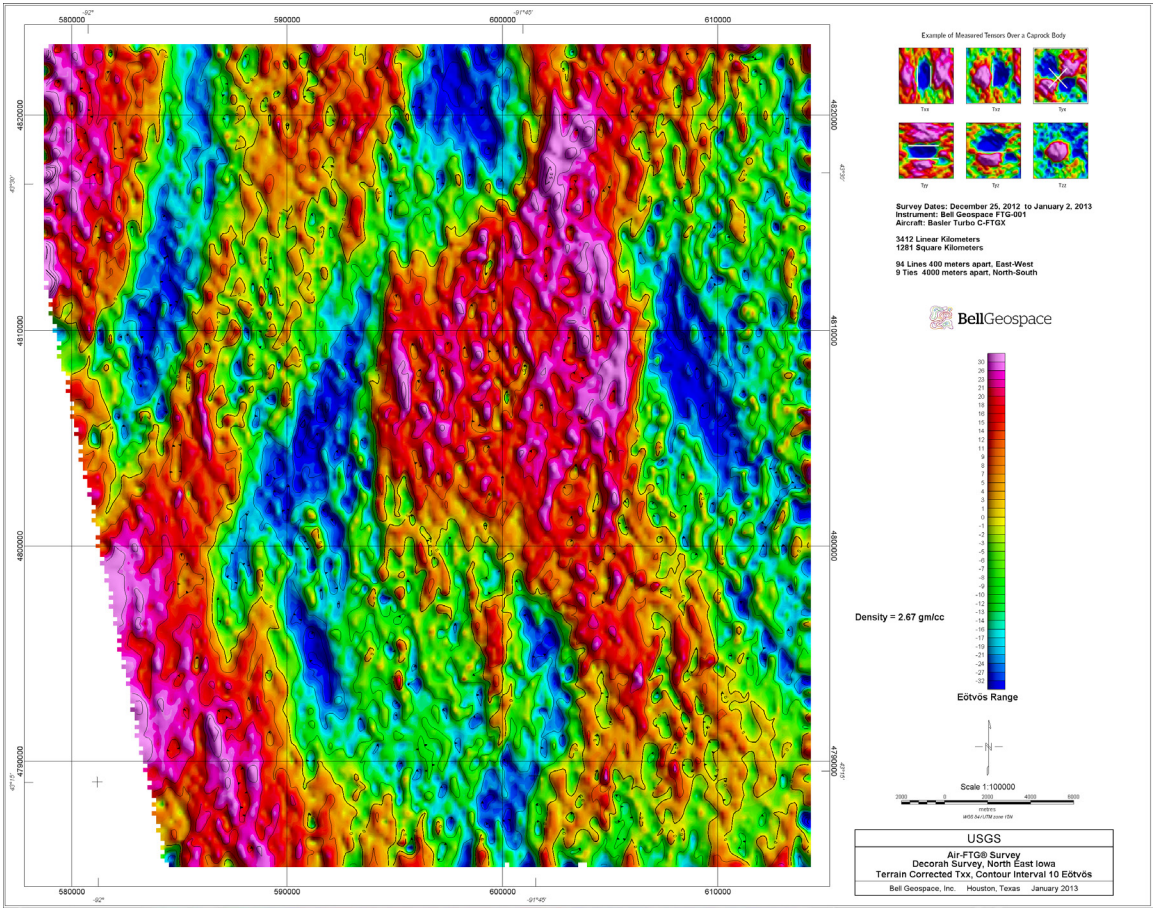
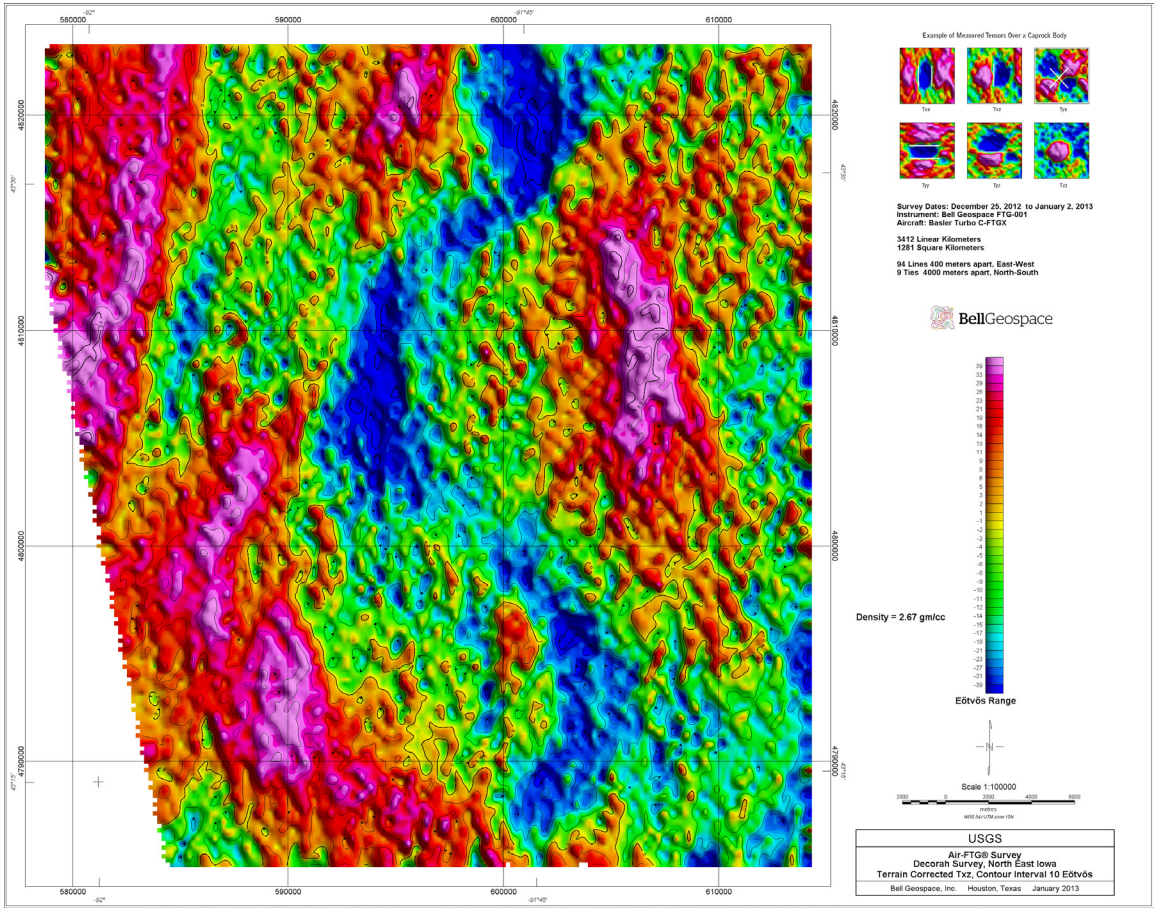
Air-FTG® Survey
Decorah Survey, North East Iowa
