



SGU Airborne Geophysical Survey

Acquisition Report

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Q4 2024



Kiskamavaara Airborne Geophysical Survey

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1. Project Overview

1.1.Introduction

This report provides information regarding the acquisition and quality control methodology performed on airborne full tensor gravity gradiometry (FTG) and gravity data, as conducted by Bellgeo Enterprises Ltd (Bell Geospace). Geophysical data processing of the acquired data is reported in a separate document, Kiskamavaara Airborne Geophysical Survey Processing Report.

The data was acquired between August and November 2024 and subjected to rigorous quality control (QC) measures ensuring high quality data are retrieved. The FTG and gravity data are deemed of high quality.

The survey equipment used for this project includes a Full Tensor Gradiometer (FTG) and a conventional airborne gravimeter (GTz). All instruments are owned, maintained, and operated by Bell Geospace and permanently installed on Basler Turbo BT-67 aircraft. The aircraft is a modified and modernised Douglas DC-3 airframe, remanufactured in 2008, owned by Bell Geospace, and operated by Enterprise Airlines of Oshawa, Canada.

1.2.Project Location

The project is titled Kiskamavaara and is located in Northern Sweden. The location of the survey area is shown in Figure 1.1.

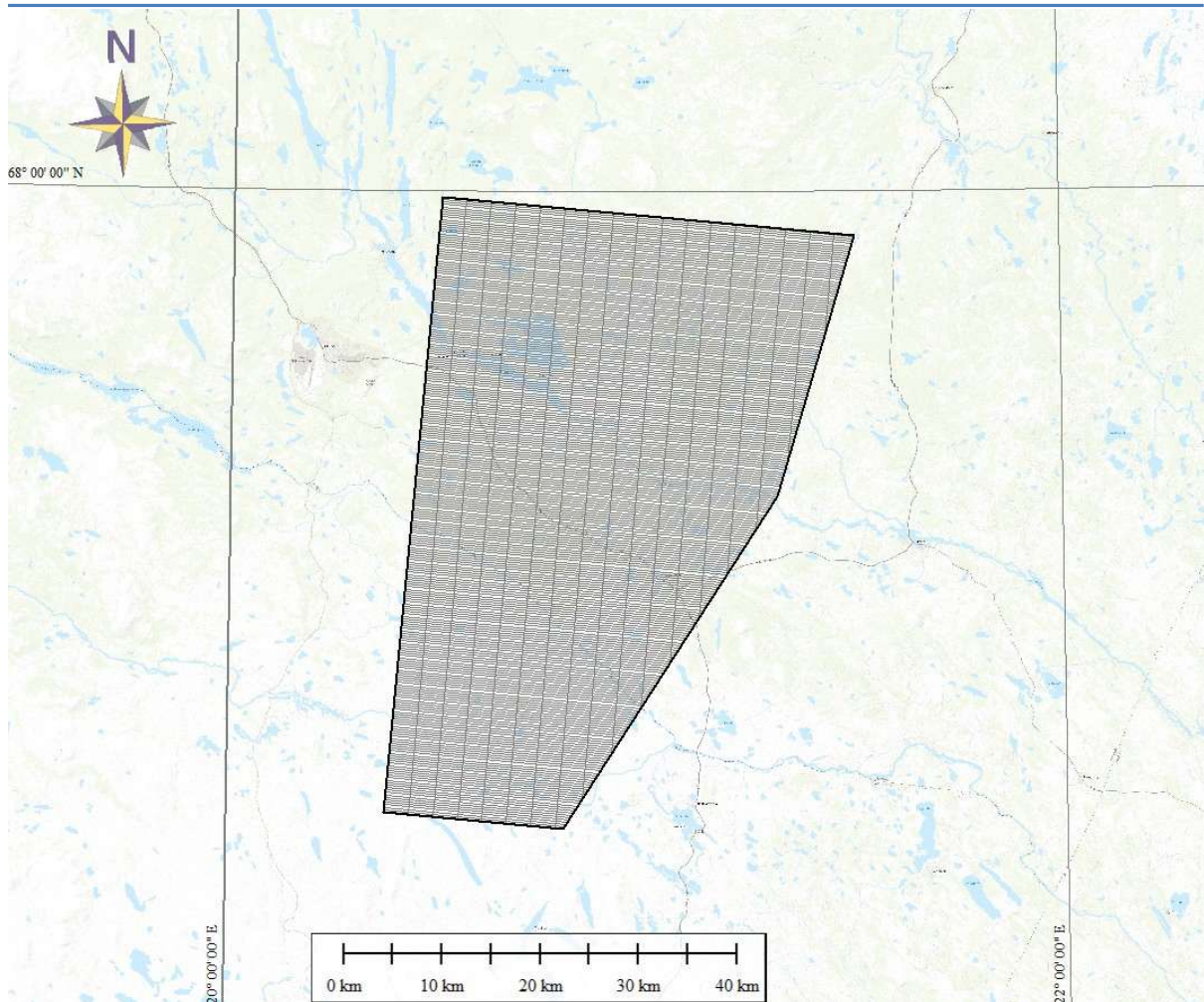


Figure 1.1: Location of the survey area

1.3. Scope of Work

The objective of the survey was:

- › The primary objectives of the project: Bedrock mapping together with targeting mineral occurrences related to various rock types
- › Acquire, process, and interpret Airborne Full Tensor Gravity Gradiometry (FTG) and Gravity data for the Kiskamavaara survey areas in Northern part of Sweden.

1.4.Key Milestones of the Project

Table 1.1 summarises the summary of events or key milestones of the project.

Table 1.1: Key Milestones of events related to the project.

Date	Activity
26 July 2024	Aircraft arrival in Gällivare Airport (GEV), Sweden, Base of Operations
26 July 2024	FTG Platform Calibration began
18 August 2024	Survey Acquisition commenced
6-9 September 2024	Standby awaiting replacement TCAS part
10-22 September 2024	TCAS maintenance
23 September 2024	Successful TCAS test flight conducted - maintenance completed
6-10 October 2024	Standby awaiting arrival of TCAS technician and replacement part
11-12 October 2024	TCAS maintenance
13 October 2024	Successful TCAS test flight conducted - maintenance completed
5 November 2024	All lines including redos have been flown and passed QC. Kiskamavaara survey officially completed.
7 November 2024	Official approval for demobilisation received.
7 November 2024	Demobilisation

1.5.Outline of Report

This report outlines the survey parameters, the sequence of acquisition and processing, and to highlight any issues which arose and the solutions which were implemented. The report is divided into seven sections plus appendices:

- › This section presents the overview of the project.
- › Section 2 details the design and specifications of the survey.
- › Section 3 details the key personnel involved, survey equipment deployed, and software used.
- › Section 4 details the operations on field, before and during survey.
- › Section 5 details all data evaluation and quality control procedures.

