Air-FTG®
Acquisition and Processing Report

Geological Survey of Sweden

Kiruna Survey, Kiruna, Sweden

October 2013

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Geological Survey of Sweden, 3D Air-FTG®

3D FTG is a technology that came to the Mining and Oil & Gas industries from the US Navy through the Dual Use Initiative. As such this technology is still covered under International Traffic in Arms Regulations (ITAR) Licensing Restrictions (22.CFR121.1). The following website: http://pmddtc.state.gov/reference.htm provides compliance details and other relevant information regarding licensing of these data.

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1 INTRODUCTION

Since 1998 Bell Geospace has specialised in the acquisition, processing and interpretation of 3-D Full Tensor Gravity Gradiometry (FTG) data. For the majority of this time, BGL 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 and offshore Shetland and Faroe Islands. In 2001 Bell Geospace successfully converted the FTG platform for use on an aircraft, and Air-FTG® surveys have since been completed in North America, South America, Greenland, Europe, Africa, India, the Philippines, Australia, and New Zealand.

The survey equipment used for this project is owned, maintained and operated by Bell Geospace and is permanently installed on Basler Turbo BT-67 aircraft with the call sign C-FTGI. The aircraft is a modified and modernised Douglas DC-3 airframe, originally built in 1944, owned by Bell Geospace and operated by ALCI of Oshawa, Canada.

Approximately 4,532 line-kilometres of Air-FTG® survey data was acquired in October 2013 by Bell Geospace Limited (BGL). BGL project name for this survey was "Kiruna". An overview map of the survey area is illustrated in Figure 1.1. The survey areas lie within UTM zone 34N. This report provides information regarding Air-FTG® instrumentation, acquisition of FTG data as well as associated processing and operational methods. Appendices 1 and 2 provide an overview of tensors, with appendices 3, 4 and 5 containing full product descriptions for FTG and aeromagnetic data.

1.1 Personnel:

The following is a summary of the Bell Geospace and ALCI Aviation Ltd personnel involved in field operations in the KSK1 Air-FTG survey, as well as associated office-based data processing and interpretation personnel.

ALCI Aviation personnel:

Jim Cook	Captain
Andrew Noonan	Captain
Paul Richter	Pilot
Miroslav Budzinski	Mechanic
Dan Levert	Mechanic
Gary MacQueen	Mechanic

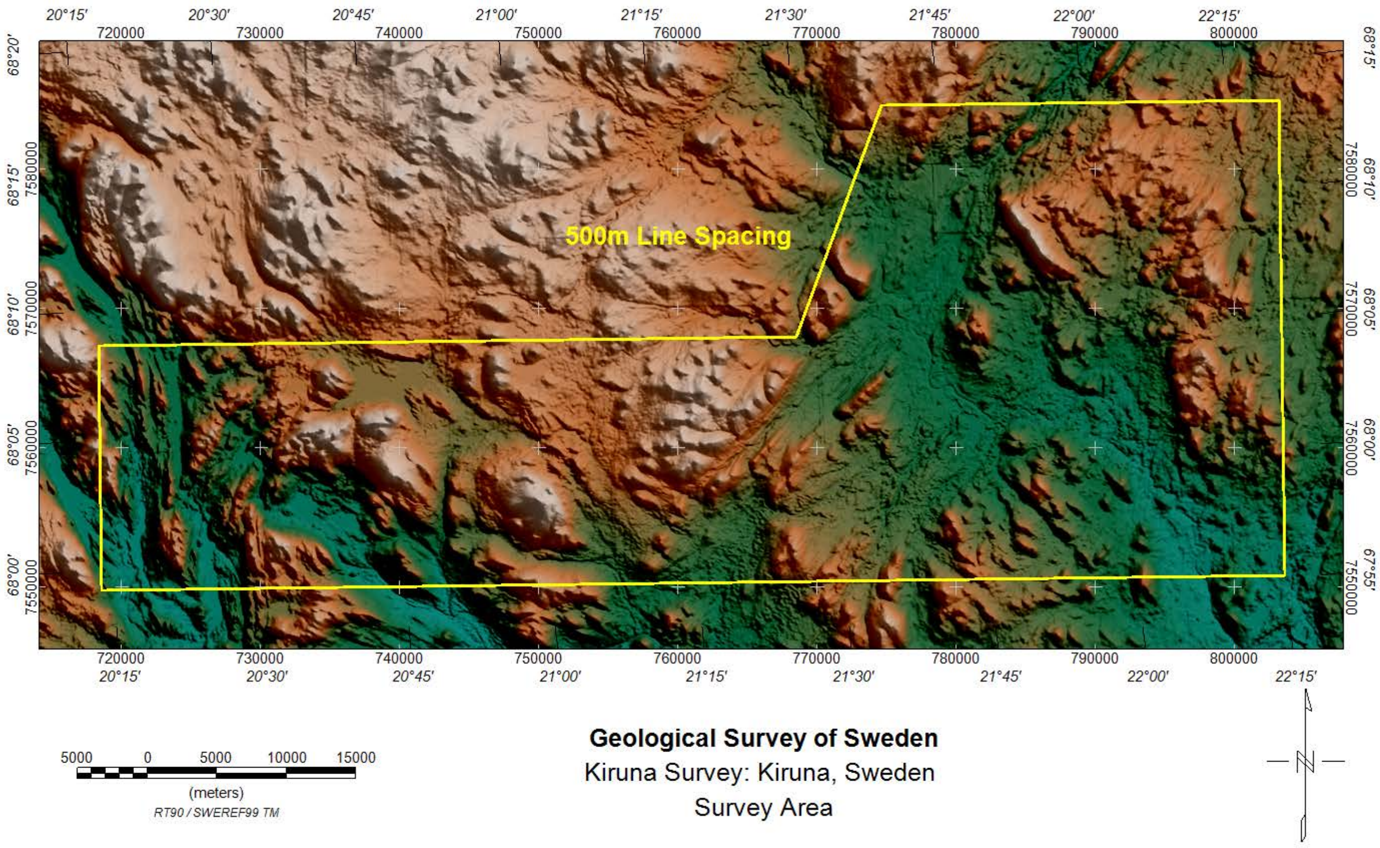
Bell Geospace Field personnel:

Scott Morrison-Smith	Logistics support
Phil Kriesa	Operations supervisor
Stef Kuna	Operations supervisor
Charley Upp	Operator
Mark Baguley	Operator
John Watkins	System specialist

Bell Geospace Office personnel:

Michael Douglas	Business development manager
Colm Murphy	Senior Geophysicist
Jade Dickinson	Geophysicist
Richard Farnell	Geoscientist
James Robinson	Software engineer
Lionel Sumner	Geoscientist
Malcolm Destro	Data processing geophysicist

Figure 1.1: The Kiruna survey area with line spacing details



2 OPERATIONS:

2.1 Operations overview:

1. The survey in Sweden was completed in October 2013 following several delays due to a plethora of issues including aircraft availability and moose migration patterns in the survey area. Prior to set up, permits were applied for through the Swedish Civil Aviation department and our contact there Margareta Brask. Permits were approved in a timely manner in what was an efficient exercise.

2. Several weeks before survey started contact was made with the Swedish Military to discuss our survey and we were informed that a NATO exercise (ACE 16) was planned over Sweden at the same time as the survey start date. Following the exchange of several emails and the distribution of our survey coordinates we received permission to fly as the survey area was just to the North of the air space being used by the military. We were however informed not to venture South of the survey air space for safety reasons.

3. From the map, Kiruna Airport was the obvious choice and contact was made with the airport staff 3 months before the due start date. Gun-Marie Toyra acted as our representative and we produced a contract with her to cover the survey including parking, fuel, hangar use, vehicles, security and hotel rooms.

4. The week before the aircraft's arrival a visit was made to Kiruna to perform the set-up. The airport facilities were excellent. The required HSE tour was undertaken with the Fire Section and the Fuel depot being inspected. The only missing document was the refuel staff annual accreditation but this was produced within the hour. Fuel supply was by means of a fuel bowser, which was less than 6 months old and immaculate. The hotel for the crew was inspected and found to be spotless with good Wi-Fi and very good food; it was a ten minute drive to the airport.

5. Once the aircraft had arrived and performed the usual FOM and tweaks etc., it soon transpired that it would be better to park the aircraft inside the hangar due to snow. Unfortunately the design of the hangar door meant that the original tow bar could not be used so it was sent to the workshops to be extended and this worked fine.

6. Mid-way through the survey there was a short delay for maintenance, which was completed in Stockholm. Other than some down days for weather which was always going to be an issue in the Arctic Circle the survey went extremely well and was completed on 31 October 2013.

2.2 Survey design overview:

The lines in the survey area were planned as one block. The line plan is shown in figure 2.1 and the design specifications are denoted in table 2.1. A total of 4,532 line kilometres was planned for the entire survey, though extra data is recorded on each line to guarantee data resolution at planned-line extremities.

Survey data was recorded with geographical co-ordinates in the WGS84 datum (6378137.00m, 298.257) used by GPS and for convenience survey flights were recorded using the WGS84 datum and

Universal Transverse Mercator projection (UTM); utilising zone 34N.

Survey Designation	Line-km: In-lines	Line-km: Tie-lines	Line-km: Total	Orientation: In-lines	Orientation: Tie-lines	Line Spacing (m)
Kiruna	4103.416	427.944	4531.360	94.82 ^{0}	4.82 °	500/ 4995

Table 2.1 - Survey design specifications (measurements to 3sf)

In order to optimise the survey pilots' flight path, a "drape surface" is calculated. The drape forms a safely flyable surface that accommodates all of the survey lines, improves the data fit at line intersections and reduces spurious variations in signal strength between lines. Survey lines lie on a drape surface initially planned at a nominal 80m above a digital terrain model (illustrated, figure 2.2). Drape surfaces are designed to be as low as safely possible, in order to maximise data resolution. The drape surface used is displayed in figure 2.3.

2.3 Survey design

This section presents the planned survey lines, digital terrain model used and the drape surface employed, in figures 2.1, 2.2 and 2.3 respectively, for the survey area.