Free Air Tz, Contour Interval 2 milliGals
Bell Geospace, Inc. Houston, Texas January 2013

Free Air Tz



Terrain Corrected Txx, Density 2.67 gm/cc.



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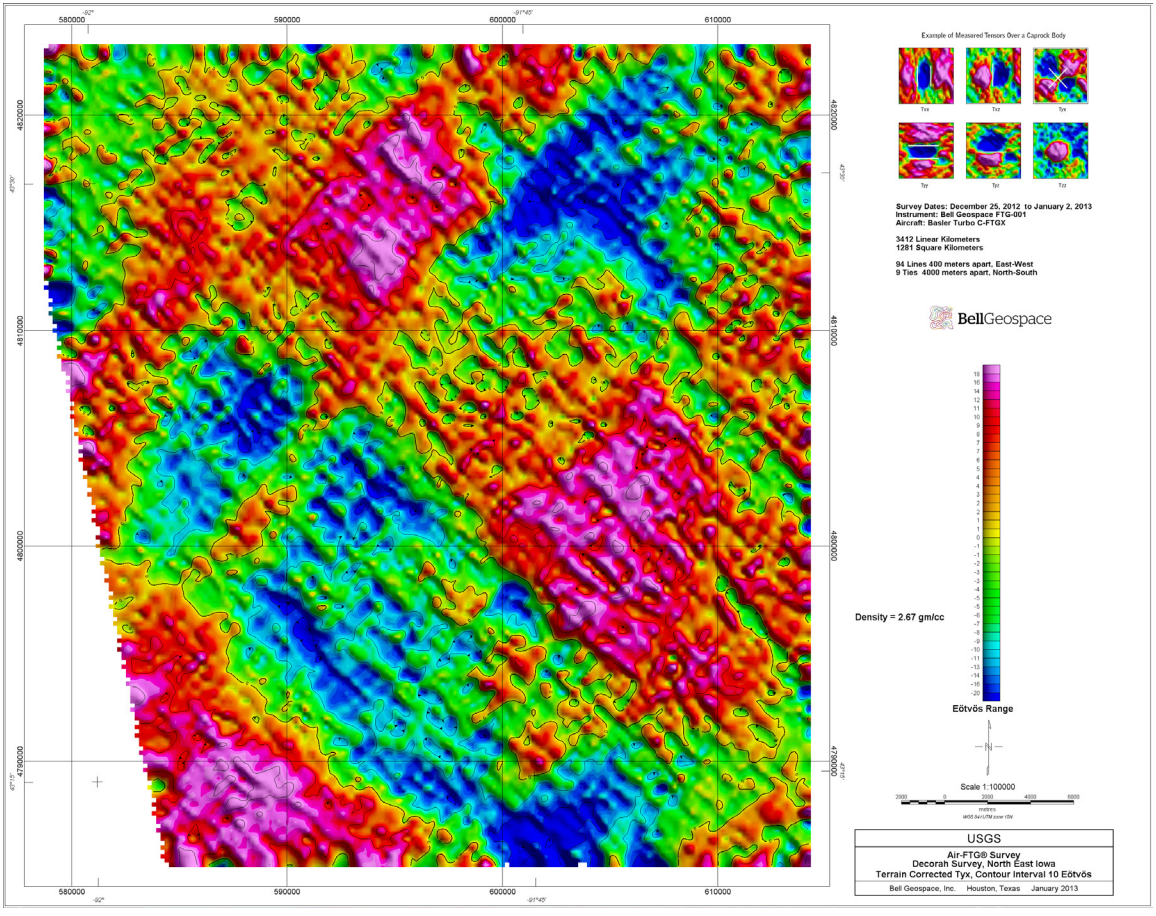