2. Survey Information & Design

2.1. Coordinate Reference System

All coordinates stated throughout the report, as well as all final deliverables, are referenced to the Coordinate Reference System (CRS) shown in the Table 2.1.

Table 2.1: Coordinate Reference System (CRS)

Projection Method	Universal Transverse Mercator (UTM)
Zone	34 N
Horizontal Datum	World Geodetic System 1984 (WGS 84)
Vertical Datum	Earth Gravitational Model 1996 (EGM 96)
Length Units	Metre

2.2. Data Availability and Sources

The following data and information were available prior to the survey commencement:

- › Country borders, cities and smaller settlements, no-fly zones.
- › Onshore topography sourced from the Aster DEM Worldwide Elevation Data provided by NASA.
- › Ground gravity station data including elevation, absolute gravity, free air and bouguer corrected anomaly data
- › High-resolution Digital Elevation Model provided by SGU.

2.3. Survey Design and Specifications

Kiskamavaara survey consisted of one block of in-lines and tie lines to be flown. Table 2.2 shows the survey specifications of the project. Figure 2.1 depicts the survey boundary and the regional topography, and Figure 2.2 depicts the final flight plan.

Table 2.2: Survey specifications

Survey Name	Kiskamavaara
Survey type	Full Tensor Gravity Gradiometry
Nominal aircraft altitude	80 m or minimum legally allowable
Approx. sample spacing FTG	60 m
Approx. sample spacing Magnetics	6 m
Nominal across in-line spacing	250 m
Nominal in-line orientation	95.48 °
Final total survey length	8,993.40km