Figure 2.1 – The survey design

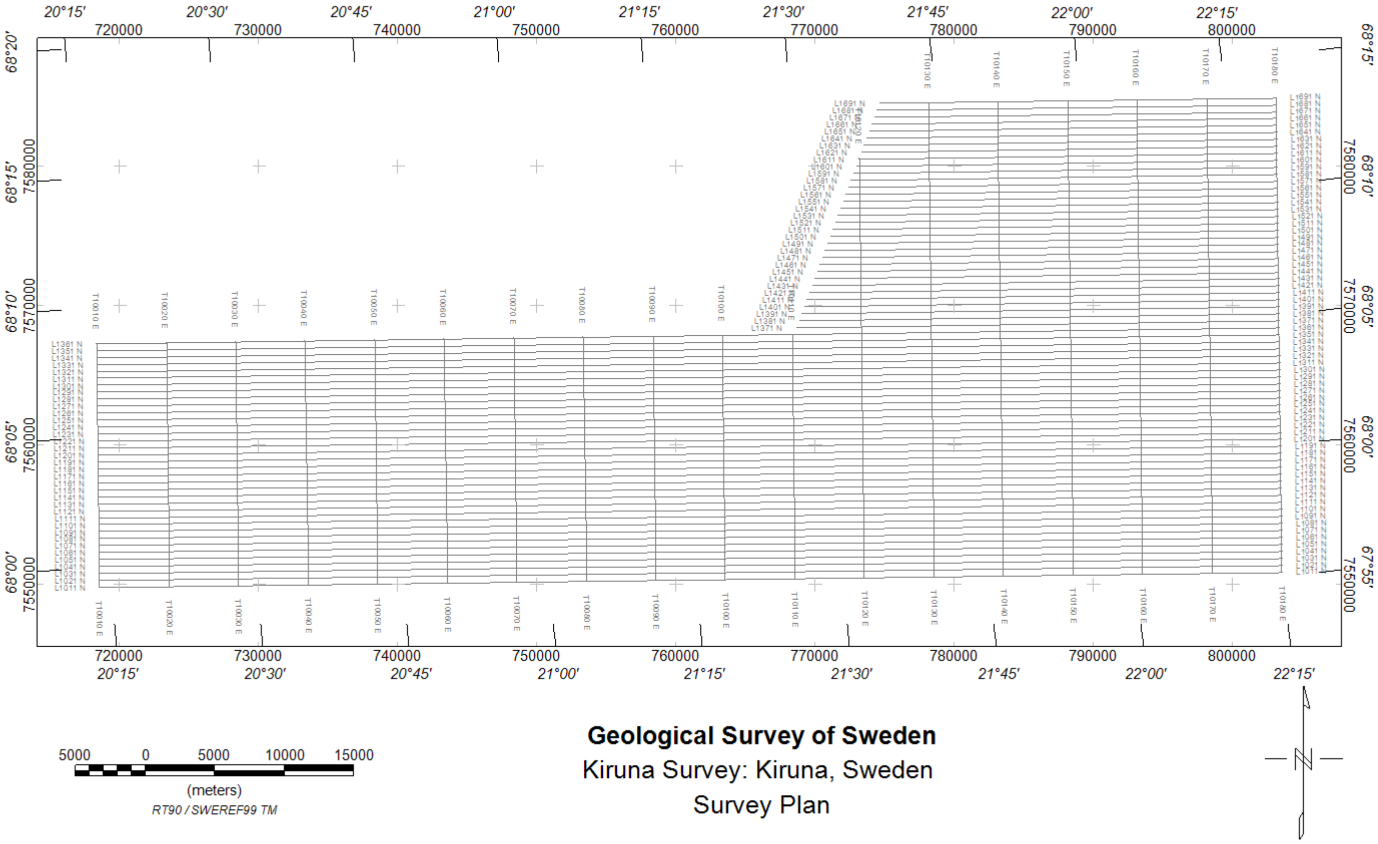


Figure 2.2 – The digital terrain model used, with survey zone

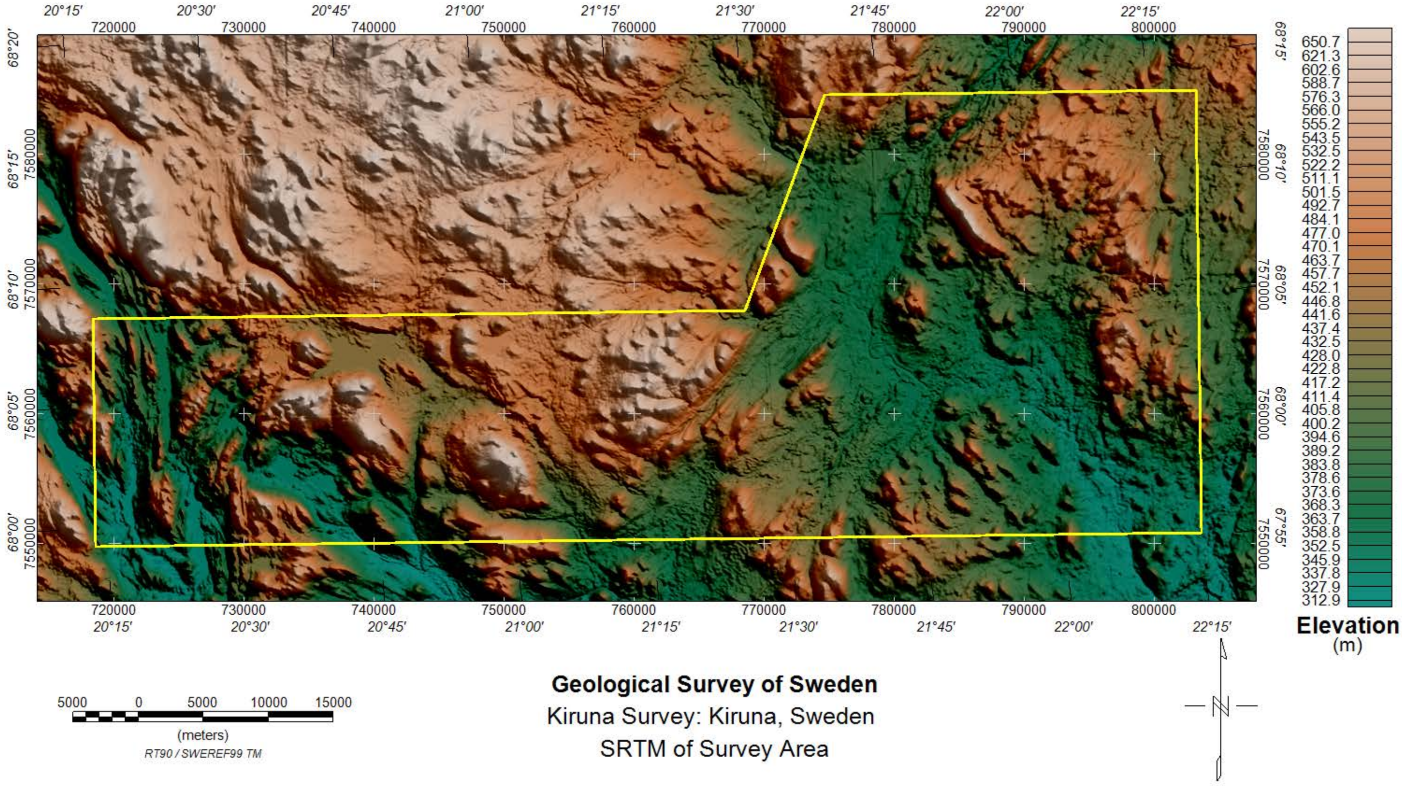
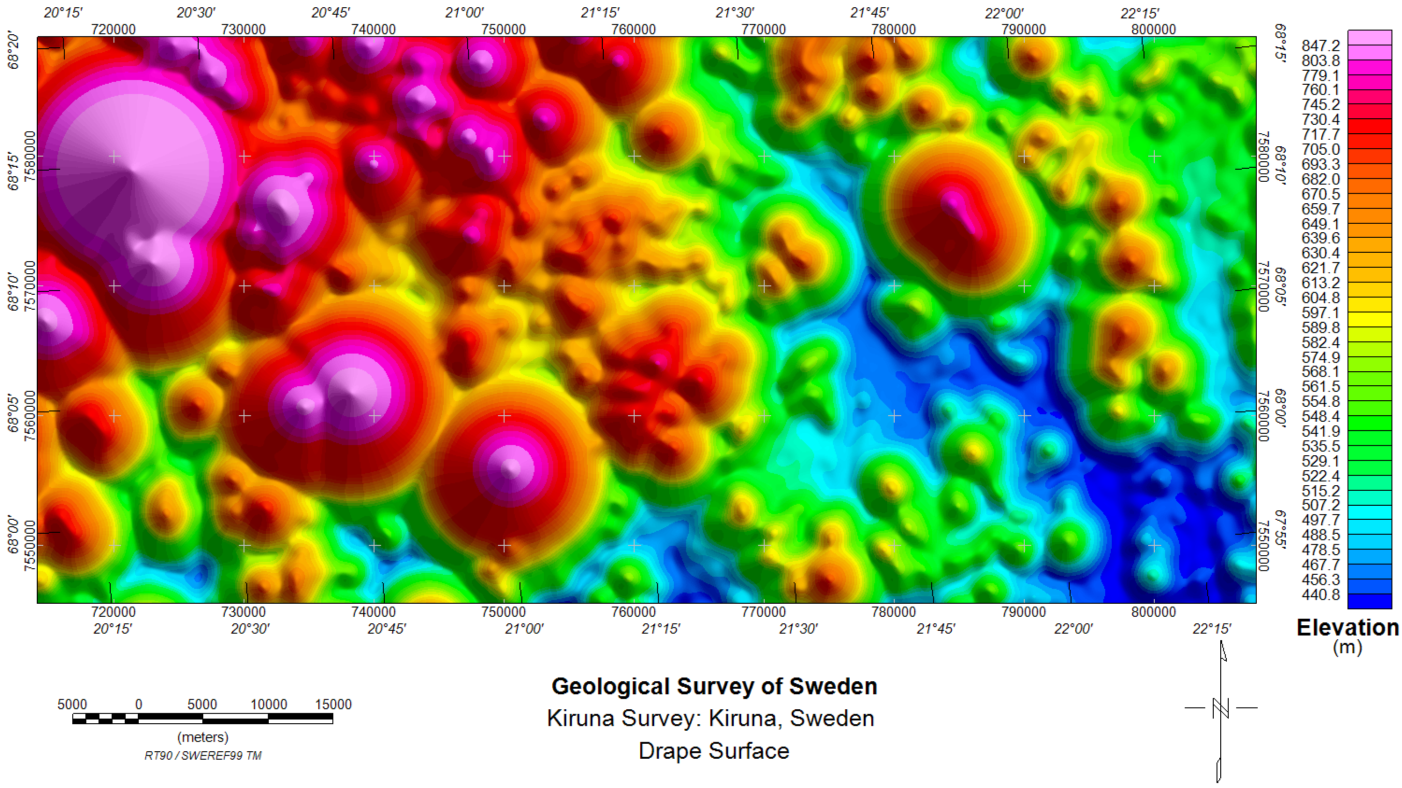


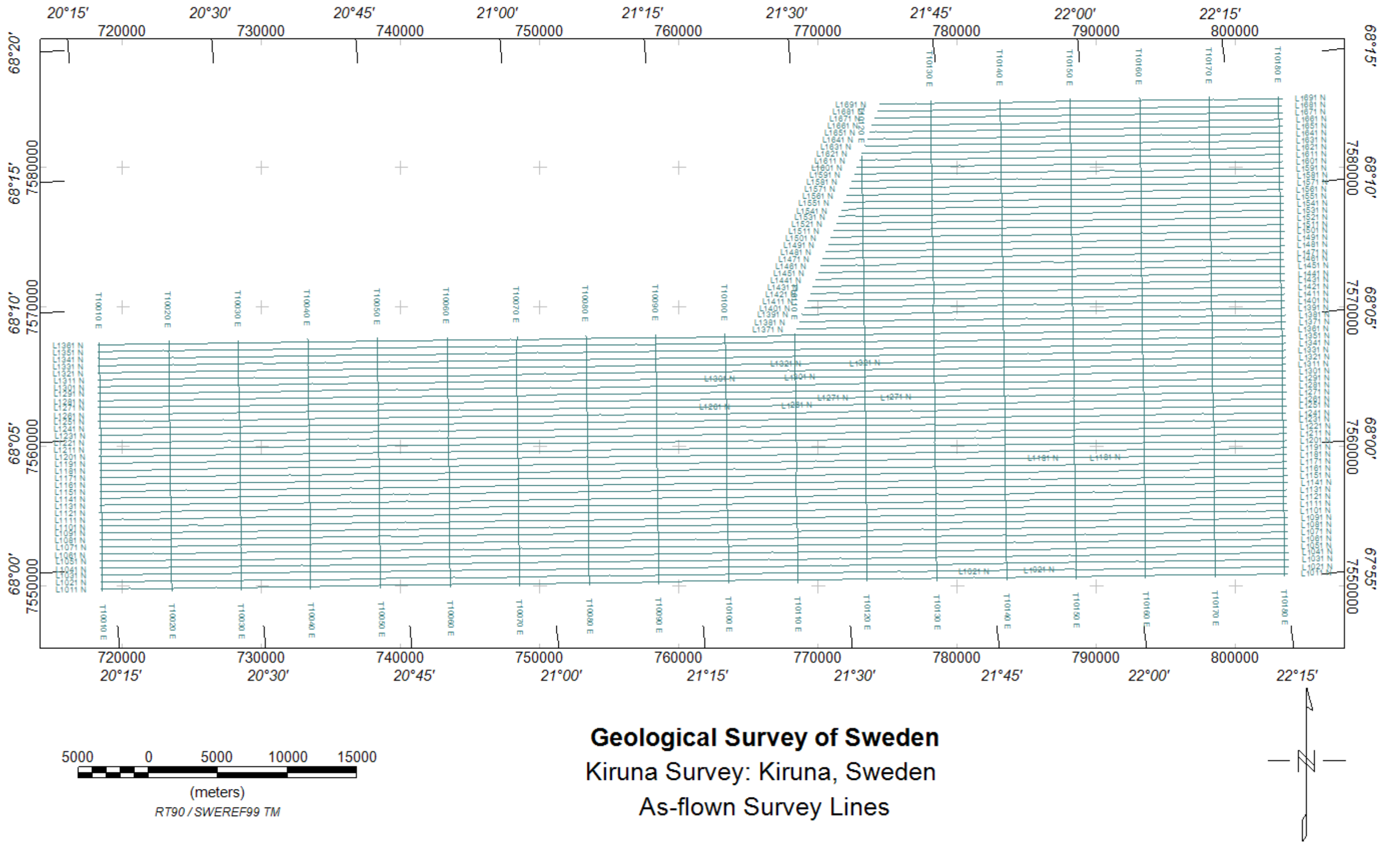
Figure 2.3 – The survey drape surface.



2.4 Flight following:

Line keeping was generally good with some lines re-flown to bring the altitude within the contract specification. Figure 2.2 shows the as-flown line plan.

Figure 2.2 – The 'as-flown' flight lines



3 INSTRUMENTATION, PERFORMANCE & OPERATING PROCEDURES

Bell Geospace operating procedures, instrument details and equipment performance summaries for the acquisition of data for this survey is detailed herein.

3.1 General survey procedure for the acquisition of Air-FTG®:

The FTG data quality is adversely affected by aircraft motion and vibration so flights must take place in calm, cool conditions, with optimal conditions being during the early morning and late afternoon. Turbulence is caused by thermal energy during the day and by wind rolling over the terrain. Acceptable data acquisition is typically viable only if the wind on the ground is under 20 knots.

The crew arrive at the airfield about 40 minutes before planned take off. This allows time for the routine aircraft checks, for any equipment problems to be identified and dealt with, for the weather to be assessed and for the inertial navigation system to be initialised.

Take off is at first light. Once airborne the operator monitors the equipment to check that it is ready for survey. Data recording is continuous from five minutes before starting the first line to five minutes after finishing the last line. The operator is seated close to the FTG electronics cabinet. He liases with the pilots to ensure that the flight is conducted efficiently, keeps a detailed log of events and monitors the system's performance.

An oscilloscope showing the GGI outputs gives a quick-look indication of how well the system is performing. The main FTG screen provides comprehensive quantitative real time performance and status indicators such as GPS status and position, binnacle temperature, pressure and humidity, GGI temperatures and stability of the uncompensated inline and cross gradients. Passive monitoring software records the raw FTG data and can also collect statistics over a selected period of time. The standard deviation of the vertical acceleration during a line is monitored as an effective measure of turbulence. In relatively flat areas where the vertical acceleration changes are mainly due to turbulence rather than terrain following acquisition is suspended if the standard deviation consistently exceeds 100mg. Many parameters monitored by the FTG software have preset operational or safety limits and prominent warnings or error messages are generated if these are exceeded so that the operator can quickly intervene.

The magnetometer displays time series traces of the uncompensated and compensated output and an LED indicates whether or not the sensor is active. Each flight's FTG data is 'high-rate' processed (described in section 4.1) in the field to generate compensated gradient data. The resulting

'SAR' files contain the essential FTG data (navigation and gradients) and can be displayed as profiles and maps in Geosoft's OASIS Montaj either on their own or merged with previous files. This allows in-field checks on line keeping and data quality. The high-rate processing also generates time series, power spectra and statistical plots of environmental conditions, navigation and system performance and suggests adjustments to 'tweak' parameters. The SAR files are compressed and emailed to Bell Geospace offices for further analysis and processing.

3.2 Lockheed Martin Full Tensor Gradiometer (FTG):

3.2.1 FTG description and operating procedures:

The FTG unit used on this project, FTG-2, is one of three owned by Bell Geospace. They have a history of performing well during several years of marine survey work and in airborne surveys since being upgraded in 2003.

The FTG comprises three gravity gradient instruments (GGIs) mounted on a stabilised platform. The platform is housed in a closed 'binnacle' in which the air temperature, humidity and pressure are tightly controlled. The platform has roll,- pitch and azimuth gimbals that are torqued, in response to gyro and navigation information, such that the frame holding the GGIs is always level and faces a constant operator-selected heading regardless of aircraft motion. The binnacle is isolated from high frequency vibrations (above 5Hz) by pneumatic mounting pads and accelerometers and gyros within the platform continually measure motion data that is used to compensate for rotations that affect the gradient data.

The GGIs are based on pairs of accelerometers mounted 10cm apart on opposite sides of a disk rotating at 0.5Hz. The accelerometers in a pair are aligned so that they are only sensitive in the direction of travel around the axis and are sensitive in opposite directions. There are two pairs of accelerometers in each GGI and their output is summed; if they are perfectly matched, unless there is a gravity gradient or a rotation of the whole assembly, the net output will be zero. A gravity gradient results in a difference in the gravity field over the 10cm distance between the accelerometers and causes a non-zero output. Rotation causes the paired accelerometers to move at different rates. As the output is indistinguishable from a gradient, rotations, being independently measured by the platform gyros, can be isoloated and their effect removed in processing. The main advantage of a gradiometer over a gravimeter (a single accelerometer) is that translations affect the accelerometers in a pair equally and are naturally cancelled out.

The three GGIs are mounted orthogonally and between them can measure all nine components of the gradient tensor. Only five components are independent and the redundancy offered by this configuration allows for improved noise suppression in processing over a single-GGI system.

The matching between the accelerometers is key to the GGI performance. Non-linearity in their responses and off-axis sensitivity are controlled by several parameters set in the controlling software. Despite being tightly regulated by heaters and being housed in sealed units the GGIs are sensitive to temperature pressure and humidity changes and as these cannot be compensated for analytically they must be minimised by controlling the environment in the binnacle.

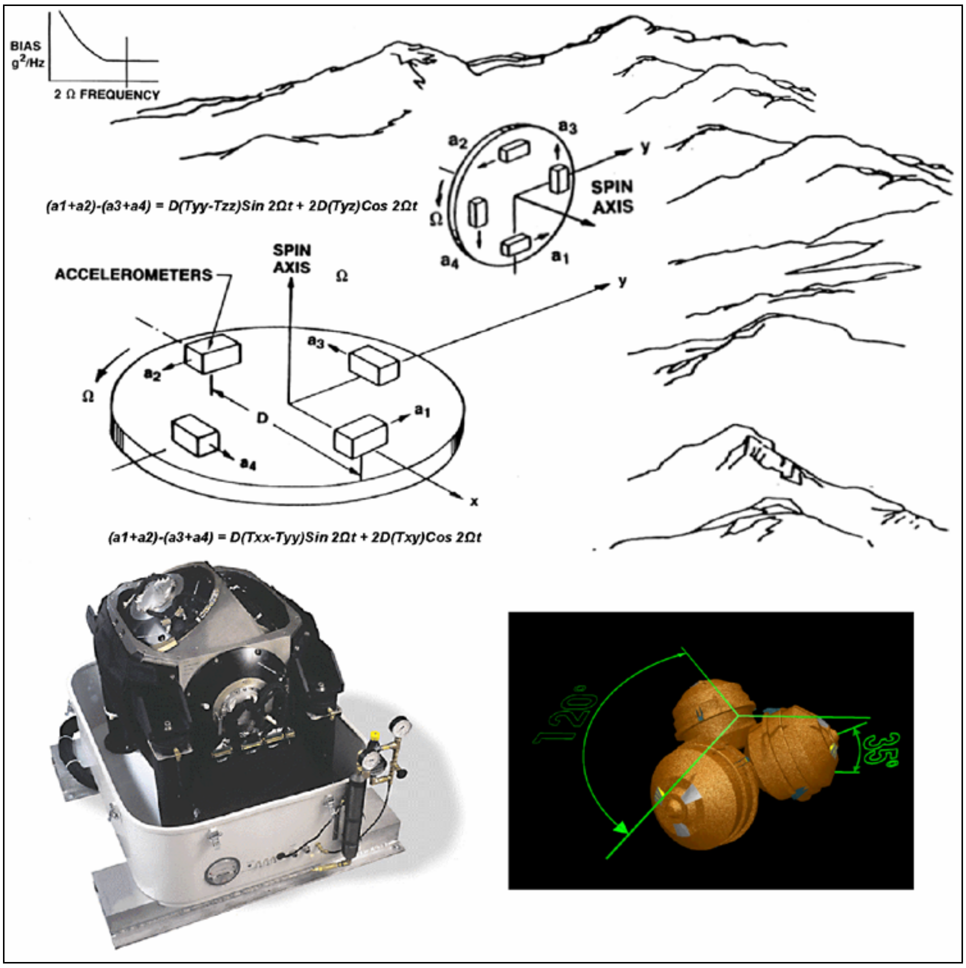


Figure 3.1: Schematic diagram of GGIs showing their sensitivity to gradient tensor components, a photograph of the binnacle with the cover removed to reveal the roll gimbal, and a diagram showing the relative positions of the GGIs.