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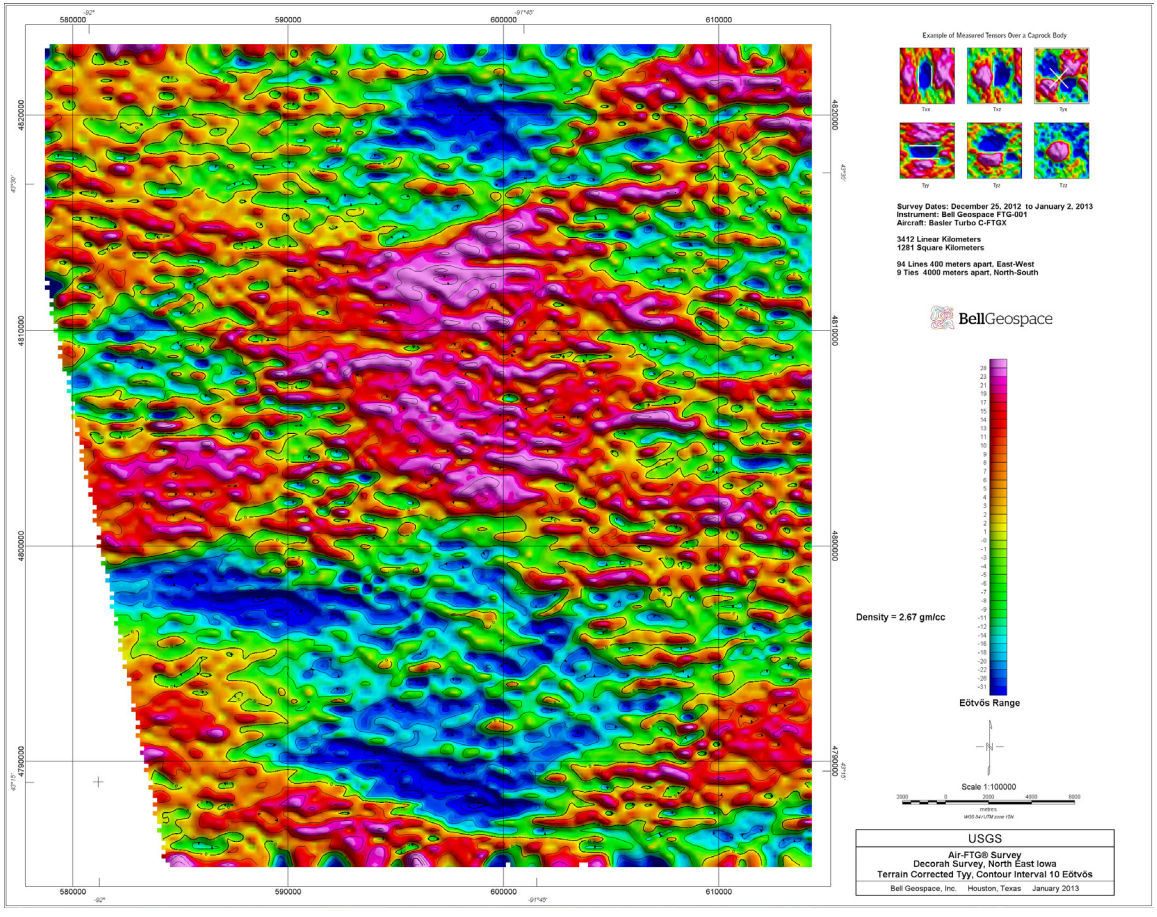
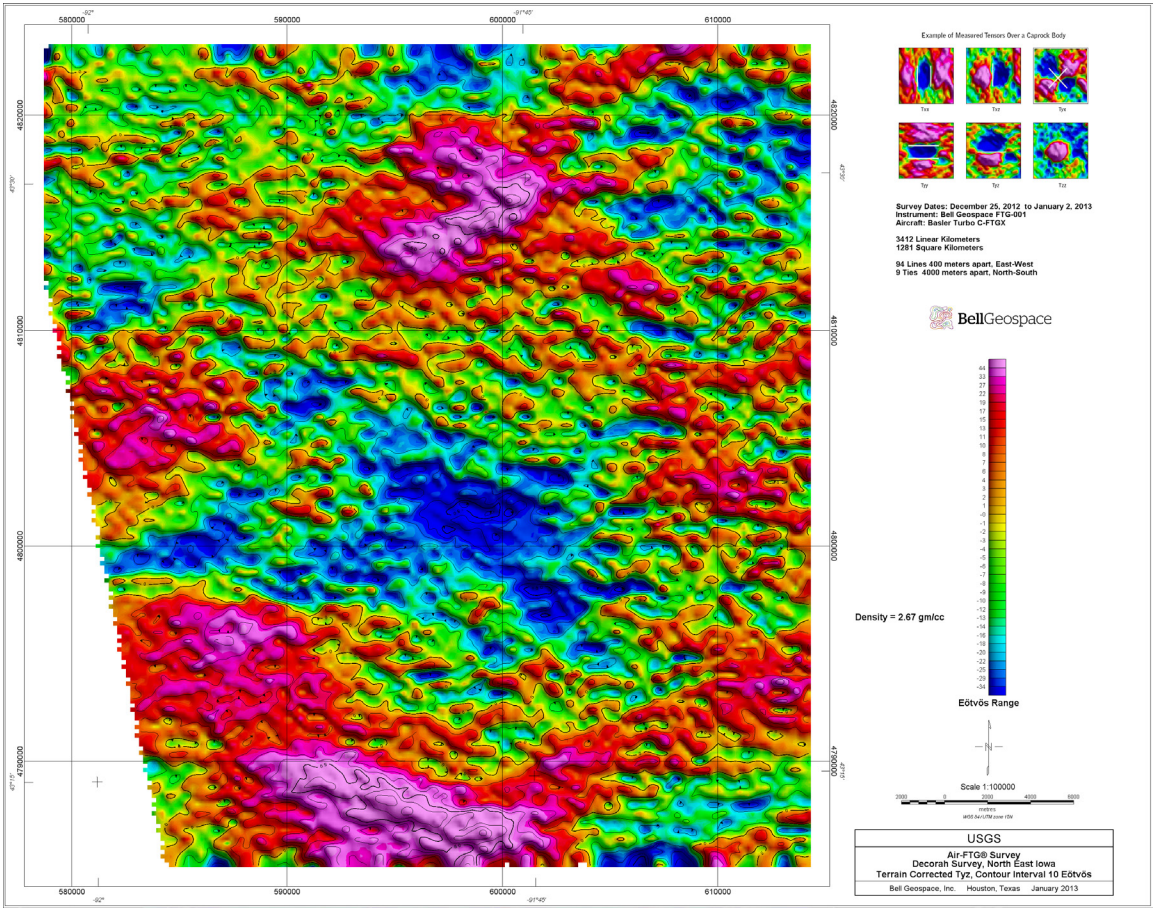
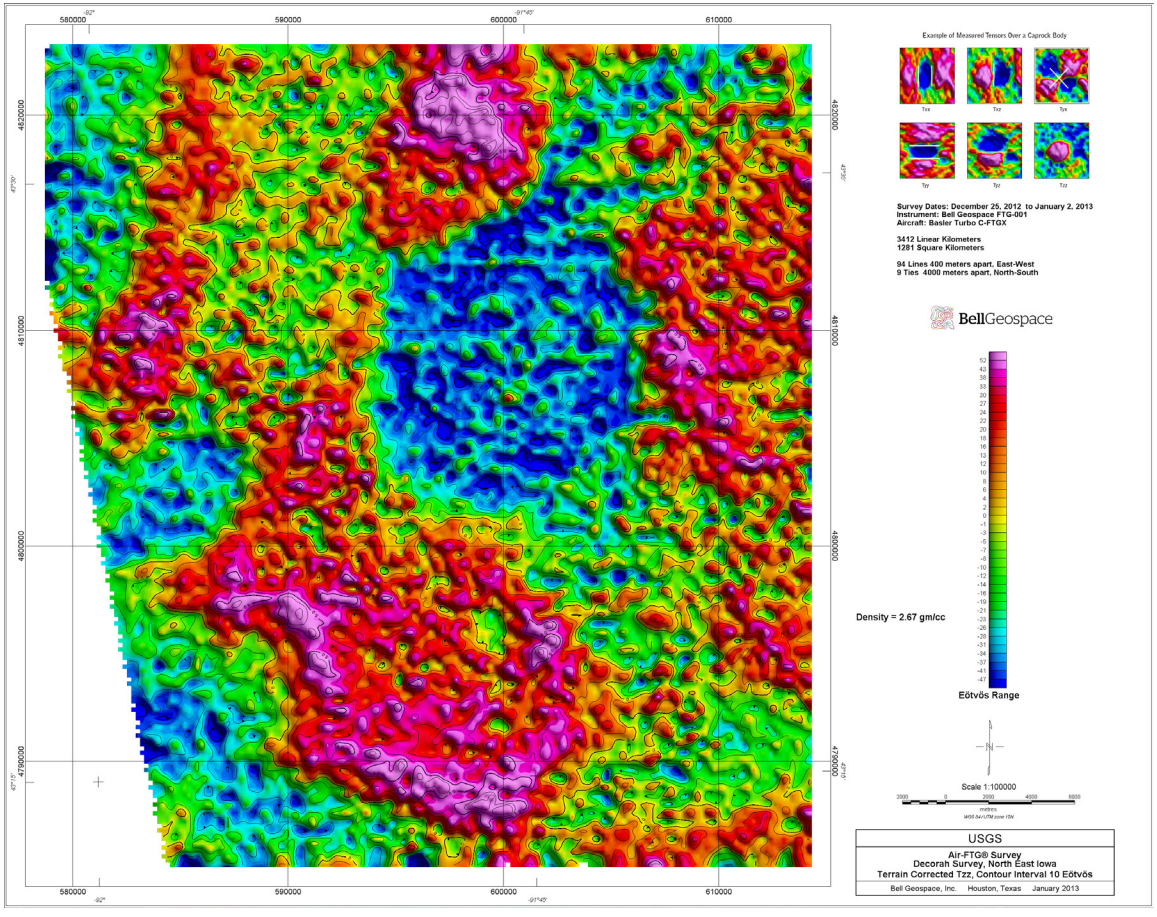