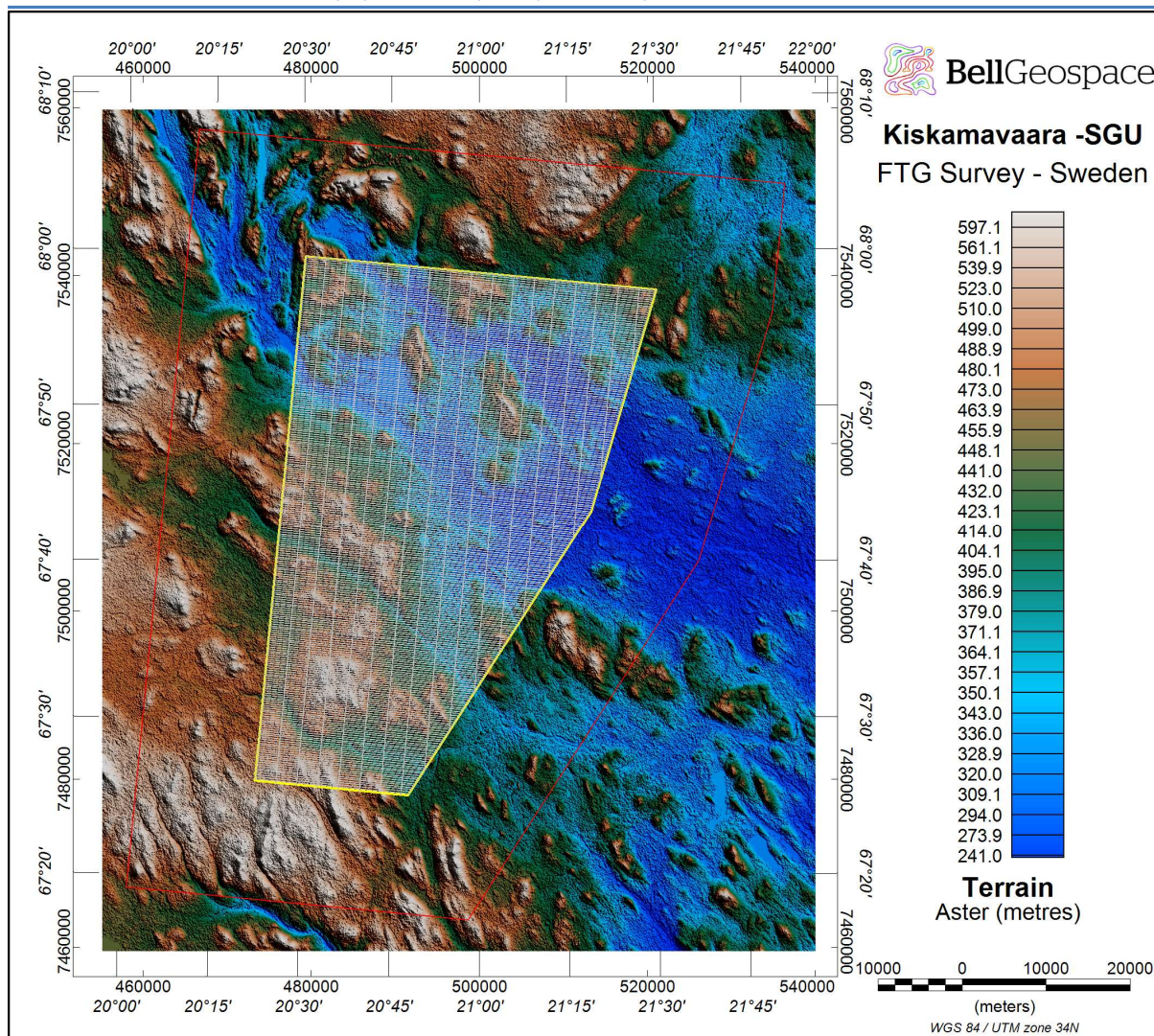


Figure 2.1: Topography over Kiskamavaara survey area

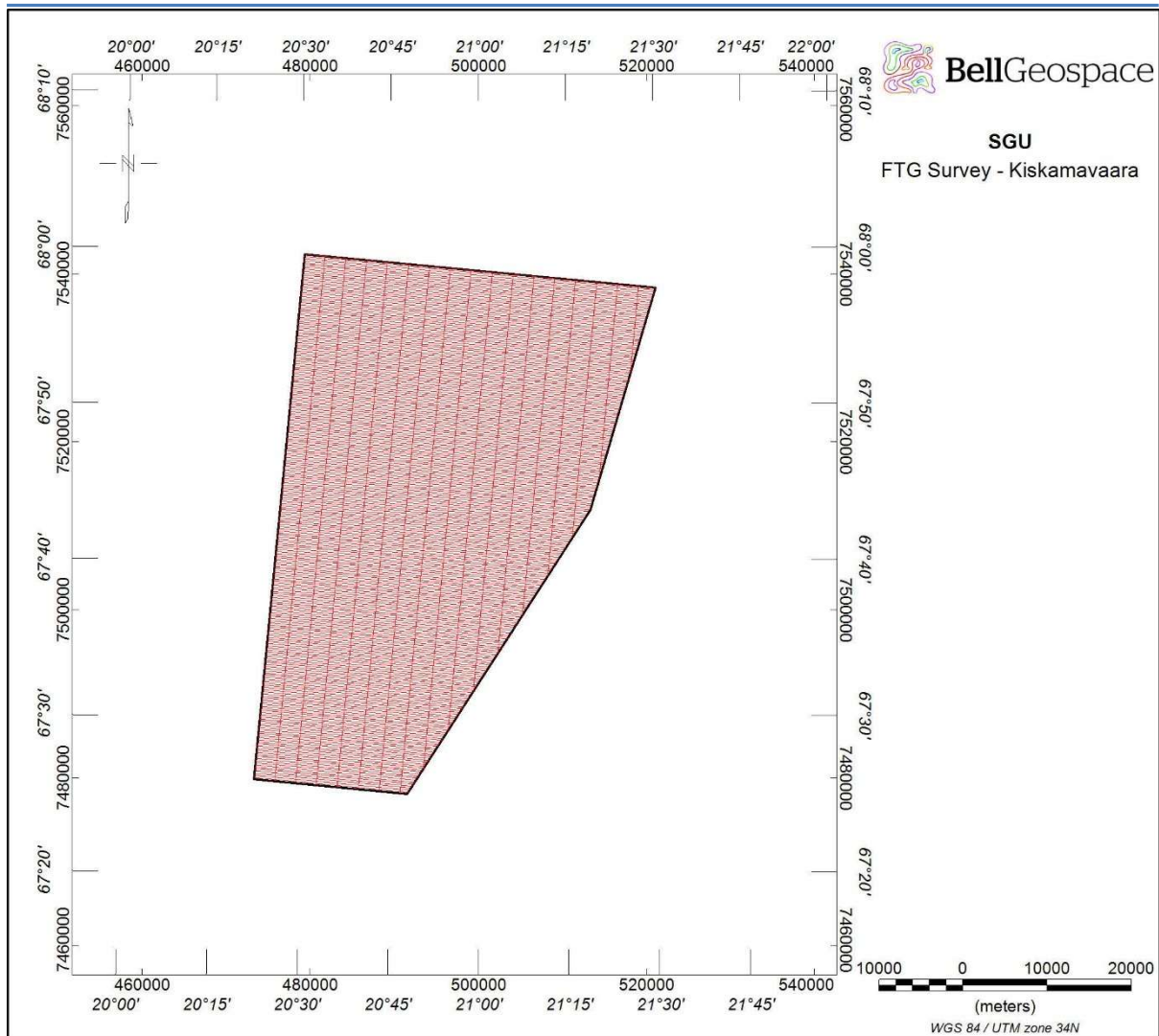


Figure 2.2: Kiskamavaara Final survey design.

2.4. Survey Drupe

In order to optimise the survey pilots' flight path, a "drape surface" was calculated, with the clearance set at a minimum of 305 metres height above terrain (ground or water surface). The drupe forms a safely flyable surface that accommodates all the survey lines, improves the data fit at line intersections and reduces spurious variations in signal strength between lines. The drupe calculation limits the climb and descent rates to 450ft/min in order to prevent rapid air pressure changes that can affect the GGI performance. Maintaining moderate climb and descent rates help the pilots maintain control of the aircraft in the event of an engine failure. Drape surfaces were designed to be as low as safely possible, in order to maximise the data resolution.

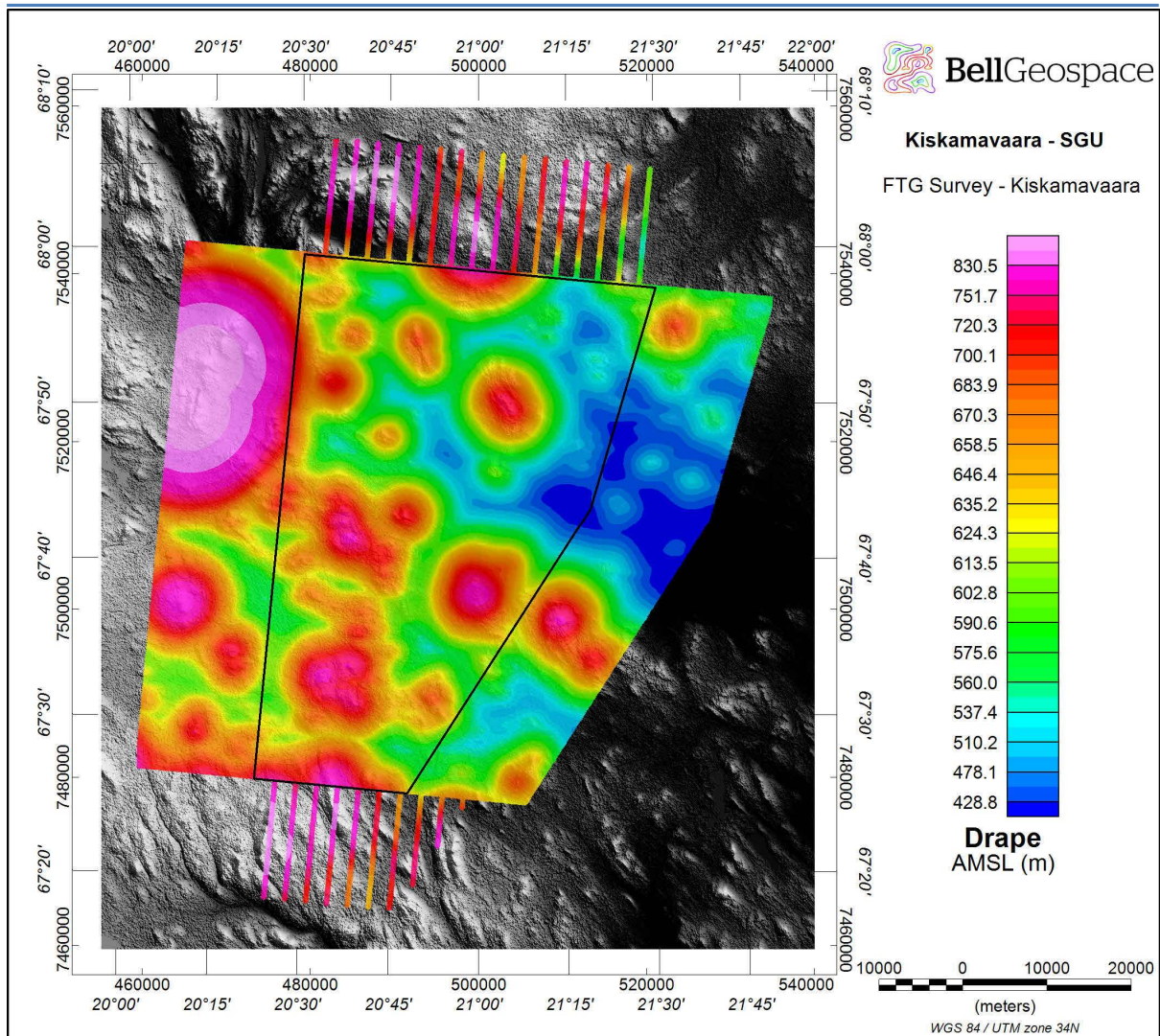


Figure 2.3: Kiskamavaara Drape surface measured at height above geoid.