During normal operations the FTG is kept running continually. Uncontrolled shutdowns, for example due to power failure, cause loss of temperature control and deactivate the electromagnetic fields constraining the GGI accelerometers. Once restarted the GGIs generally require recalibration, ensuring that the system runs continually is an important responsibility of the field crew.

Figure 3.2: FTG1 installed in C-FTGX.

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 an East-North-Down coordinate system with x and y in the plane of the earth's surface and z perpendicular to that plane downward towards 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.

3.2.2 FTG calibration:

The FTG platform and inertial navigation system and the GGIs (gravity gradient instruments) are calibrated according to standards set out by the manufacturer, Lockheed Martin. They are performed under still conditions, preferably in a hangar, after installation or significant changes in the system configuration.

The platform calibrations ensure that the FTG platform is correctly oriented and that the accelerometers and gyroscopes used for inertial navigation and platform stabilisation are accurately aligned and scaled. This is essential for good platform stability and in order to be able to accurately convert the gradient data from the GGIs' internal reference frame to real world coordinates.

GGI calibrations calculate instrument alignment and scale factors and correct for local system and in-aircraft gradients. Any significant bias in the raw gradients is removed by resetting to prescribed values. The calibrations also result in GGI parameters that are used in the high rate data processing to optimise gradient calculation.

3.2.3 FTG performance:

All calibrations passed in accordance to Lockheed Martin and Bell Geospace requirements and the FTG performed well throughout the project. The very high vertical acceleration environment in the survey area noticeably affected the raw data quality but that is a normal response. Although processing techniques can greatly reduce the noise it is still necessary to limit the turbulence experienced by flying in good weather conditions or by maintaining higher ground clearances.

3.3 Magnetometer:

3.3.1 Magnetometer description and operating procedure:

The magnetometer system comprises the airborne magnetometer and a base station. The airborne system measures total field using a Geometrics 882 caesium vapour sensor mounted in a boom (stinger) extending from the aircraft tail. Data is recorded at 10Hz and compensated in real time by an RMS DAARC500 data acquisition system. As the survey area is close to the equator, where the field lines are roughly parallel to the Earth's surface, the sensor is only sensitive in some headings.

The base station, used to monitor diurnal variations in the background field, is a Geometrics G-856 proton precession magnetometer. It was situated at a magnetically quiet location within the airport and left to record at 5s intervals.

3.3.2 Magnetometer calibration:

The DAARC500 magnetometer and data acquisition system has an in-built facility for collecting compensation parameters while flying a figure of merit (FOM). The aircraft is flown in the survey line headings and, once the sensor is active and stable and the DAARC shows that it is ready, the pilots perform 20s each of roll (±10º) pitch (±5º) and yaw (±5º) manoeuvres. Because at tropical latitudes the sensor loses sensitivity during turns the FOM was split into partial calibrations. The DAARC500 produces a recursive least squares solution that improves if successive FOMs are flown so the calibration was repeated. Finally a verification FOM was flown whereby the uncompensated and compensated output could be compared.

3.3.3 Magnetometer performance:

The magnetometer system worked reliably throughout the project.

3.5 Global Positioning System (GPS):

3.5.1 GPS description and operating procedure:

The position data was based on differential GPS output from a Novatel ProPak OEM4 receiver connected to a combined L1/L2/RTCM antenna. The differential corrections, provided by Trimble OmniSTAR's XP service, are applied within the receiver and typically 95% of positions are accurate to around 10cm. The OmniSTAR VBS service, accurate to around 1m, is suitable for FTG surveys.

The pilots are guided by an PicoDAS navigation system that reads the aircraft's GPS position and compares it to the planned line and drape. A simple and intuitive display mounted on the dashboard shows the pilots where they are relative to the line.

The FTG incorporates a sophisticated inertial navigation system that uses a Kalman filter to combine the relatively low-rate differential GPS data with high rate precise motion and attitude input from the platform gyroscopes and accelerometers. This results in an accurate record of the FTG positions but also provides the high-resolution motion data required to maintain platform stability and compensate the gradient data in post-processing. The FTG data is time-stamped with GPS and UTC times allowing it to be merged with other data sets.

The GPS positions are also recorded by the DAARC500 data acquisition system along with the magnetometer and radar altimeter data.The 1PPS output from the GPS receiver is used to precisely synchronise positions with the FTG and DAARC500 data.

3.5.2 GPS performance:

A daily check on GPS repeatability was made by recording fifteen minutes of data with the aircraft parked at roughly the same location and producing statistics for the file. The positioning system worked reliably throughout the survey and there was no indication of problems in the data.

4 QUALITY CONTROL

4.1 FTG on-board quality control:

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 monitored 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 on-site off-line analysis of the data. In addition to the on-board QC checks, final survey data is sent to Bell Geospace offices 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 aircraft leaves the survey area.

4.2 Magnetometer on-board quality control:

The magnetometers on-board RMS DAARC500 data acquisition system incorporates a real time display of sensor output and compensator output. Outputs are ideally displayed as straight, or near straight signal lines. Field crew particularly monitor this display for survey points at which the outputs being to exhibit spikes. Such spikes indicate that a problem exists in the data collection which may compromise magnetometer data quality. However, this is not used for real-time quality control of data in the field, but is noted in the field logs for the benefit of the data processing team should a problem with the acquired data be observed at the processing stage.

4.3 GPS on-board quality control:

The FTG data post-processing produces several quality control plots including a time series of the number of GPS satellites seen. Typically eight or more satellites were used in the solution.

If there is uncertainty in the FTG position (the Kalman filter output) the platform gyroscopes generally over-correct in response. The operator monitors the correction rates in real time and if they exceed maximum values the platform attitude and possibly position is assumed to be uncertain and no survey data is recorded. A time series plot is reviewed after each flight to check that the platform was stable throughout but the problem is reliably avoided by following procedures that properly initialise the platform before flight.

4.4 Flight following quality control:

The position of the aircraft on each line is assessed against an ideal line plan and smoothed drape surface according to a specified contract specification. A line where the aircraft has been found to deviate horizontally and/or vertically is identified for re-flight. The assessment of flight accuracy is determined during the daily processing stage by Bell Geospace office personnel.

4.5 External quality control of acquired data:

In addition to Bell Geospace's own quality control procedures, where an external quality control agent is required by the client, data is sent regularly as agreed throughout the survey duration. In this instance, no external quality control was requested.

4.6 Environment and Health & Safety:

No major safety incidents were reported during the project, and minor incidents were dealt with according to ERP and HSE plan guidelines. All project personnel completed operations safely, and there have been no reported follow-on medical incidents resulting from Bell Geospace operations at this location.

5 AIR-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 generalised FTG data processing scheme is provided in Appendix 1.

5.1 High Rate Post Mission compensation (HRPMC):

HRPMC is conducted in the field by Bell Geospace personnel. 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 is 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 choose the data sample rate for all subsequent processing and final data. The final sample rate is currently limited to 1 second. 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.

5.2 FTG-specific line corrections:

This step calculates the tensor components from the measured inline and cross data sets 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 stabilised 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. Feedback 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 synchronised and time stamped with the GMT time at one second intervals. The dGPS 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 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 very little line error evident.

5.3 Final line levelling:

After the FTG data is levelled and bulk corrected, some small miss-ties at line 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 miss-ties and noise, a low-pass Butterworth filter usually between 0.5 and 1 kilometre in length is applied and miss-ties are calculated at every line intersection. The miss-ties in the filtered data are analysed on a line-by-line basis. Each GGI component is shown in profile form with intersection miss-tie information from crossing lines displayed as well. In most cases the largest miss-ties 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 miss-tie. 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 miss-ties are calculated and analysed 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 miss-ties and applying a successively higher order fit to the data until the miss-ties 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 miss-tie adjusted, unfiltered data. The unfiltered data can then be mapped without any apparent line oriented error. Tensors are computed from the levelled GGI data and gridded and examined for remnant errors. Often another pass through the GGI signals is needed to produce the best tensor data possible.

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

5.4 Full Tensor Noise Reduction (FTNR):

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 FTNR is the wavelength cut-off. This is the minimum wavelength that FTNR 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 FTNR runs may be performed with various cut off wavelengths. Data presented for this product is "FTNR1000" with a cut-off wavelength of 1000 m.

5.5 Variable Density Terrain Corrections

After the FTNR process the complete dataset is corrected for Terrain using an inferred density distribution – represented in the file names as 'vTC'. The method investigates for correlation between the Free Air measured FTG response and a forward modelled FTG response of the input DTM (for unit density, 1/0g/cc) by making use of signal wavelet processing techniques. It quickly identifies areas of locally higher relative density (topographic highs) from areas of low relative density and applies the correction.

The final output is a variable Terrain Correction.