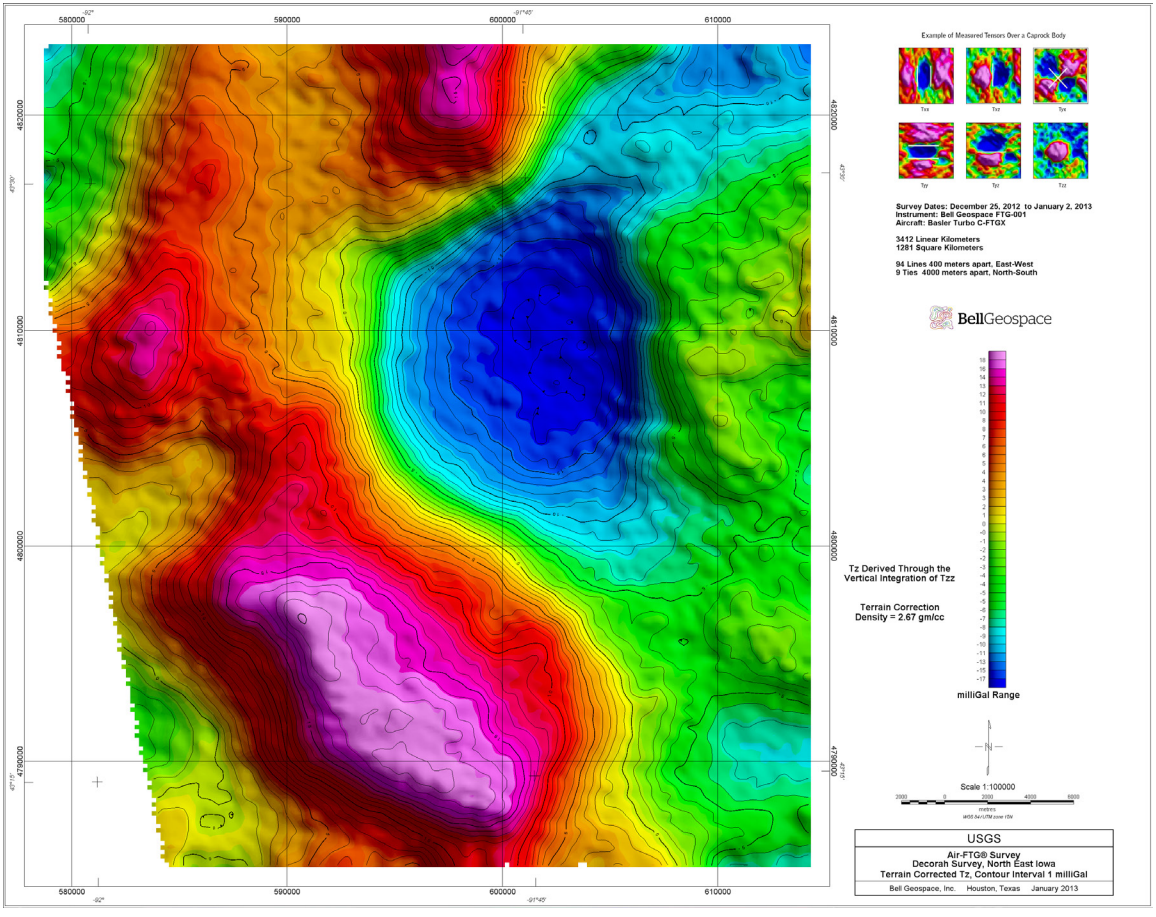
Terrain Corrected Tyy, Density 2.67 gm/cc



Terrain Corrected Tyz, Density 2.67 gm/cc.