3. Key Personnel & Technical Resources

3.1. Project Management/Key Personnel Involved

Bell Geospace formed a survey acquisition team to undertake the field operations. This field crew comprised of, at minimum, two pilots – a captain and a first officer – subcontracted from Enterprise Airlines and two Bell Geospace system operators. One of the operators was also designated as the Field Operations Supervisor, who had overall responsibility for the field operation, reported to Bell Geospace management, and ensured that the survey was conducted efficiently, safely, and in accordance with the contract specifications. Exchanges of survey field crew happen every few weeks, particularly on extensive projects.

The Bell Geospace Service Support Department provided technical advice and support to the field crew and its technicians were regularly sent to the field to perform routine or essential maintenance to the survey equipment.

All data acquired and processed on field was sent to Bell Geospace's QC Geoscientist that was assigned to be analysed and processed further.

Details of the personnel involved in the acquisition and processing phase are listed in Table 3.1.

Table 3.1: Key personnel involved in the project

Name	Organisation	Position
Ben Czuczman	Enterprise Airlines	Captain
Andrew Noonan	Enterprise Airlines	Captain
Phillippe Viotto	Enterprise Airlines	Captain
Thierry Gaillot	Enterprise Airlines	Captain
Jack Caise	Enterprise Airlines	First Officer
Greg Noonan	Enterprise Airlines	First Officer
Michael Hudson	Enterprise Airlines	First Officer
Tanner Kaspardlov	Enterprise Airlines	First Officer
Steve Pettifer	Bell Geospace	Supervisor
Kenny Burnett	Bell Geospace	Operator
Phil Kriesa	Bell Geospace	Supervisor
Dan Levert	Enterprise Airlines	Mechanic

Xavier Jacques	Enterprise Airlines	Engineer
Mac MaCoy	Enterprise Airlines	Engineer
Daniel Rioux	Enterprise Airlines	Avionics Technician
Cate Fraser	Bell Geospace	Project and QC Manager
Ikhsan Zikrurramadhan	Bell Geospace	Project and QC Manager
Malcolm Destro	Bell Geospace	Processing Geophysicist
Scotty Morrison Smith	Bell Geospace	HSE & Logistics Manager
Gaud Pouliquen	Bell Geospace	Business Development Manager - Eastern Hemisphere
Joel Puryear	Bell Geospace	Operations Manager
Colm Murphy	Bell Geospace	Chief Geoscientist

3.2.Aircraft & Survey Equipment

The following aircraft and survey equipment were deployed for this survey:

Table3.2: Aircraft Summary

Aircraft Type	Manufacturer	Model
Fixed Wing Aircraft – Basler Turbo BT 67	Douglas	C-FTGI

Table 3.3: Survey Equipment Summary

Survey Equipment	Manufacturer	Model
Airborne Gravity Gradiometer	Lockheed Martin	FTG 2
Airborne Gravity	Transparent Earth Geophysics	The GTz® gravimeter
Global Positioning System	Novatel	ProPak LB

Additional details of the aircraft and survey equipment are in the following appendices:

- › Appendix 1 provides technical details on the survey aircraft.
- › Appendix 2 specifies the locations of survey systems installed on the aircraft.
- › Appendix 3 provides technical details on the Air-FTG system.
- › Appendix 4 provides technical details on the other survey systems.

3.3. Software & Data Visualisation

ODIN is a company-wide central database, developed internally, that stores and shares operational and analytical information gathered from the field and office operations. It facilitated tracking of survey progress, monitored system health, and collaborated on survey designs and data evaluation.

Much of the Air-FTG software used in the field is proprietary and by Lockheed Martin, the Air-FTG system manufacturer. This software displayed the FTG response as well as key parameters that were crucial to the correct operation and provided warnings when components were not operating within technical specifications. Lockheed Martin software was also used to perform FTG calibrations and on-field processing.

Geosoft's Oasis montaj is a geoscience software package used primarily in the office for data analysis and processing. It was also for generating the deliverables for the client, including databases and maps.

Additionally, the following commercial interfaces were also used for data analysis:

- › Pico Envirotec's PEIConvert is a program used for designing the survey flight plan.
- › Pico Envirotec's ANAV is a navigation interface system used by the aircraft crew to monitor real-time flight data.

4. Field Operations

4.1. Health, Safety & Environment Audits & Incidents

There were no major HSE issues observed in this project area. Daily Toolbox meeting and Weekly HSE meeting were held throughout the field operations.

4.2. Permits and Visa Applications

As contracts and documents were ready and there were no restrictions from ITAR (there are some restrictions from the US Government to use FTG technology in some countries) the flight permits were straight forward.

4.3. Pre-Survey Mobilisation

The personnel, aircraft and equipment arrived at Gällivare Airport (GEV), Sweden on 26th July 2024; mobilisation commenced on the same day. Gällivare Airport was the base of operations, including for equipment mobilisation, system calibrations and regular maintenance.

The mobilisation itinerary included, but was not limited to, the following:

- › Positioned the aircraft for power supply.
- › Unloaded the equipment from the aircraft to a designated store room.
- › Static calibrations
- › Aircraft maintenance
- › Tested satellite phone communications.
- › Uploaded final survey plans to on-field computers.
- › HSE meetings.

Static and airborne calibrations were performed on the survey systems 26th July 2024 and during the survey acquisition; further details are in the next section of the report.

4.4. Survey Acquisition

Surveying officially commenced on 15th August 2024 and was completed on 5th November 2024; a summary of acquisition is shown in Table 4.1.

Table 4.1: Acquisition summary

Days of acquisition	26 days
Pilot Rest Day	10 days
Downtime (Weather)	23 days
Downtime (Maintenance)	9 days
Downtime (Technical)	5 days
Standby	10 days

The survey was suspended multiple times throughout the course of the project for various reasons, which are listed in the following table in chronological order:

Table 4.2: Survey downtime summary

Dates	Reason
15-16 August 2024	Poor Weather conditions
17 August 2024	Pilot Rest Day
19 August 2024	Poor Weather conditions
21-23 August 2024	Poor Weather conditions
24 August 2024	Pilot Rest Day
25 August 2024	Poor Weather conditions
27 August 2024	Poor Weather conditions
30 August 2024	Poor Weather conditions
31 August 2024	Pilot Rest Day
3-4 September 2024	Poor Weather conditions
6 September 2024	Down Technical – TCAS issue
7-9 September 2024	Standby awaiting replacement TCAS part
10-13 September 2024	Down Maintenance - TCAS
14-17 September 2024	Standby awaiting replacement TCAS part
18 –22 September 2024	Down Maintenance - TCAS
23-25 September 2024	Poor Weather conditions

27 September 2024	Poor Weather conditions
28 September 2024	Pilot Rest Day
1 October 2024	Poor Weather conditions
5 October 2024	Pilot Rest Day
6-7 October 2024	Down Technical – TCAS Issue
8-10 October 2024	Standby awaiting replacement TCAS part and technician
11 October 2024	Down Maintenance - TCAS
12 October 2024	Pilot Rest Day
13-14 October 2024	Poor Weather conditions
18 October 2024	Down Technical – Platform issue
19 October 2024	Pilot Rest Day
20-21 October 2024	Poor Weather conditions
25 October 2024	Poor Weather conditions
26 October 2024	Pilot Rest Day
27 October 2024	Poor Weather conditions
30 October 2024	Poor Weather conditions
2 November 2024	Pilot Rest Day
3 November 2024	Down Technical - ATC opens at 1430 on Sundays, sunset at 1450

A total of 1938.11km was re-flown as the original lines had issues with the data quality. Details on the QC methodology are in the next section. Statistics on line kilometres acquired throughout the survey, including re-flights, are in Figure 4.1; blue statistics are first survey flights (partial or complete), and red statistics are re-flights.