5.6 Products: Air-FTG® Free-air, levelled

Figure 5.1: Free Air Txx, Levelled

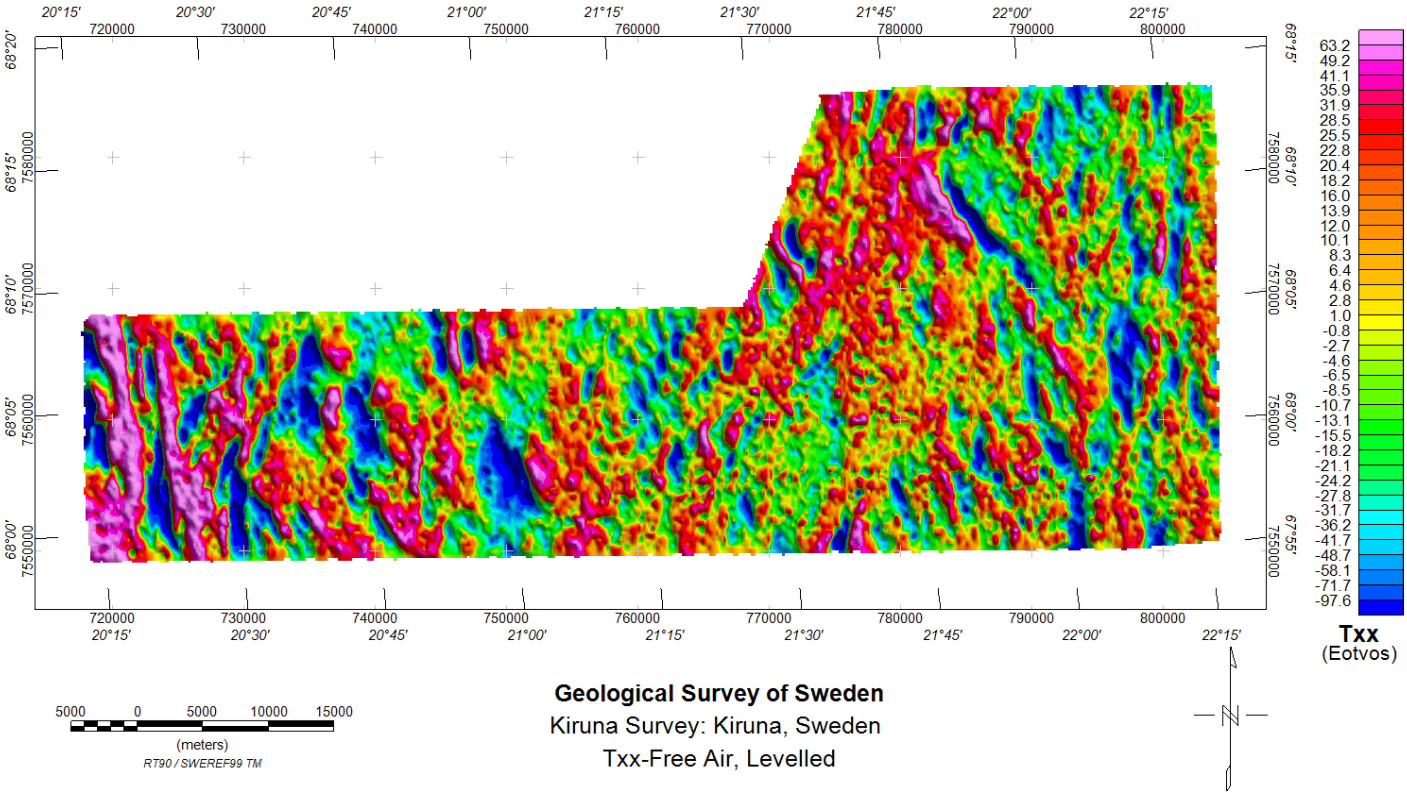


Figure 5.2: Free Air Txy, Levelled

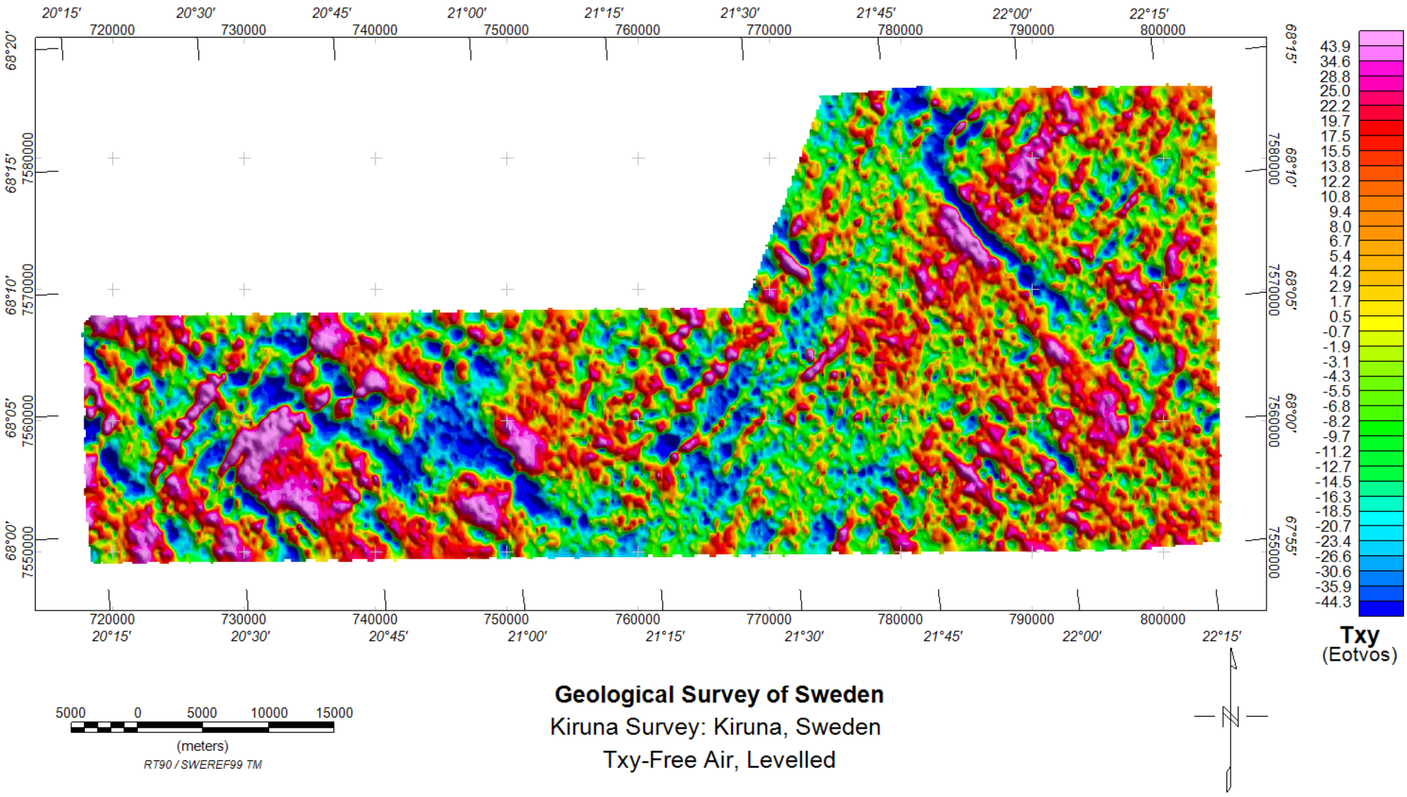


Figure 5.3: Free Air Txz, Levelled

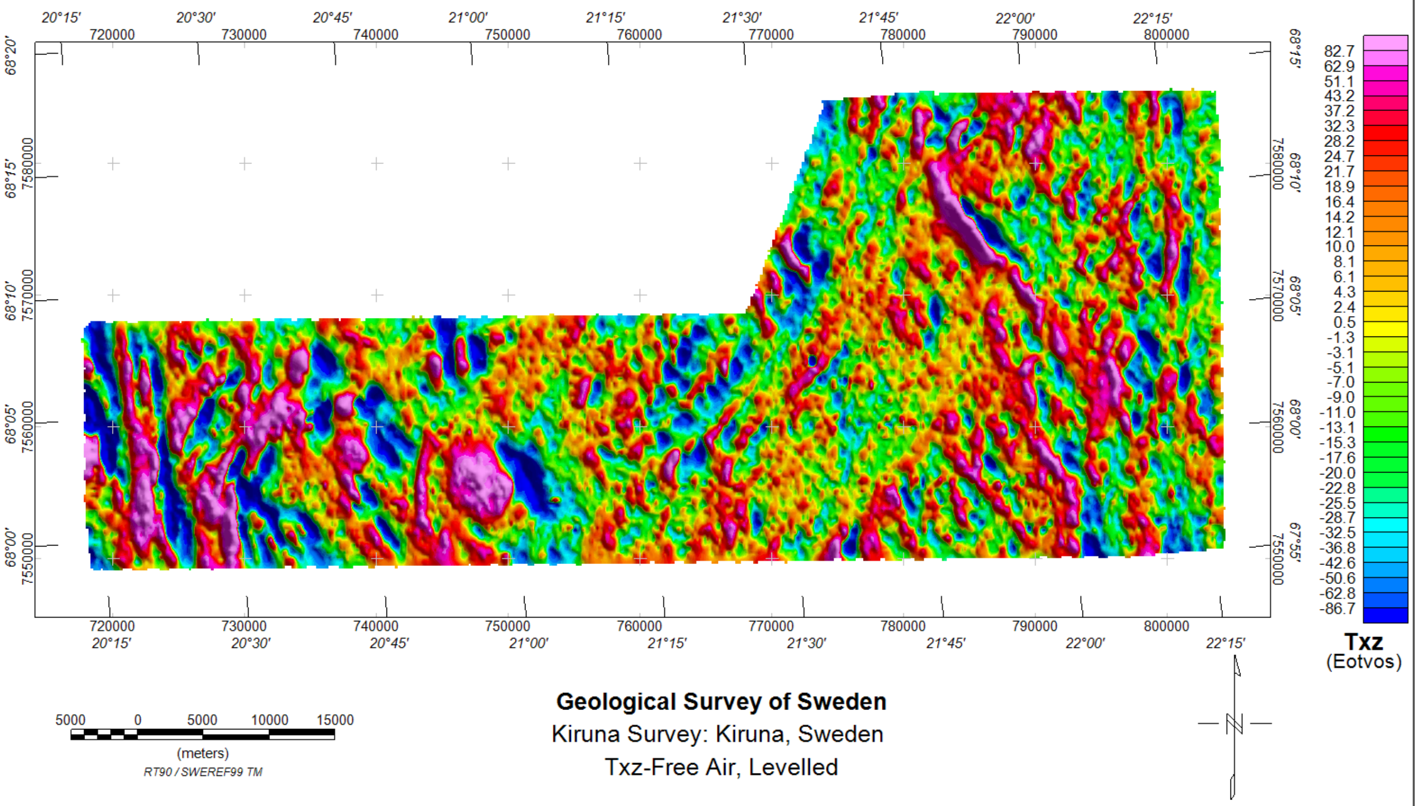


Figure 5.4: Free Air Tyy, Levelled

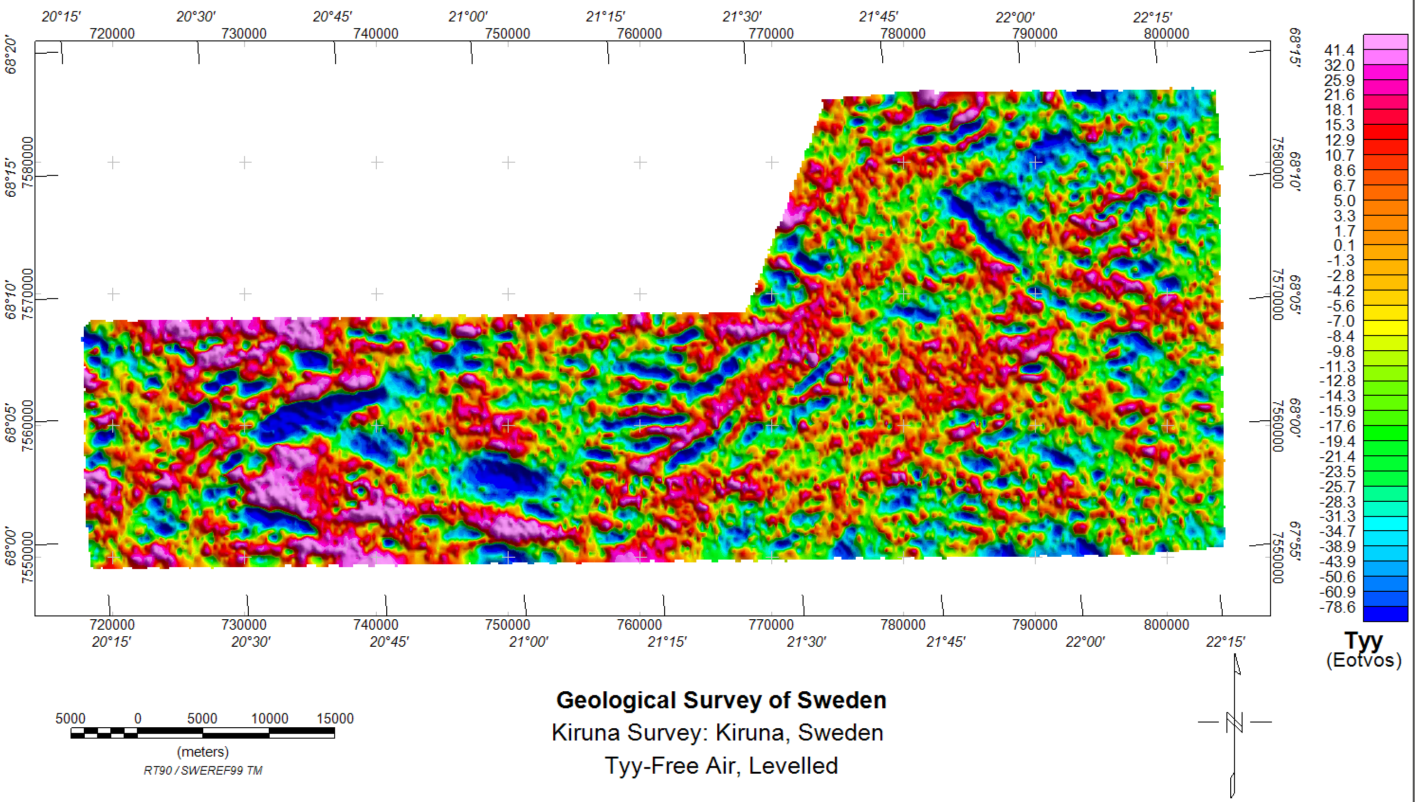


Figure 5.5: Free Air Tyz, Levelled

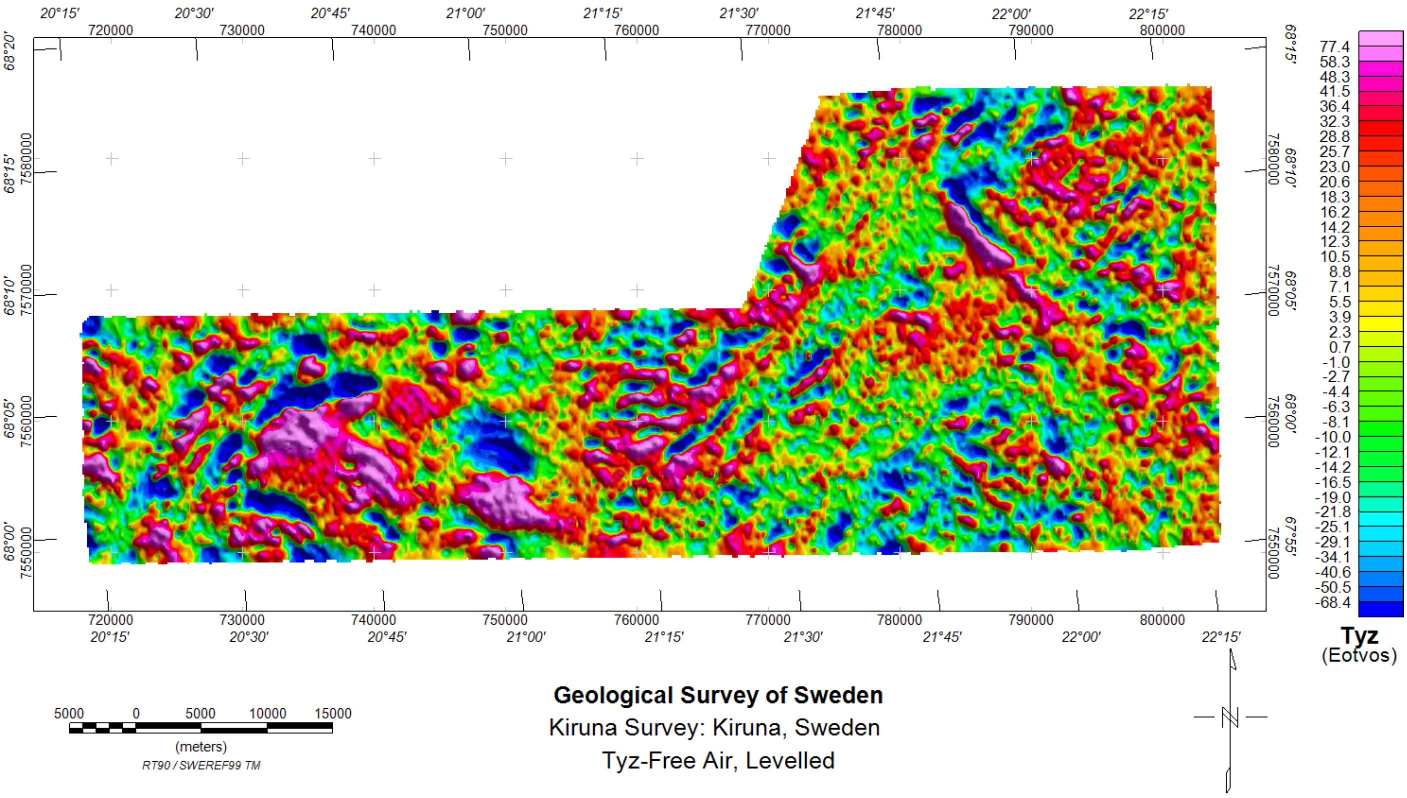
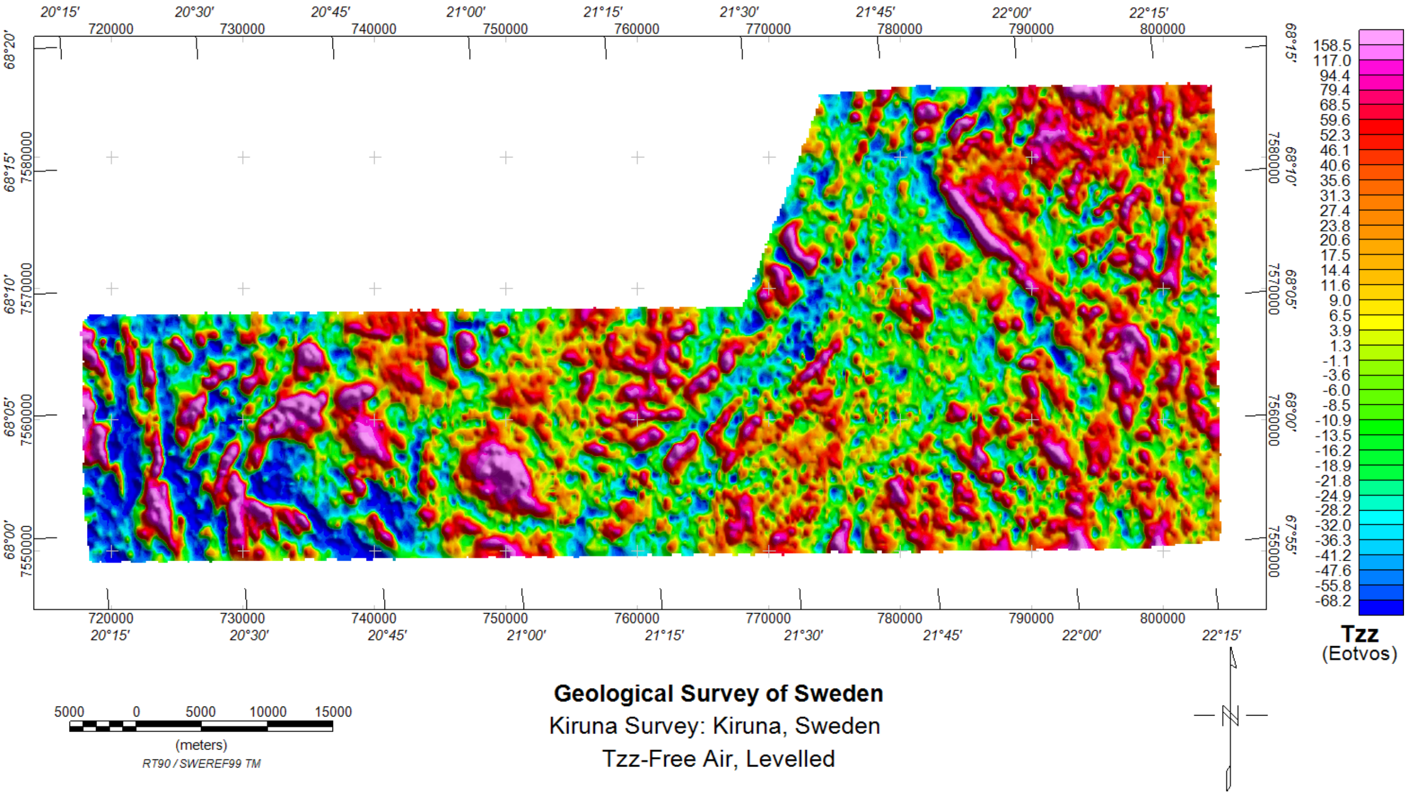