Terrain Corrected Tzz, Density 2.67 gm/cc



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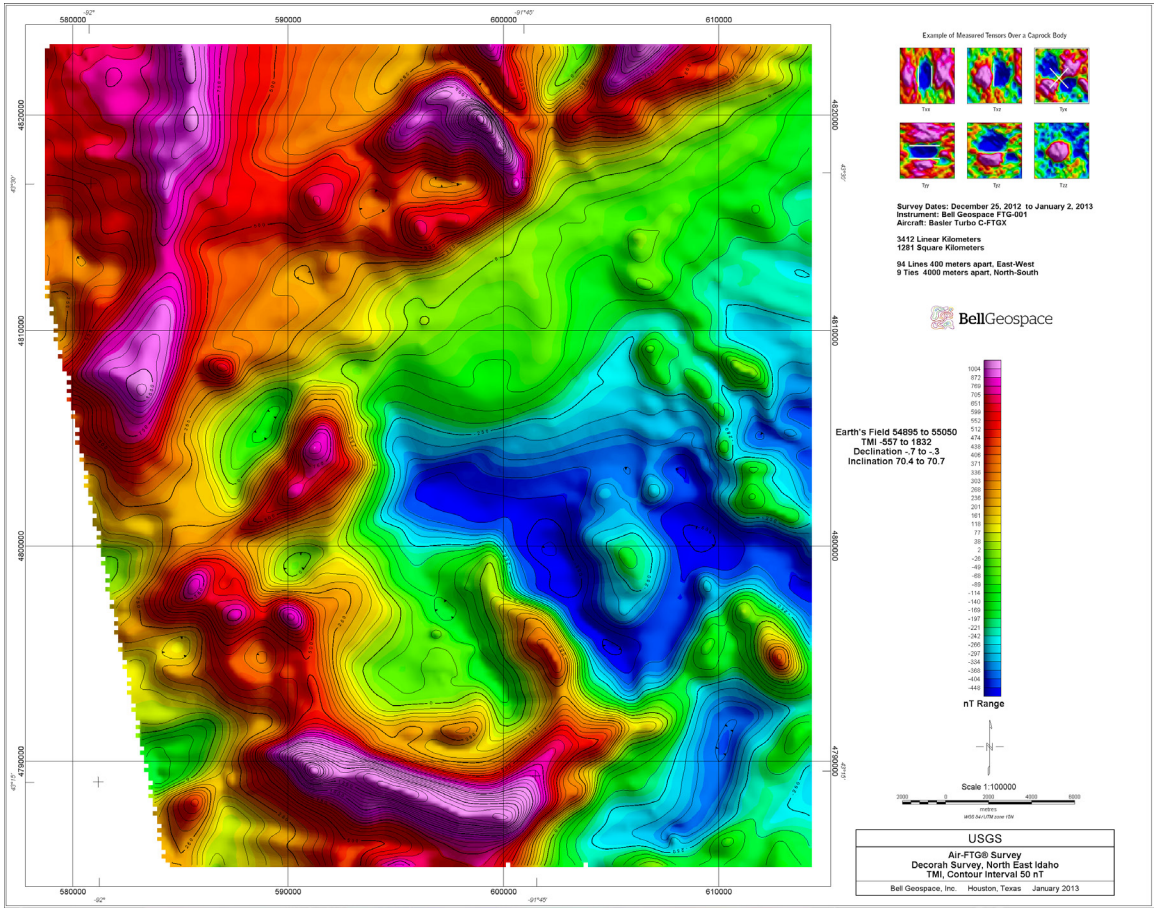