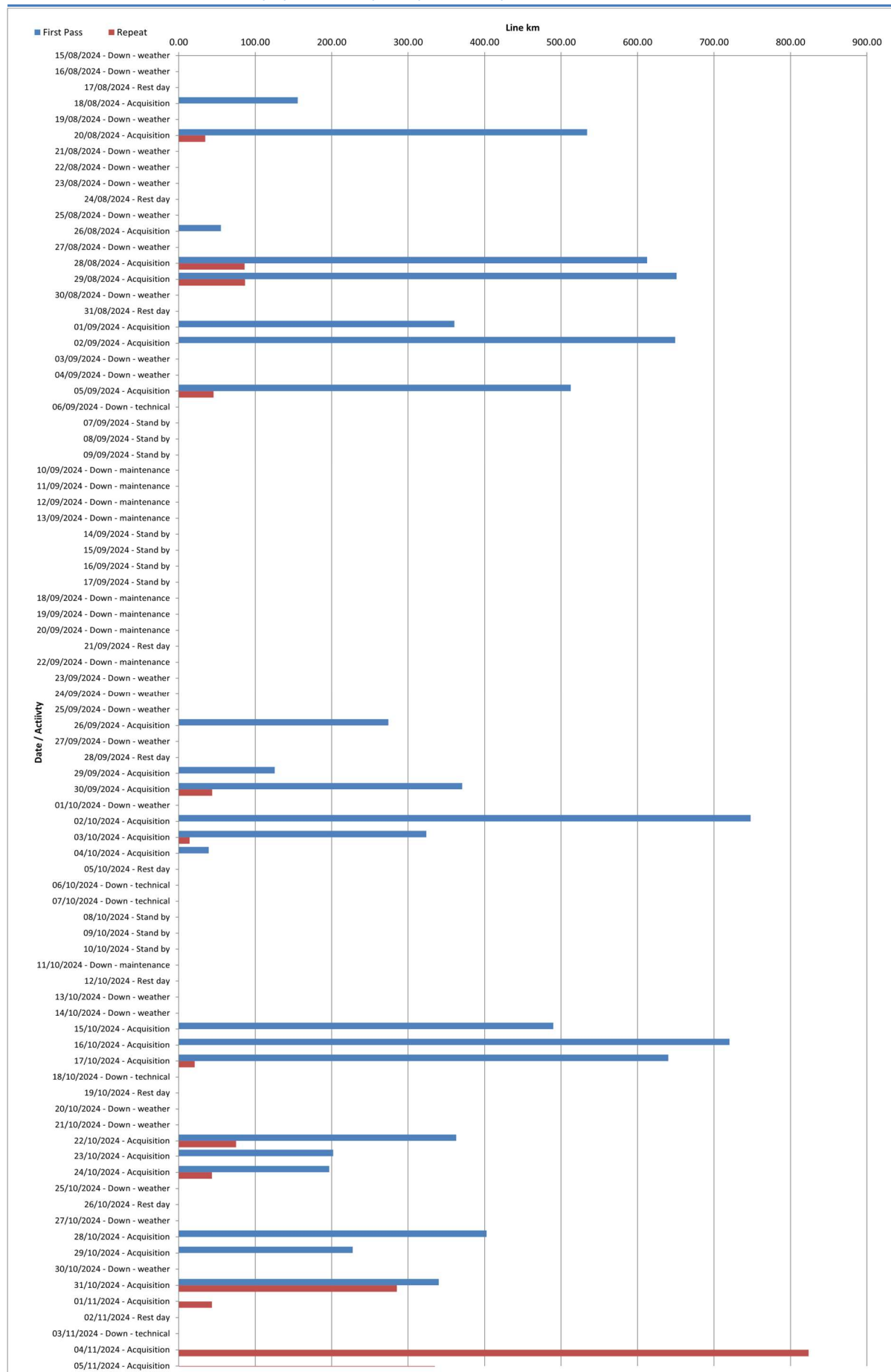


Figure 4.1: Field operations throughout survey.



5. Data Analysis & Quality Control

5.1. Calibrations & Verification Results

Air-FTG: A series of Air-FTG calibrations, both stationary and airborne, was performed for the platform, accelerometers, and gyros, optimising the FTG system. The calibrations were undertaken prior to the start of survey and whenever significant changes were made to the FTG system configuration. Air-FTG was also evaluated after every survey flight ensuring optimal performance. Calibration results cannot be provided as they are proprietary to the system manufacturer Lockheed Martin.

GTz: Key parameters of the GTz platform stability are continually monitored while the system is powered, and an "Auto-Calibration" will be conducted if/when these parameters approach the manufacturer's recommended limits. These key parameters relate to the estimations of mechanical and fibre optic gyroscope drift rates, and the alignment of the mechanical gyroscope vertical axis with the vertical sensor's axis. The Auto-Calibration process is controlled by the gravimeter's operating software and is completed over the course of approximately 5 hours.

Typically, upon arrival on-site, the system is powered up and system parameters are evaluated once the full warm-up is complete. The stability of the system at this time will determine whether an Auto-Calibration is warranted.

Upon arrival in Gällivare, the system had already been operating for a number of weeks, and its stability was well within tolerance.

At that time, the gravimeter was operating with Auto-Calibration parameters determined through an Auto-Calibration performed on 1st February 2024.

During the course of the survey, an Auto-Calibration was conducted on 28th September 2024, with the results well within specification.

5.2. Air-FTG Data Quality Control

Bell Geospace had several controls on Air-FTG data quality, both on field and in the office, and any survey line with poor signal quality was assessed for re-flight; a summary of QC specifications is in Table 5.3. Once new lines were acquired, the process was repeated until all survey lines passed the QC checks. Technical documentation on the QC methodology of Air-FTG data is in Appendix 5.