Figure 5.6: Free Air Tzz, Levelled



5.7 Products: Air-FTG® Free-air, levelled, FTNR

Figure 5.7: Free Air Txx, Levelled, Full Tensor Noise Reduction

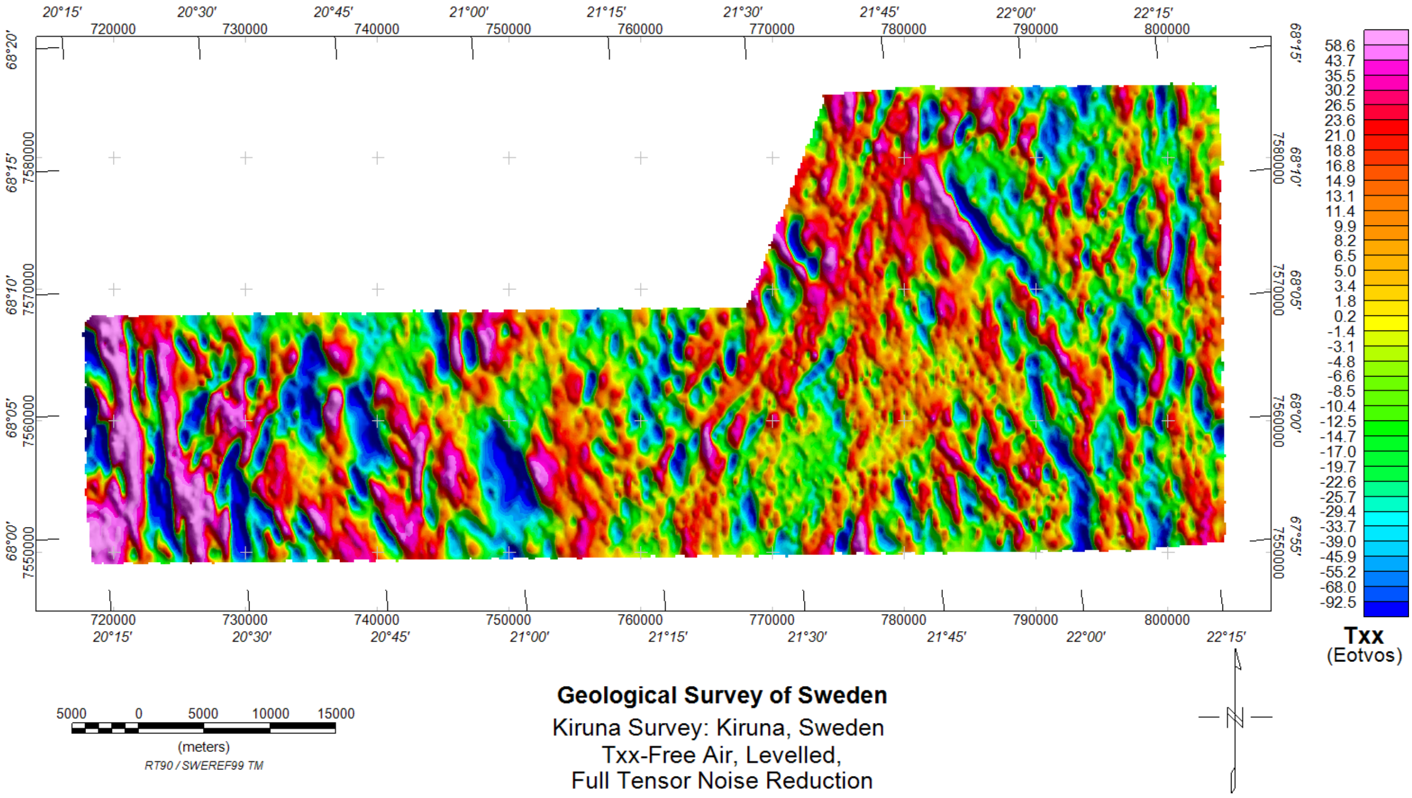


Figure 5.8: Free Air Txy, Levelled, Full Tensor Noise Reduction

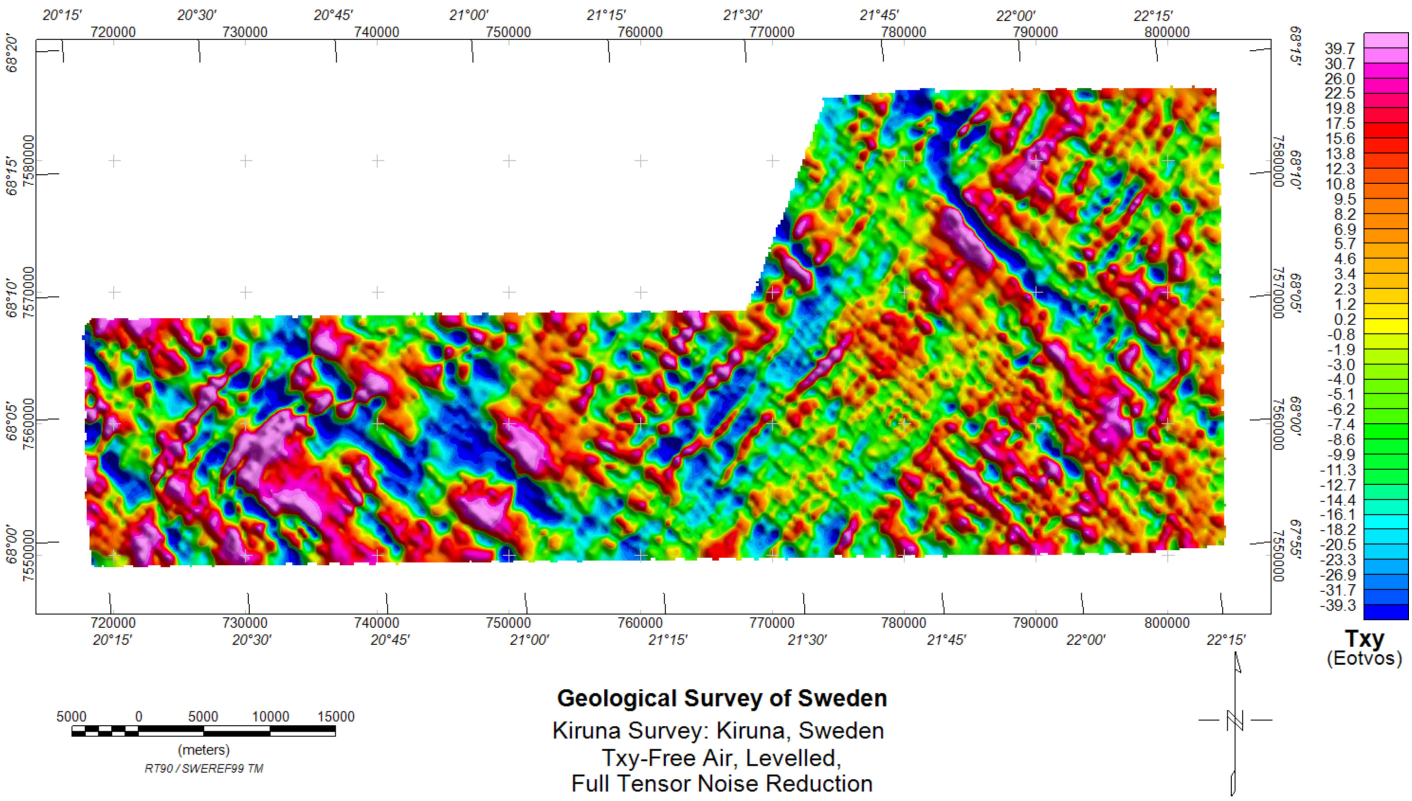


Figure 5.9: Free Air Txz, Levelled, Full Tensor Noise Reduction

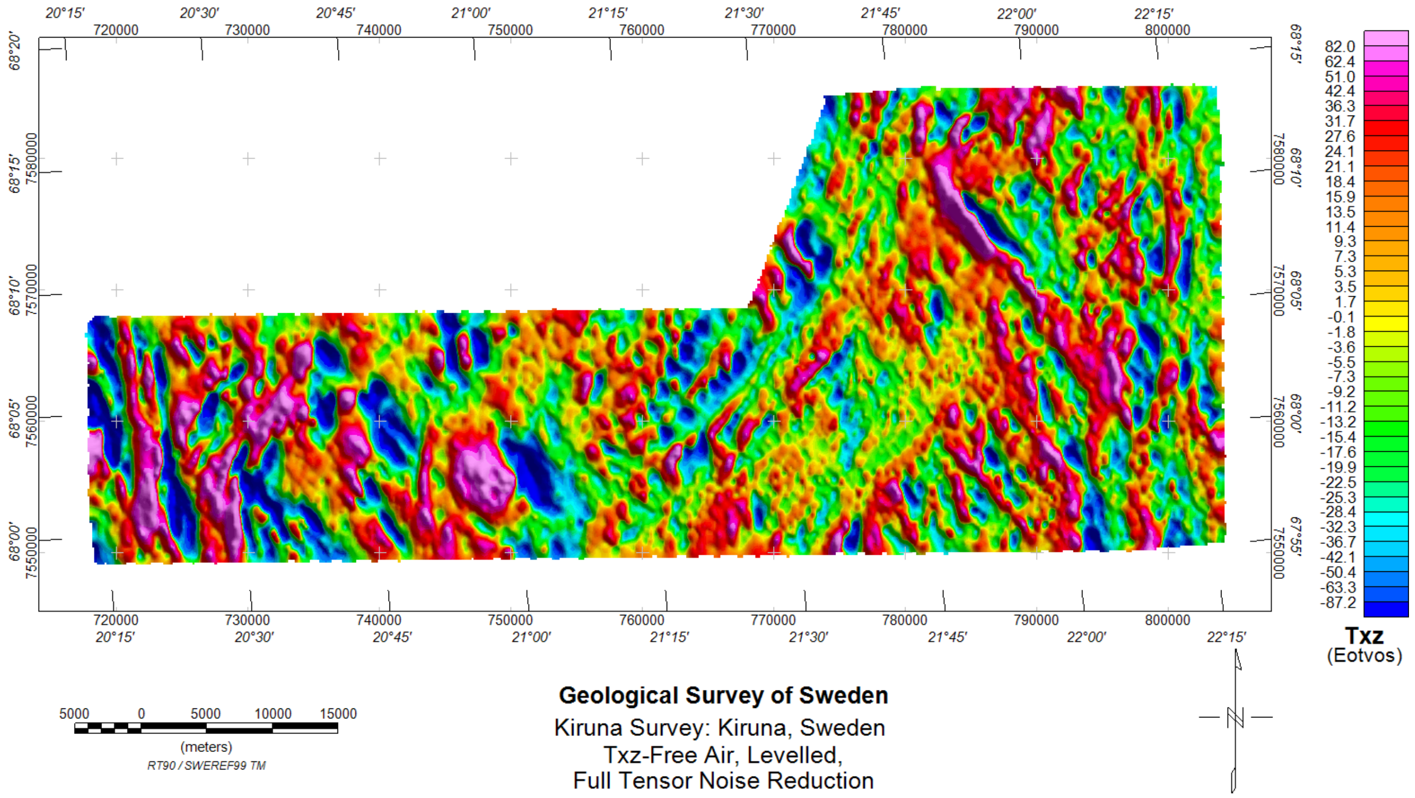


Figure 5.10: Free Air Tyy, Levelled, Full Tensor Noise Reduction

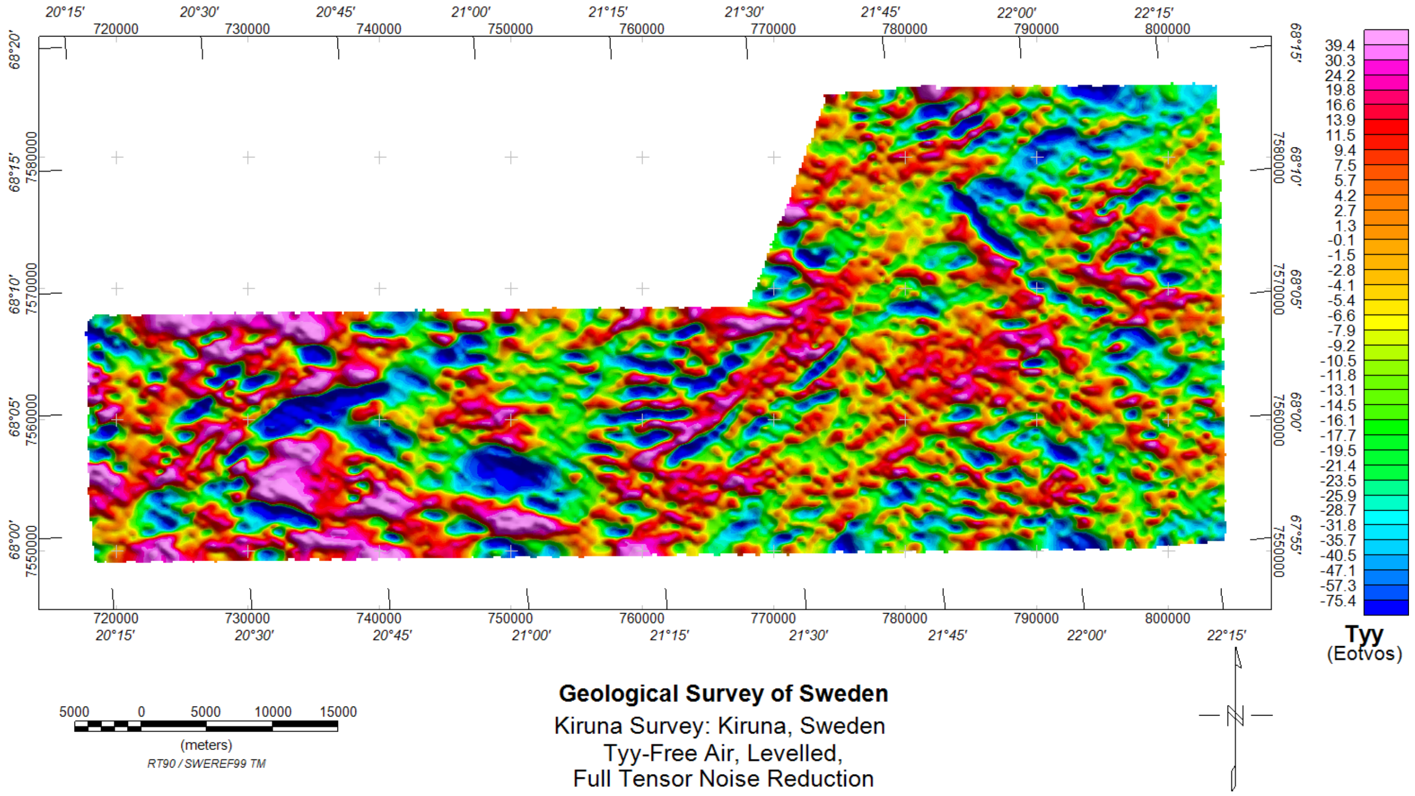


Figure 5.11: Free Air Tyz, Levelled, Full Tensor Noise Reduction

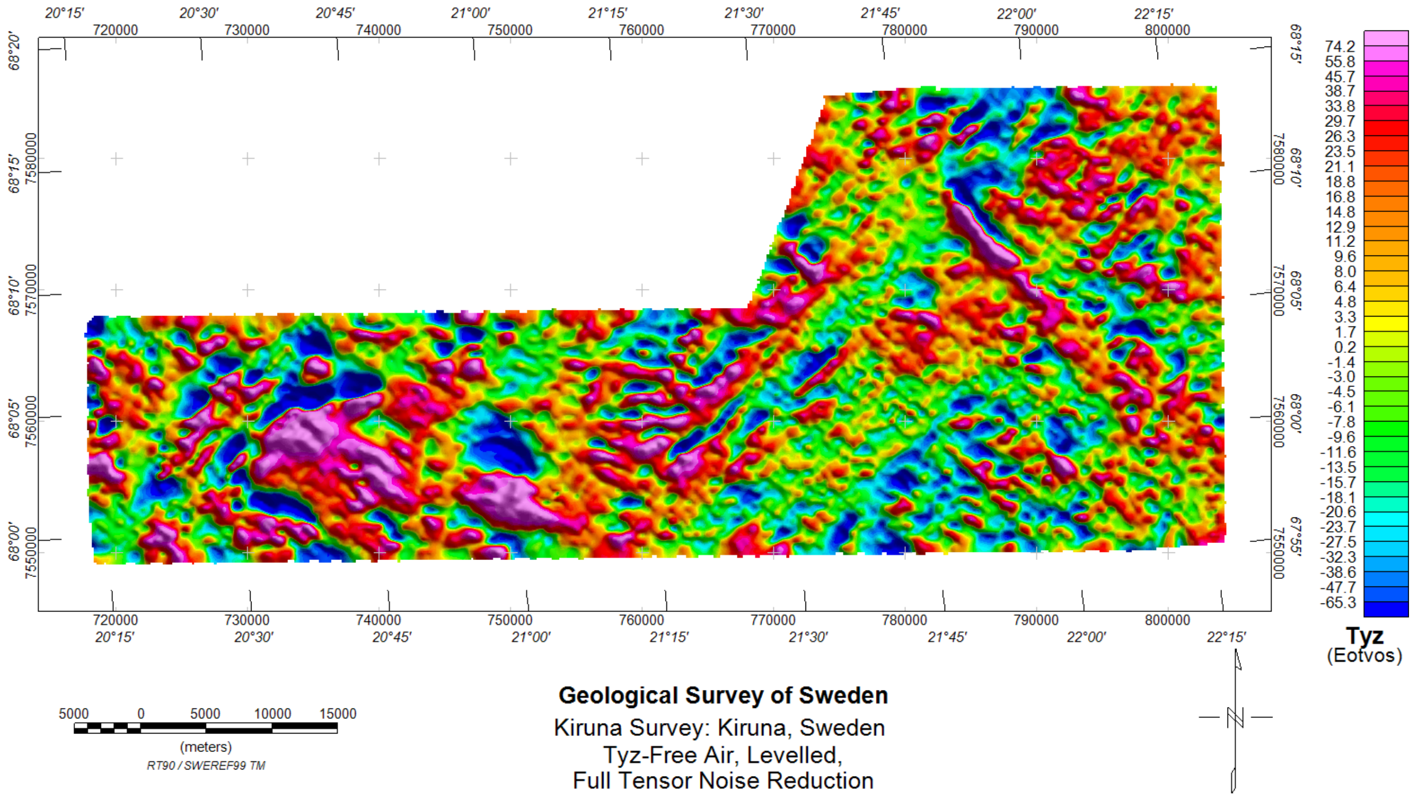
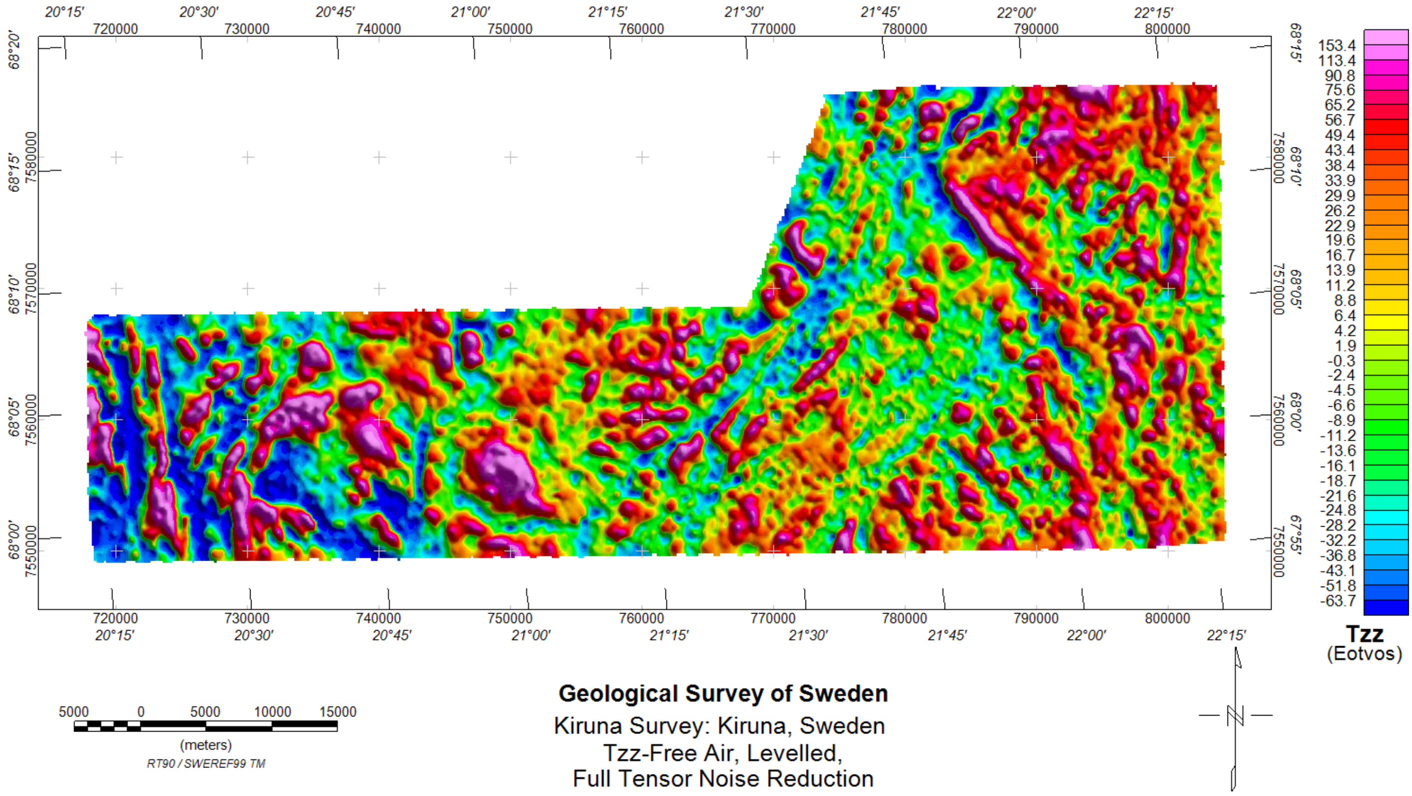