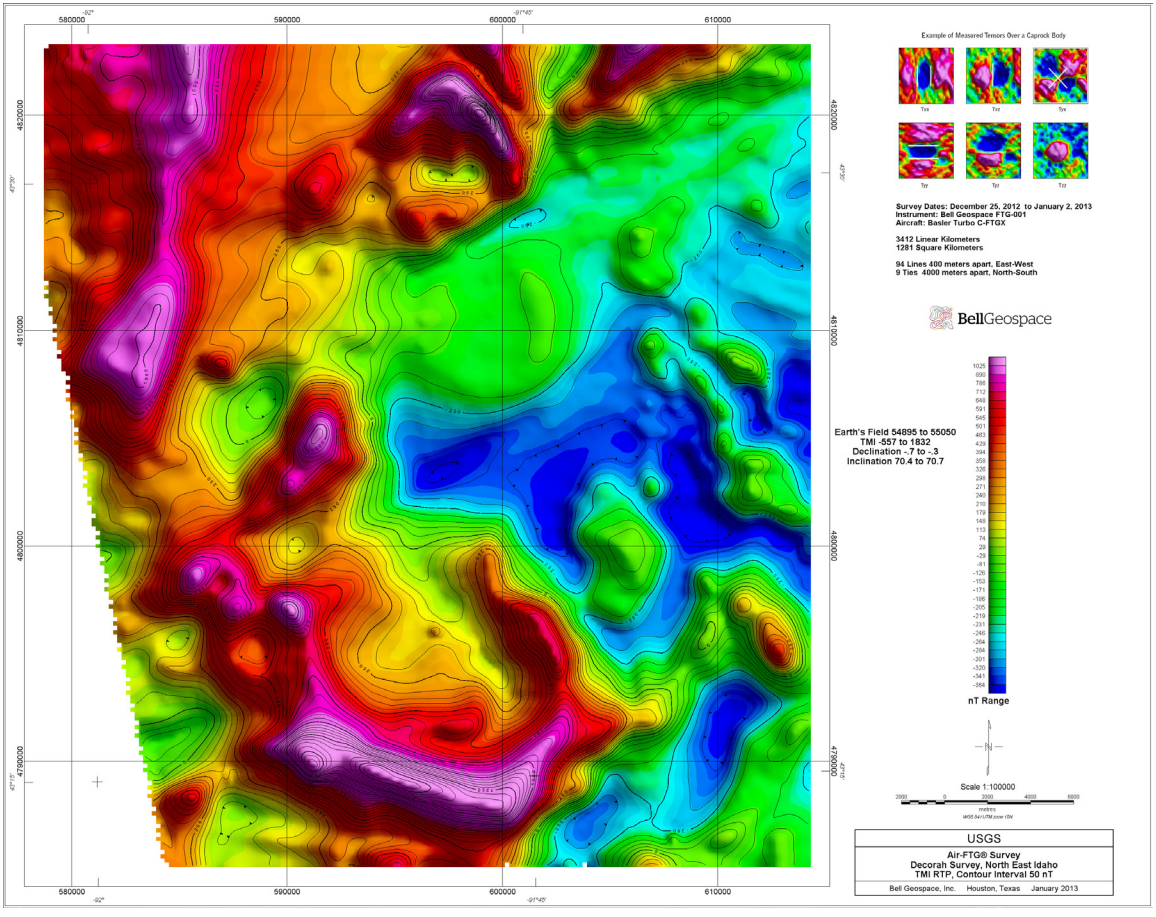
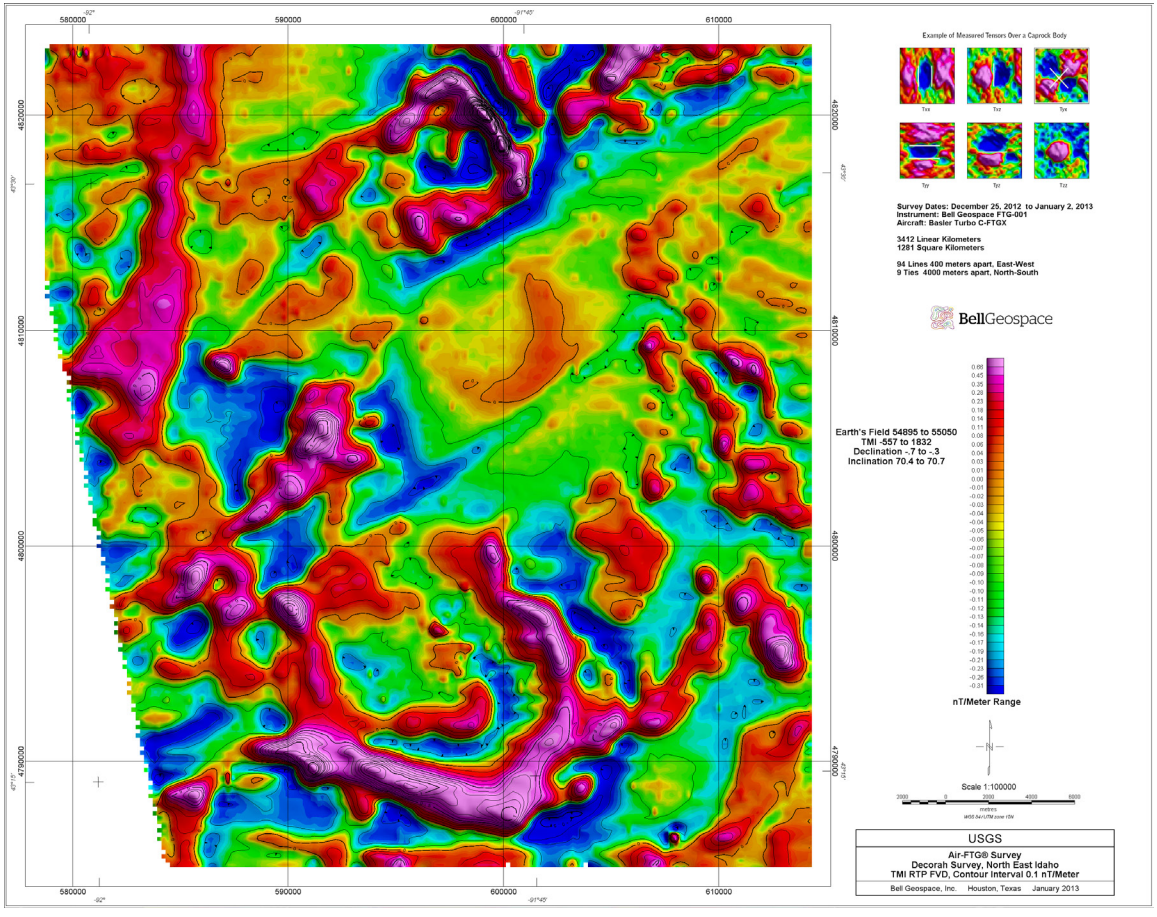


Total Magnetic Intensity



Total Magnetic Intensity, Reduced to the Pole



Total Magnetic Intensity, Reduced to the Pole, First Vertical Derivative

End of Report