Table 5.3: Air-FTG QC specifications

Full Tensor Gravity Gradiometry		
Signal levels on 3 GGI outputs, torque levels	Consistency between GGI's, no spiking.	Stop survey to investigate system performance
Vertical acceleration	$< 100 \text{ mg}$ $100 - 120 \text{ mg}$ $> 120 \text{ mg}$	Acceptable Assess for re-flights Unacceptable, unless exceptional circumstances
Gaps in Digital Data	$> 2 \text{ sec}$	Interpolate if possible else redo line
AILS*	$> 17\text{E}$	Unacceptable, unless exceptional circumstances

Figure 5.3 shows the contract Inline Sum for all the survey lines flown on Kiskamavaara. As shown in the figure, no survey lines exceeded QC constraints. However, some of the lines were re-flown due to being failed by Internal QC. The average Inline Sum across Kiskamavaara was 7.44 Eötvös.

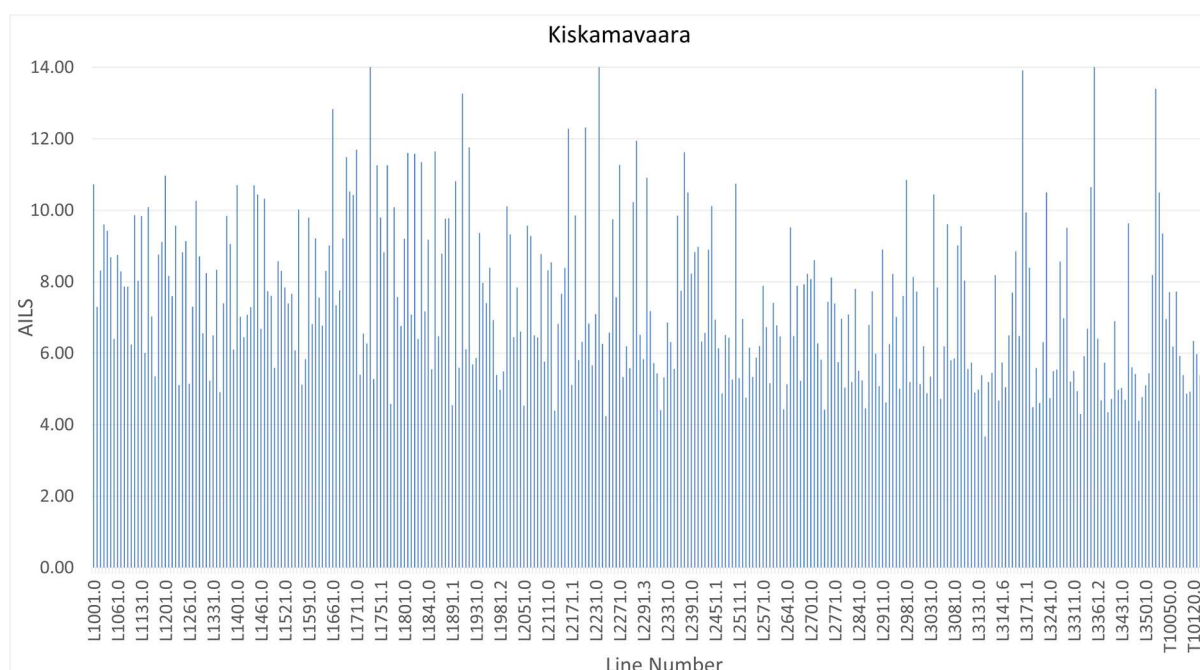


Figure 5.3: Inline sum from the Kiskamavaara

Figure 5.4 shows the vertical acceleration values for all the survey lines flown on Kiskamavaara. The average across Kiskamavaara survey was 55.01 mg.

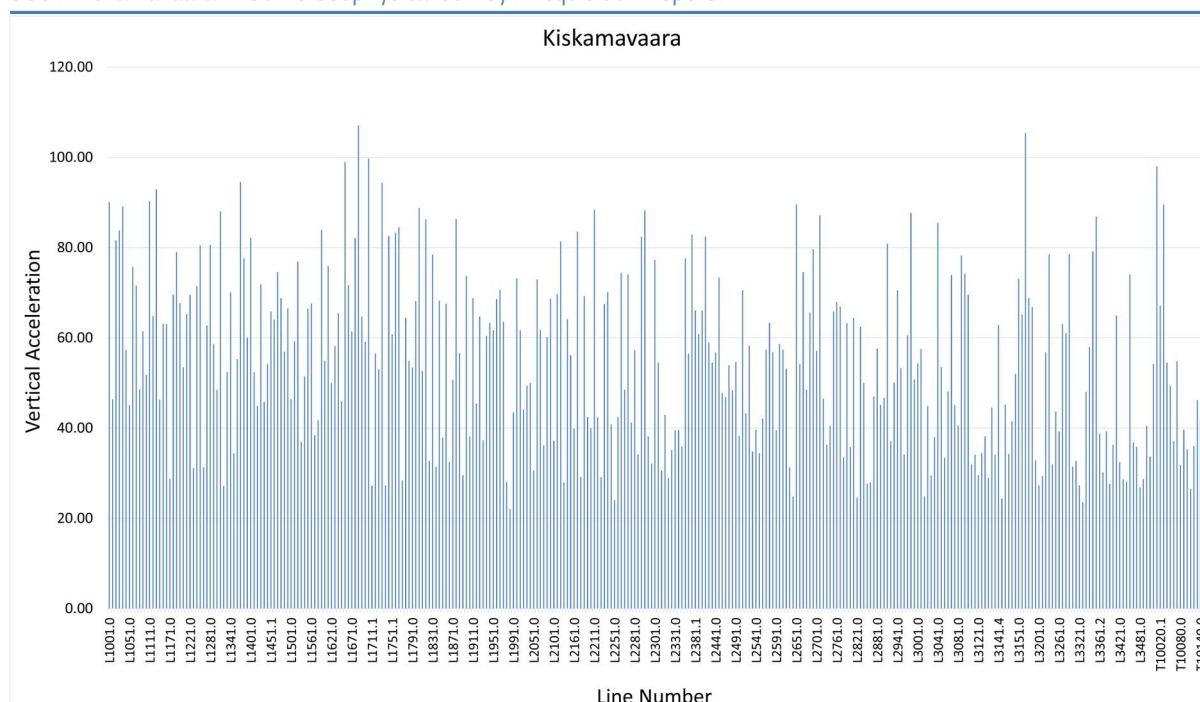


Figure 5.4: Vertical Acceleration values of Kiskamavaara

5.3. Navigation & Positioning Quality Control

On field, as well as general checks, the GPS sensors continually monitored the number of satellites available at all times. Additionally, on-flight checks were made that real-time differential corrections for the GPS were being received. In the office, the position of the aircraft on each survey line was assessed against an ideal line plan and smoothed drapage surface according to the specified contract specification. A line where the aircraft had been found to deviate horizontally and/or vertically was identified for potential re-flight. The assessment of flight accuracy was determined during the daily processing stage by Bell Geospace's office personnel. A summary of QC specifications is in Table 5.5.