Figure 5.12: Free Air Tzz, Levelled, Full Tensor Noise Reduction



5.9 Products: Air-FTG® Free-air, levelled, FTNR, variable Terrain Corrected

Figure 5.13: Terrain Corrected Txx

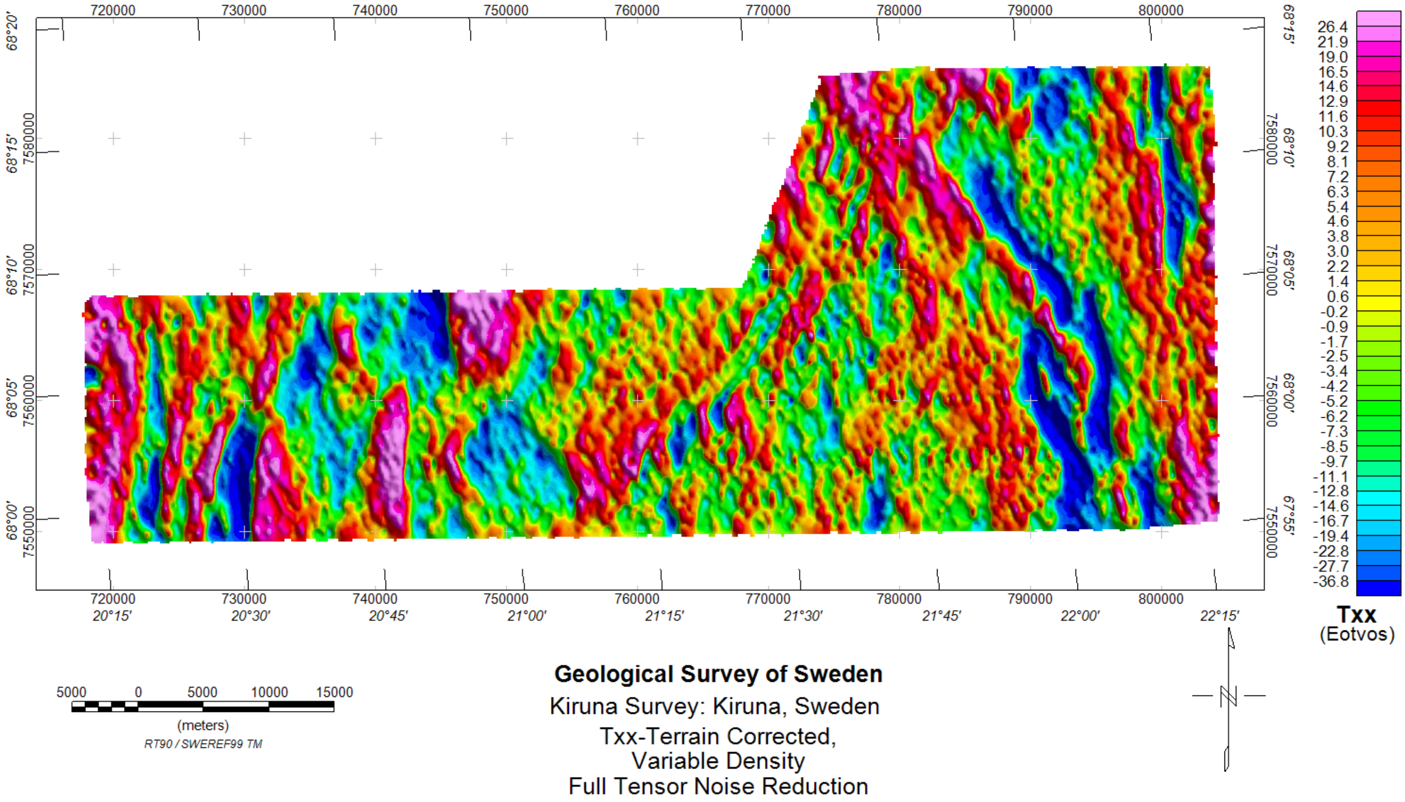


Figure 5.14: Terrain Corrected Txy

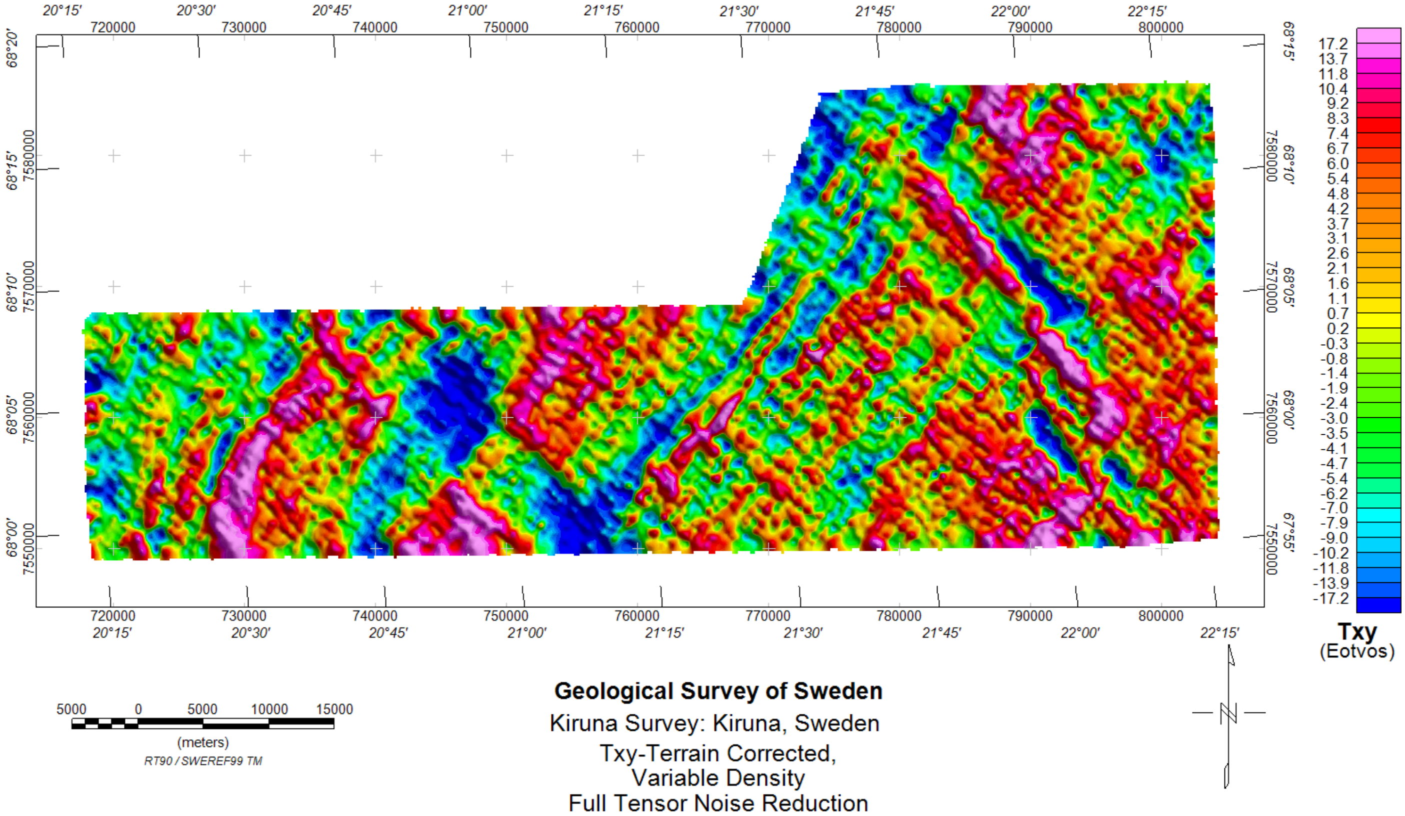


Figure 5.15: Terrain Corrected Txz

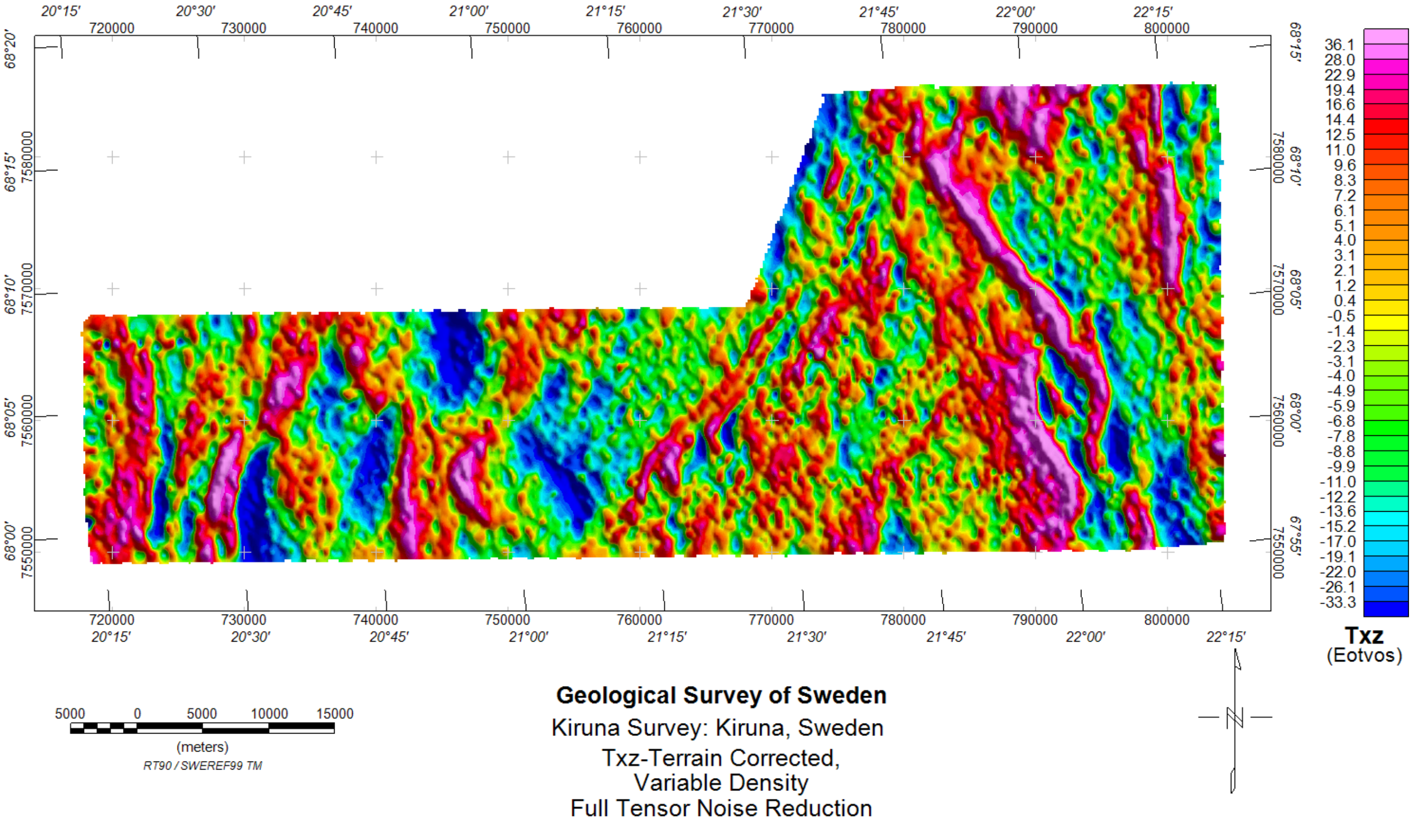


Figure 5.16: Terrain Corrected Tyy

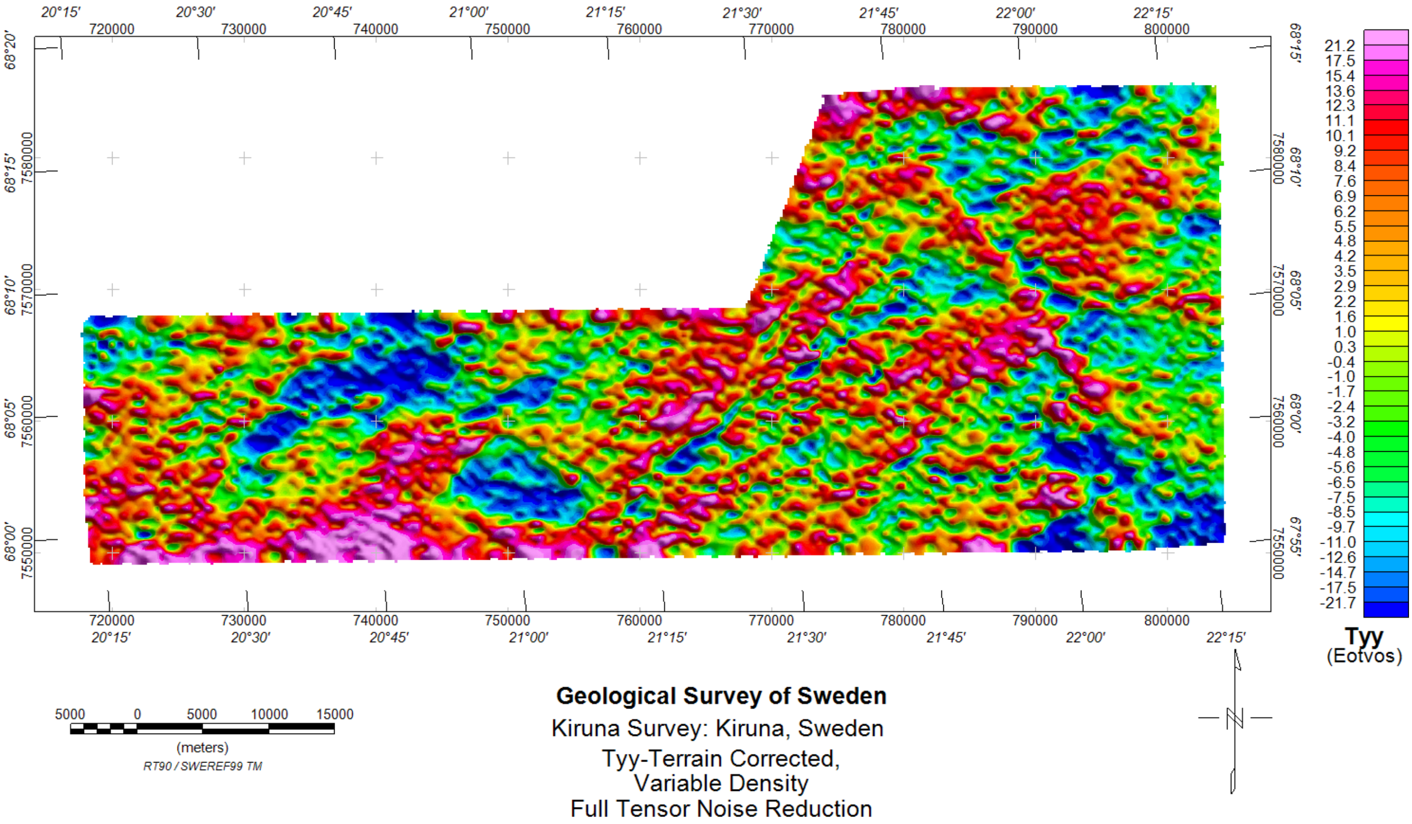


Figure 5.17: Terrain Corrected Tyz

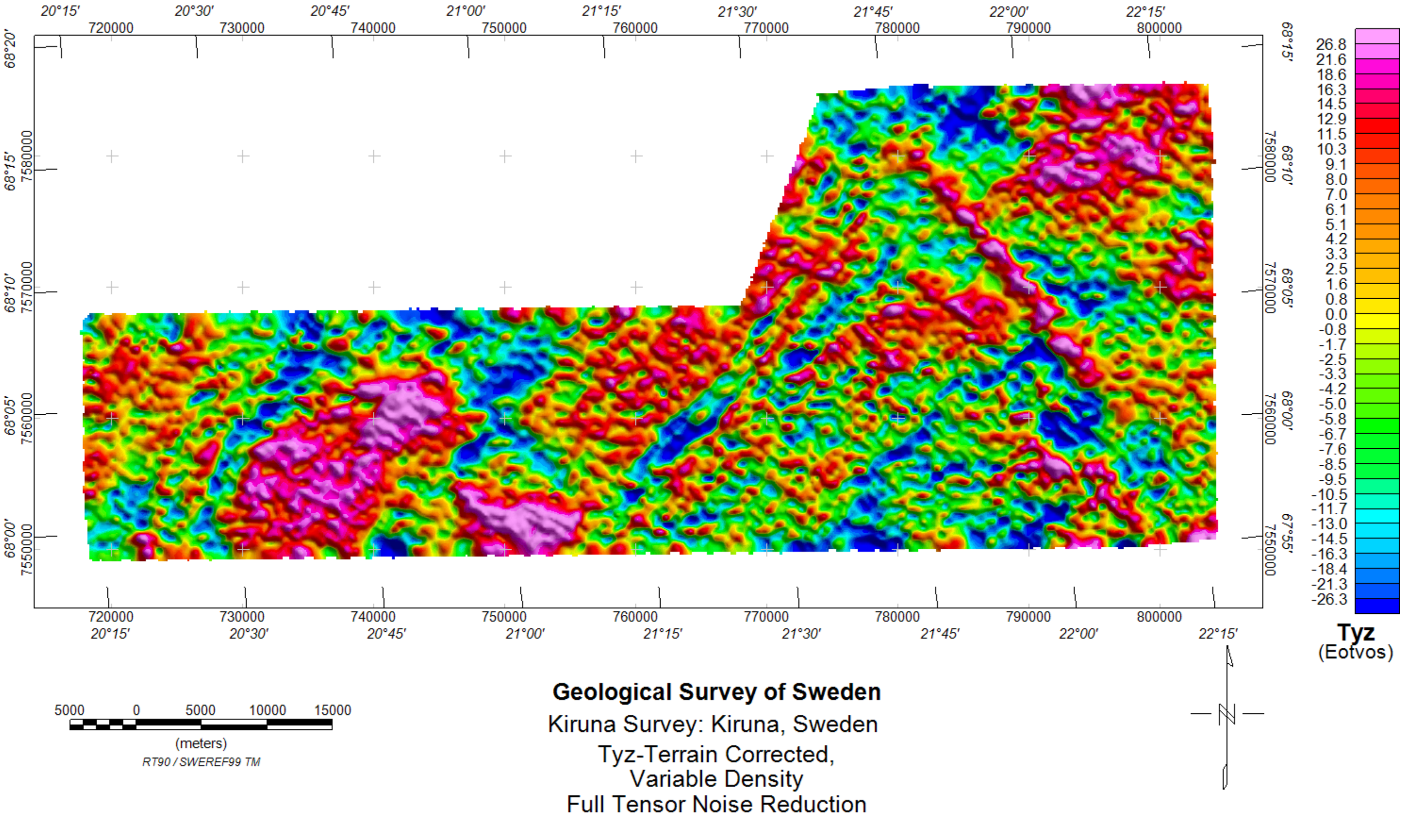
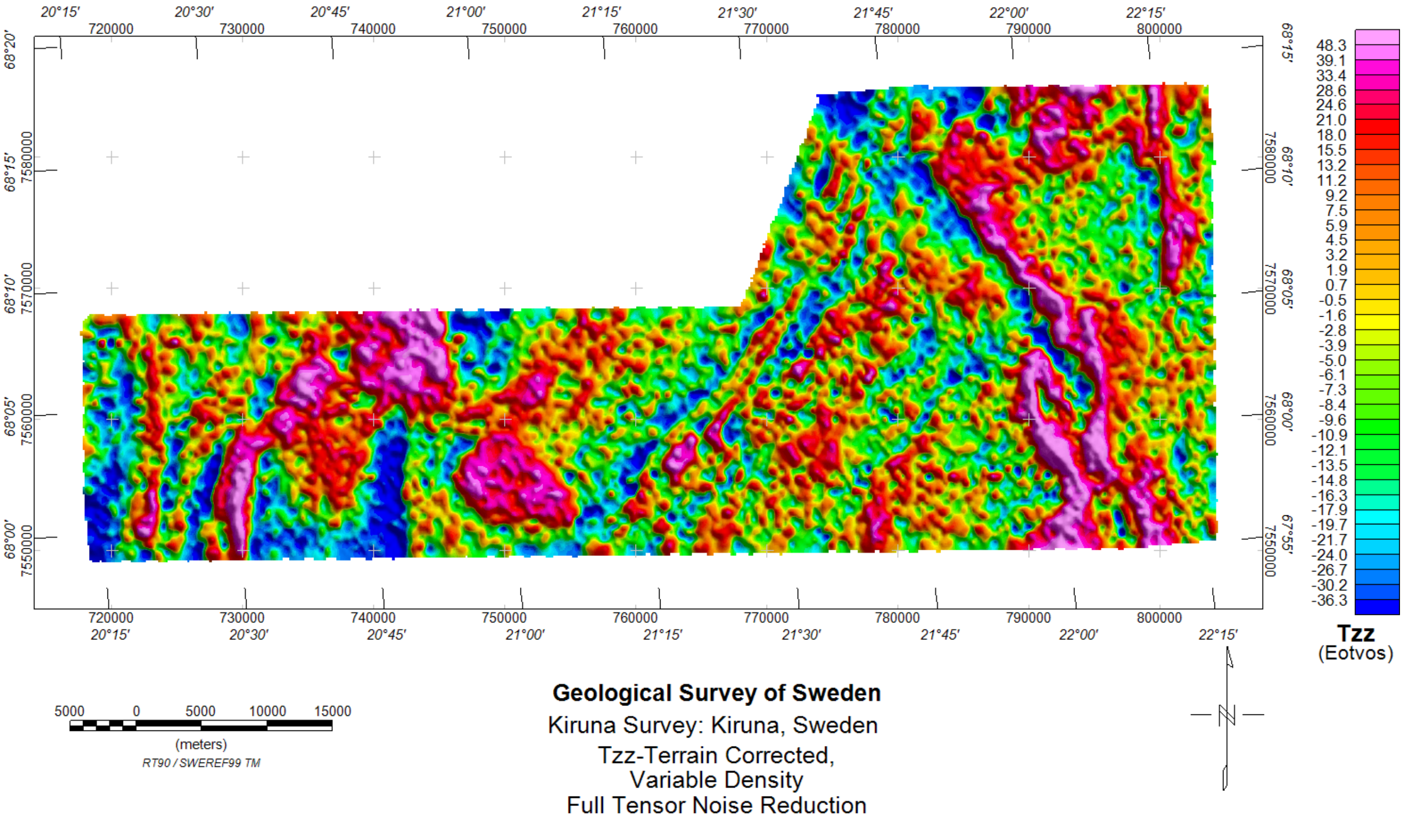


Figure 5.18: Terrain Corrected Tzz



6 AEROMAGNETIC DATA PROCESSING

6.1 Earth's field removal:

To better isolate local anomalies, Earth's regional magnetic field is removed from the survey data. Earth's field is computed using Geosoft Oasis Montaj. The IGRF Tables from year 2010 were extrapolated to the time, date and acquisition height of the survey. The IGRF was removed from the compensated data prior to final line levelling.

6.2 Removal of the magnetic diurnal drift:

The Geomagnetic field changes with time, this change in time is referred to as the diurnal drift. Typically, a base station magnetometer is used to record the total magnetic intensity (TMI) at a stationary point in order to determine the diurnal drift. The magnetic base station data is subtracted from the measured TMI data recorded from the aircraft.

The magnetic base station records data continuously at 5 second intervals while the aeroplane is on survey. The system is started prior to take-off and the data is retrieved after the aeroplane has landed. A 30 second low pass filter is applied to the base station data prior to the subtraction of the diurnal drift.

6.3 Final line levelling:

The magnetic data is levelled using Geosoft Oasis Montaj's levelling module in a similar way as the FTG data (see section 5). The magnetic data is shown in profile form with intersection miss-tie information from crossing lines displayed as well. In most cases the largest miss-ties are due to a noise spike on a line near an intersection or remnants of turns from either turning on to or off of a line. Usually the spike occurs over very few data points but still may affect the trace sufficiently to introduce a miss-tie. The erroneous data is either interpolated across, or vertically adjusted for a better fit with the surrounding points. After each component has been edited by this method on every line, the miss-ties are recalculated and analysed again. This procedure is repeated until all obvious errors are removed. After a thorough edit, the data can generally be levelled by the application of low order polynomials or a tensioned spline. This is done in several passes, each time re-calculating miss-ties, and applying a successively higher order fit to the data until the miss-ties are very near zero, and/or well within the noise envelope.

After each polynomial adjustment, the data is gridded and mapped to the screen as an additional quality control step to aid in miss-tie evaluation. 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. This procedure finally produces miss-tie adjusted line data. The levelled data can then be mapped without any apparent line orientation error.

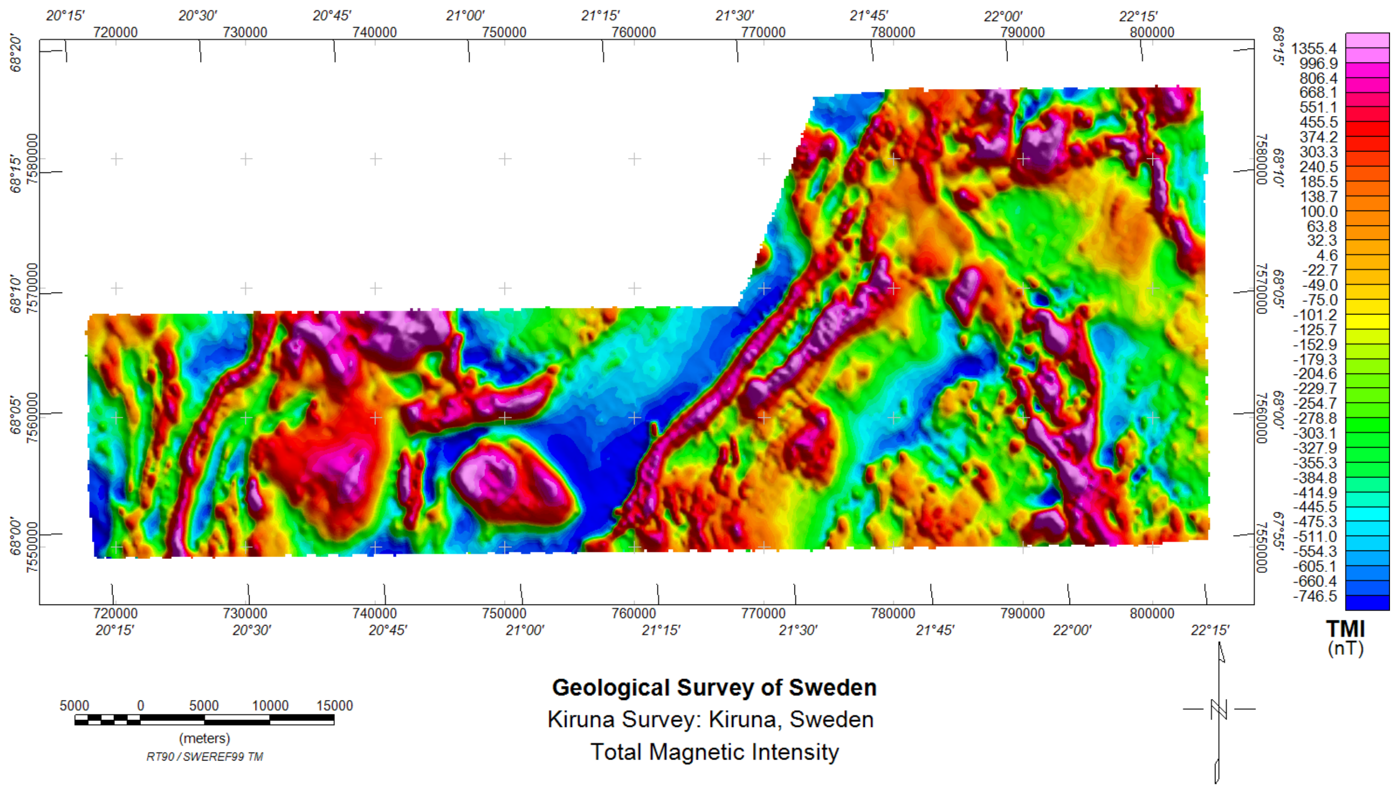
From time to time, residual noise remains in the dataset that the line levelling method cannot remove. Additional improvements can sometimes be achieved through micro-levelling. This is a process in which tie lines are excluded, and the correlation between parallel lines is analysed. The user can specify various filter lengths, tolerances, and other parameters to better address the residual noise that line levelling was unable to remove. This process attempts to remove or reduce various frequencies in each line that are not present in neighbouring 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 the data analysis package Oasis Montaj, by Geosoft.