Table 5.5: Navigation/Positioning QC specifications

<i>Navigation and Positioning</i>		
Line navigation	> 20% of line spacing off plan over any stretch longer than 2km	Redo line or partial line
Line navigation vertical positioning	> 20% of terrain clearance off plan over	Redo line or partial line

	any stretch longer than 1km	
GPS # satellites	<5 satellites	If longer than 10 seconds duration, redo line (part), else investigate consequences to quality
PDOP	>5	If longer than 5 minutes duration, redo line (part), else investigate consequences to quality

Line keeping was generally good throughout the survey. Figure 5.7 shows flight trajectories flown over survey area.

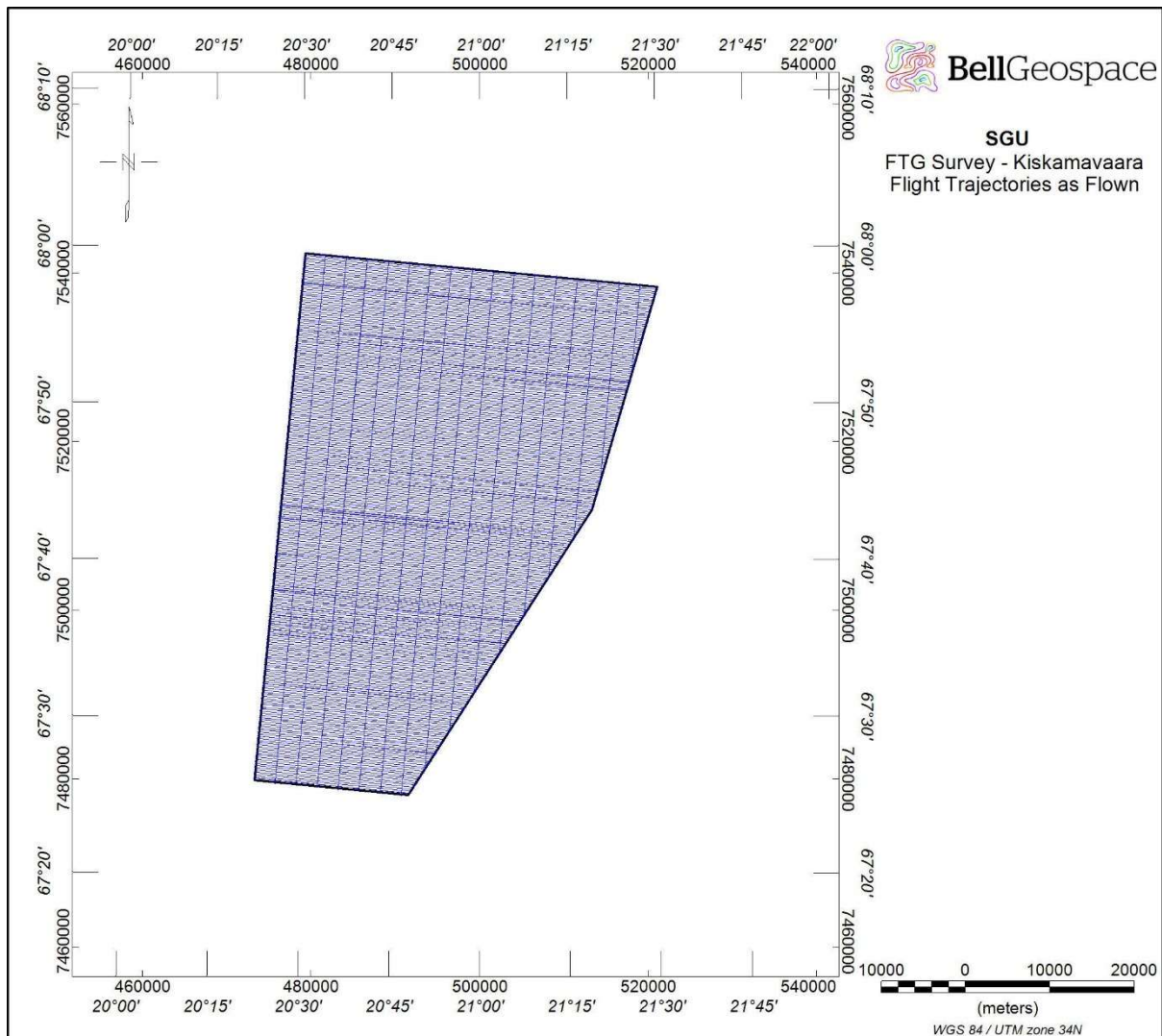


Figure 5.7: Kiskamavaara Flight Trajectories

5.4 GTz Data Quality Control

Bell Geospace employed several technical specifications for airborne Transparent Earth Geophysics GTz data quality control. Field practice ensured all instruments were working and the data was extracted and uploaded daily to the office for assessment. A summary of QC specifications is in Table 5.8.

Table 5.8: GTz QC specifications

Transparent Earth Geophysics GTz		
GPS # satellites	<5 satellites	If longer than 5 minutes duration, redo line (part), else investigate consequences to quality.
Vertical acceleration	>100 mg	Unacceptable, unless exceptional circumstances;
Drift rates	> 1 mgal / hr	Interpolate if possible (COMPANY representative to be informed) else redo line
RMS intersection error on individual flight lines	> 2 mgal over 6km full wavelength after 1st order levelling	Redo line
Gaps in Digital Data	> 2 sec	Interpolate if possible else redo line

The survey met all specifications listed.

Figure 5.10 shows a plot of the Daily Static readings for the Main survey. Minimal drift is evident in the instrumentation.