6.4 De-meaning:

The final step in processing the aeromagnetic data is de-meaning and is largely a cosmetic effect. De-meaning is simply a bulk DC shift of the total magnetic intensity of the entire survey block. The mean value of the final TMI channel for the entire survey is subtracted from the final TMI channel. From a signal processing point of view, this has the effect of removing the DC component of the magnetic data left over from data processing and leaving just a relative AC component.

6.5 Products Main Survey: Total Magnetic Intensity (TMI)

Figure 6.1: Total Magnetic Intensity (TMI)



APPENDIX 1 TENSORS: BACKGROUND INFORMATION

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 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,

$$\mathbf{grad}T = \left[\frac{\partial T}{\partial x}\frac{\partial T}{\partial y}\frac{\partial T}{\partial z}\right] \ \mathbf{or}[Tx\,Ty\,Tz]$$

Then,

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

In the expressions above, Tx, Ty, and Tz represent the familiar acceleration of gravity in the three coordinate directions. Txx, Tyx, Tzx etc, 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 Laplace's equation. 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 A1.1)

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 centre 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 centre 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).

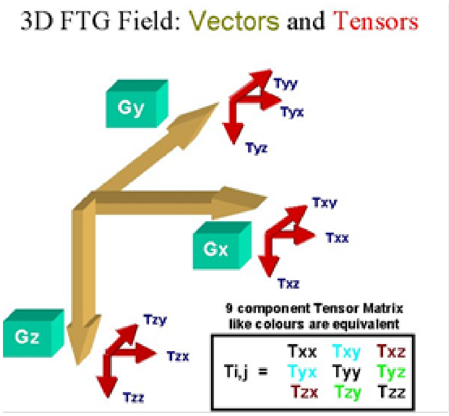


Figure A1.1: Relationship of the gravity vector (Gx , Gy, Gz) to the FTG Tensor

APPENDIX 2 FTG DATA PROCESSING SUMMARY

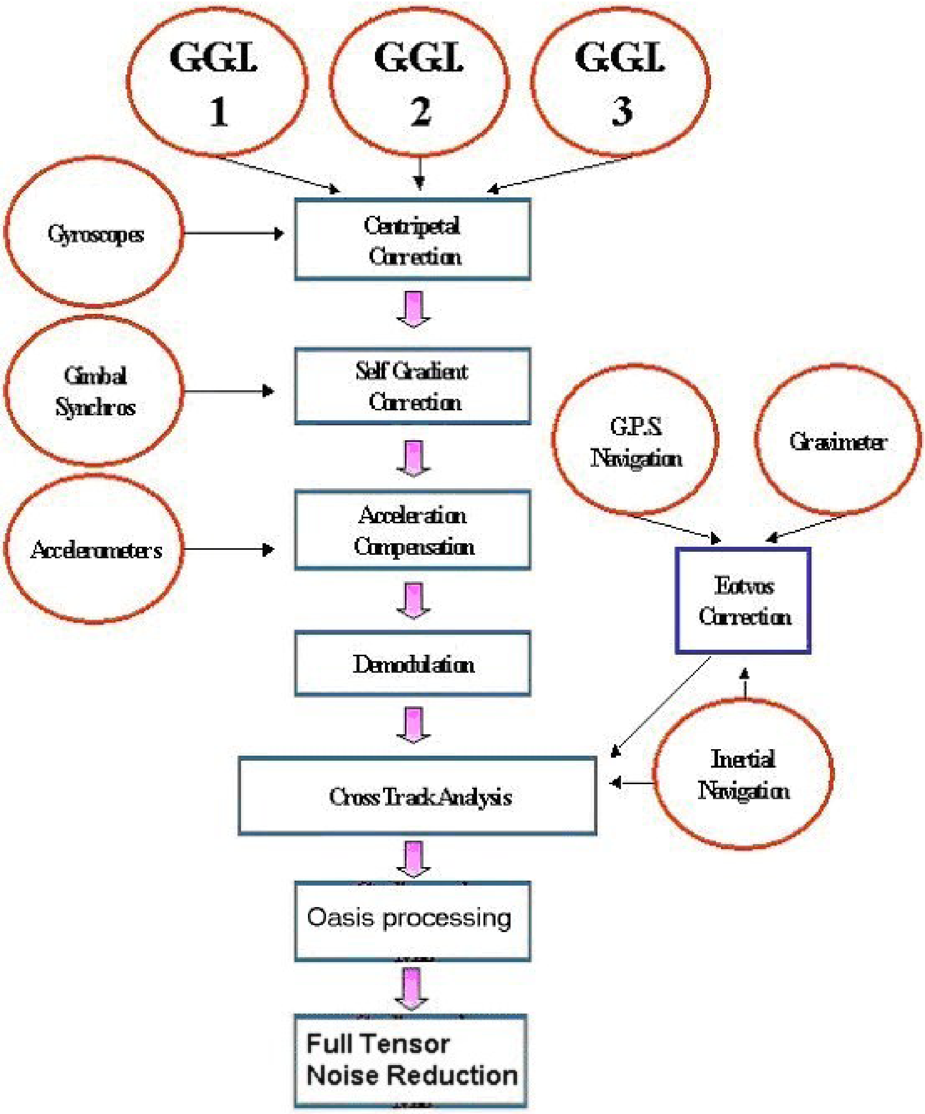


Figure A2.1: A Schematic diagram showing different stages of FTG data processing

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

APPENDIX 3 INTERPRETATIVE PROCESSING SUMMARY

The final processed and terrain corrected data were interpreted to isolate and enhance signature patterns associated with key sub-surface geological sources. The intricate steps and imagery are surmised in the PPT Interpretational Report. The following is a brief explanation of the procedures adopted.

Wavelength Slices:

Potential field data recorded at any given location is a cumulative response of the entire geological section beneath that location. The final data show a series of anomalies of variable amplitude and wavelength. Wavelength slicing allows us to separate the wavelength content that not only arises from differing sized geological sources, but also sources from various depth levels. Large scale geology yields long wavelength anomalies, small scale geology short wavelength signal. Signal amplitude is primarily dependent on density / susceptibility contrast but also on depth to source. The PPT shows a series of Wavelength slices generated from the Air-FTG® and Magnetic data.

Invariant Analysis:

Air-FTG® data, by its very design detects edges or geological contact information. FTG is a Tensor field and can be mathematically described using Laplachian or Matrix mathematics. Because of this, we invoke the usage of Invariant analysis to extract anomalous responses associated with geological contacts from the Air-FTG® data. A product from the Invariant analysis approach is an estimate the strike direction (orientation) of the imaged contact lineament. The PPT report describes a series of such contact lineament maps and strike angle analyses for differing sets of wavelength slice maps.

An additional Invariant Analysis procedure lends it useful for directly locating 3D shaped geological targets such as fault blocks, igneous intrusives, salt etc. This was performed for wavelength slices from the map data.

Analytic Signal:

This is a procedure particularly suited to airborne magnetic data acquired at or near equatorial regions, i.e. areas of low magnetic latitude. The benefit is that it displays all magnetic sources, be they reversely magnetised or not, as a positive anomaly. This was performed on individual magnetic wavelength slices to determine whether or not the magnetic signature pattern is sourced within basement or overlying volcanics. The PPT surmises the imagery.

Inversion:

Only the vertical component of the gradient (Tzz) was inverted, although the code has the capability of simultaneously inverted all tensors to obtain a representative density contrast model of the target sub-surface geology. Prior to running an inversion, a band pass filter between 0.5 -10km wavelengths was applied to the data.

The mesh is composed of rectangular prisms or cells with constant density contrast within each cell. The discretization mesh has cell sizes of 50 m in the easting by 50 m in the northing by 50 m in depth in the central region of the mesh, with padding cells beyond the data area.

The density contrast model was obtained by unconstrained inversion of the Tzz data alone. Generic inversion parameters were used with little a priori information incorporated into the inversion.

A zero reference model was used with an initial model of 0 g/cc. Lower and upper bounds on the density contrast were set as 0 g/cc and 5.0 g/cc using the knowledge that a positive density contrast is expected from the dense ore body in the less dense host rock.

:

APPENDIX 4 DATA DELIVERABLES INDEX

The deliverable products reside in separate directories on the CD. The digital flight line data is provided in a Geosoft Oasis database and/or other formats. Oasis maps, grids of the data and images of the data are also provided. Database, grid and image files (where applicable) are delivered in the UTM coordinate system. Each database channel is described in Appendix 5, and the images and grids are named for the channels they originate from.

Reports

- Acquisition and processing report
- Phase 1 Interpretation PowerPoint report

Databases

- Geosoft **.gdb** (FTG, MAG)

Grids

- Geosoft **.grd** & **.xyz** formats

Grids have a cell size of 50m and are named in the format detailed below. Grids with XYZ format are ascii formatted grids and contain just Xcoord, Ycoord and Zdata information.

FTG GRIDS

*_FA_FTNR.grd - The final Full Tensor processed Free Air anomalies for all FTG component;

Tz_FA_FTNR.grd - Computed Free Air Gravity response from vertical integration of the Tzz anomaly field;

Tz_vTC_FTNR.grd - Computed Variable Terrain Corrected (vTC) response from vertical integration of the Tzz anomaly field;

*_vTC_FTNR.grd - The final Full Tensor processed and Variable Terrain Corrected anomalies for all FTG component;

TCD_*_slice_1.grd - High Pass filtered Terrain Corrected FTG data extracting all wavelengths shoRTPr than 0.5km;

TCD_*_slice_2.grd - Band Pass filtered Terrain Corrected FTG data extracting all wavelengths between 0.5km and 2km;

TCD_*_slice_3.grd - Band Pass filtered Terrain Corrected FTG data extracting all wavelengths between 2km and 10km;

TCD_*_slice_4.grd - Low Pass filtered Terrain Corrected FTG data extracting all wavelengths greater than 10km;

TCD_*_slice_2+3.grd - Band Pass filtered Terrain Corrected FTG data extracting all wavelengths between 0.5 and 10km;

TCD_*_slice_2a+3.grd - Band Pass filtered Terrain Corrected FTG data extracting all wavelengths between 1 and 10km;

RotInVar2.grd - InVariant Tensor computed using all Tensor components for wavelengths between 1km and 10km; units Eotvos^3

RotInVar2_CR.grd - Cubed root of the InVariant Tensor computed using all Tensor components for wavelengths between 1km and 10km; units Eotvos

FTG_Lineaments.grd - Amplitude of lineament edges detected by combining results for both Invariant Tensors for wavelengths between 1 and 10km; units Eotvos/m

MAG GRIDS

TMI.grd - The levelled, demeaned, IGRF corrected Total Magnetic Field

RTP.grd - The levelled, demeaned, IGRF corrected Total Magnetic Field, reduced to equator;

RTP_AS.grd - The calculated analytical signal of the TMI RTP grid;
RTP_1VD.grd - The first vertical derivative of the TMI RTP grid;
TDR_RTP - The calculated tilt derivative of the TMI RTP grid;
HDR_RTP - The calculated horizontal derivative of the TDR grid;
TDR_lineaments - Amplitude of lineament edges detected from the TDR grid;

RTP_slice_1.grd - High Pass filtered Magnetic RTP data extracting all wavelengths shoRTPr than 0.5km;

RTP_slice_2.grd - Band Pass filtered Magnetic RTP data extracting all wavelengths between 0.5km and 2km;

RTP_slice_3.grd - Band Pass filtered Magnetic RTP data extracting all wavelengths between 2km and 10km;

RTP_slice_4.grd - Low Pass filtered Magnetic RTP data extracting all wavelengths greater than 10km;

RTP_slice_2_AS.grd - The calculated analytical signal of the RTP TMI grid for all wavelengths between 0.5km and 2km;

RTP_slice_3_AS.grd - The calculated analytical signal of the RTP TMI grid for all wavelengths between 2km and 10km;

3D INVERSION

Inversion voxel -3D density cube as generated using Oasis Montaj by converting UBC density model into geosoft voxel model;

Inversion_Geosurfaces -Density isosurfaces created from 3D density model using different cut off density contrast

Inversion database - A *.gdb with X, Y, Z(depth), density contrast and density(with assumied background desnity 2.7g/cc added) channels

Inversion.XYZ - An *.xyz file of the inversion database

Inversion.PDF - 3D final inversion dispalying various geosurfaces

APPENDIX 5 OASIS DATABASE CHANNEL INDEX

Deliverables:

FTG Database

Altitude	The altitude of the aircraft
Drape	Ideal planned drape surface
EastVelocity	Horizontal velocity of the aeroplane, in the East-West direction. Positive: East
NorthVelocity	Horizontal velocity of the aeroplane, in the North-South direction. Positive North
VertVelocity	Vertical velocity of the aeroplane
Heading	Aircraft compass heading in radians. Positive: clockwise from North. Negative: counter-clockwise from North
Pitch	Pitch of the aircraft from horizontal
Roll	Roll of the aircraft from horizontal.
HHMMSS	Time in hours-minutes-seconds
Time	Interval FTG time in seconds after January 6, 1980
YYMMDD	Date in year-minute-seconds. YYYYMMSS
Lat	Latitude
Lon	Longitude
Terrain	Digital Terrain Model of terrain above water level. Derived from SRTM data.
X_WGS84; Y_WGS84	X, Y coordinates in WGS84, UTM 34N
X_RT90; Y_RT90	X, Y coordinates in RT90 Datum
TC100_*	Modelled FTG terrain response with a density of 1.00 g/cc. Derived from SRTM data
TC100_*_FTNR	Modelled FTG terrain response with a density of 1.00 g/cc. Full Tensor Noise Reduced. Derived from SRTM data
*_FA	Unlevelled free air FTG data in E.N.D. coordinates
*_FA_lev	Levelled free air FTG data in E.N.D. coordinates
*_FA_lev_FTNR	Levelled free air FTG data in E.N.D. coordinates. Full Tensor Noise Reduced
*_TCD_FTNR	Variable Density Terran Corrected Data. Full Tensor Noise Reduced

Notes:

>> E.N.D. coordinates are called East-North-Down. It refers to a coordinate system where the direction of increasing x coordinate is oriented east,
the direction of increasing y coordinate is oriented north, and the direction of increasing z coordinate is oriented down.

>> Terrain corrections performed using a Wavelet processing technique that correlates signal from the TC100 with FA_lev_FTNR

>> The terrain correction is performed to reduce all data signal to the survey flying datum.

Magnetic Database

Alt	The GPS altitude of the Aircraft
GPSSeconds	UTCTime in seconds after midnight.
HHMMSS	UTCTime in HMS format
UTCTime	UTCTime in seconds after January 6, 1980.
YYMMDD	Date of acquisition
Lat	Latitude
Lon	Longitude
RadarAlt	Height above sea level - radar altimeter output
RadarAlt_dtm	DTM estimated from Radar Altimeter, generated as RadarAlt_dtm = Alt - RadarAlt
Basemag	Basestation magnetometer data
MagXRaw	Fluxgate Magnetometer. Oriented in the transverse direction. As part of the Compensator
MagYRaw	Fluxgate Magnetometer. Oriented in the longitudanl direction. As part of the Compensator
MagzRaw	Fluxgate Magnetometer. Oriented in the verticial direction. As part of the Compensator
TFUncomp	Uncompensated Total Magnetic Intensity
TFComp	Compensated Total Magnetic Intensity
TFComp_MicLev	Compensated Total Magnetic Intensity. Levelled and Micro-Leveled.
TFDiff4	4th Difference of TFComp
TMI	Final Processed, Total Magnetic Intensity. Levelled and Microlevelled, IGRF removed
IGRF_TF	Regional IGRF TMI
IGRF_Dec	Regional IGRF Declination
IGRF_Inc	Regional IGRF Inclination
X_WGS84; Y_WGS84	X, Y coordinates in WGS84, UTM 34N

X_RT90; Y_RT90	X, Y coordinates in RT90 Datum

<u>Inversion Database</u>

X,Y	X, Y coordinates in WGS84, UTM 49S
Z	estimated depth
Density Contrast	Estimated density contrast for model to work
Density	Background density