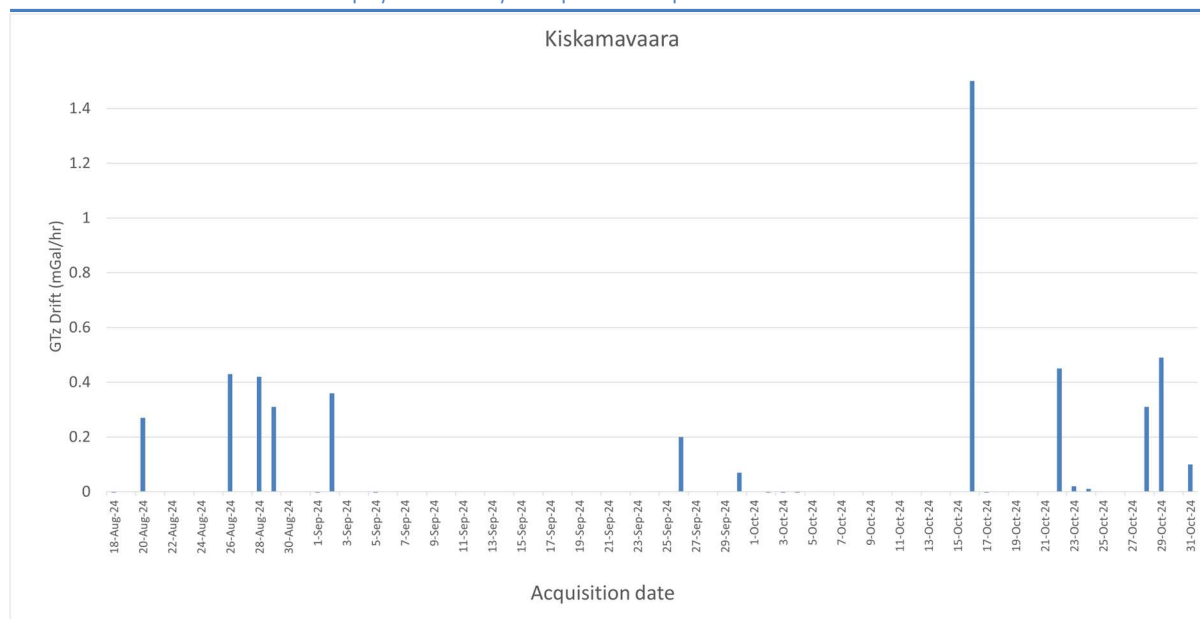
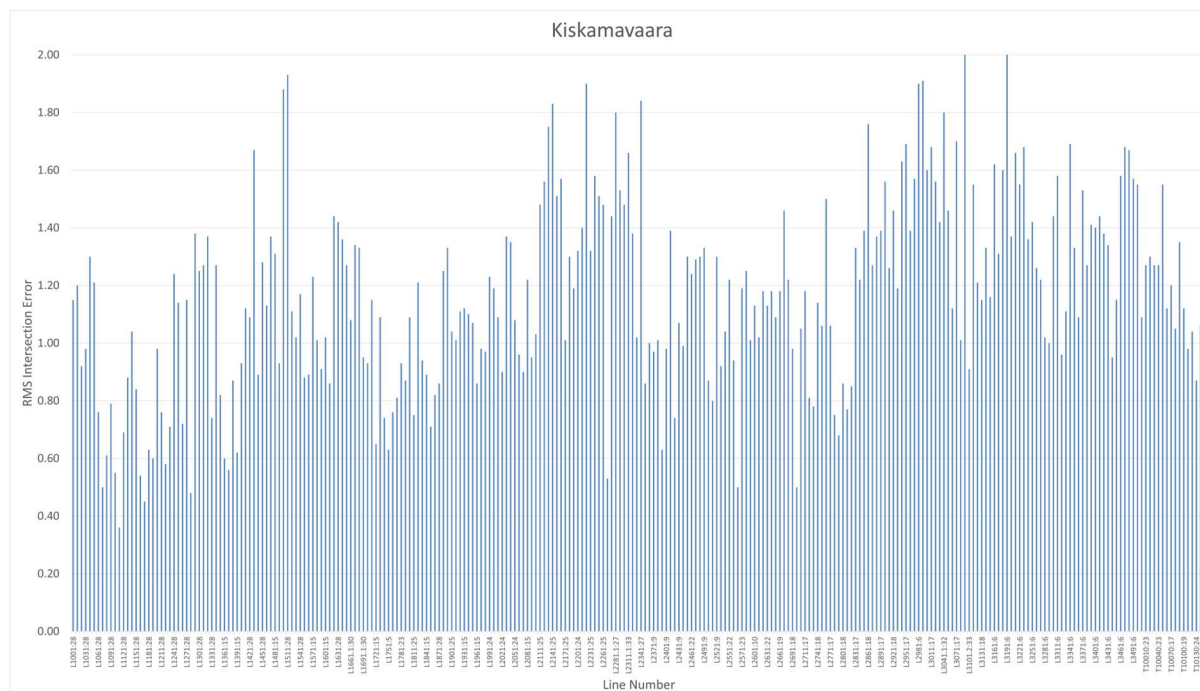


Figure 5.11 shows the RMS Intersection error values for all the survey lines flown. As shown in the figure, two survey lines exceeded QC constraints. However, their exceedance is considered marginal and will not impact final data quality. The overall RMS Intersection error value is 1.20 mGal.



Appendices

Appendix 1 Basler Turbo BT-67 Aircraft and Crew

The aircraft used for this survey is a Basler Turbo BT 67 (Figure A2.1). This was a Douglas DC3 originally built in 1944 but converted by Basler Turbo Conversions of Oshkosh, USA, in 2008. The conversion includes fitting of more powerful and reliable Pratt & Whitney PT-6 turbine engines, lengthening the fuselage by 40" behind the cockpit, modifying the wing tips and installing a modern avionics suite. The aircraft is well suited for low level airborne survey work because of its low stall speed and stability in turbulent conditions. With powerful twin engines and a requirement for two pilots it is a safe choice for long offshore sorties. The table below lists the specifications of the aircraft.

Table A1.1: Aircraft specifications

Length:	67 ft 8 in
Wingspan:	95 ft 8 in
Height:	18 ft 3 in
Empty weight:	15,750 lb
Maximum take-off weight:	28,750 lb
Powerplant:	Twin Pratt & Whitney Turbine engines, 1,424 hp (1,062 kW) each.
Propellers:	Five-bladed Hartzell
Maximum speed:	215 knots (247 mph)

The aircraft is owned by Bell Geospace but managed and operated in accordance with Transport Canada regulations by a contractor, Enterprise Airlines, based in Oshawa, Canada. Enterprise has a long record of operating Baslers, much of it supporting scientific bases in Antarctica.

The aircraft is continually supported by two pilots and one mechanic, even when on standby. These personnel work monthly shifts dedicated to the Bell Geospace Baslers and, along with the geophysicists, form the core of the survey crew. The pilots are highly experienced in low level survey work and are able to fly safely and accurately. In the field the Captain is in charge of the aircraft but its operation and maintenance are also monitored by the Enterprise Chief Pilot and Chief Mechanic to ensure that they comply with Transport Canada, local regulations and IAGSA guidelines.

The partnership between Bell Geospace and Enterprise is very successful resulting in an excellent safety record and efficient operations.

The geophysical survey equipment (FTG unit, GTz, magnetometer, GTZ, Lidar, GPS, and radar altimeter) is permanently installed (as shown in Appendix 2) and the aircraft is capable of carrying crew, spares and support equipment to survey locations around the World. This protects equipment from damage and reduces mobilisation times after arrival. The FTG system requires continual electrical power, and the plane is fitted with power supplies and transformers to safely use mains or generator power of various voltages while on the ground.



Appendix 2 Equipment Location On-board

Acquisition equipment (permanently installed in Basler BT-67; Figure 5):

- Lockheed Martin Full Tensor Gravity Gradiometer System
- Transparent Earth Geophysics GTz
- RMS Instruments DAARC 500 real time magnetic compensator
- Geometrics G-822A Cesium Vapour magnetometer
- Pico Envirotec ANAV navigation package
- NovAtel GPS ProPak-LB – Terrastar XP differential corrections

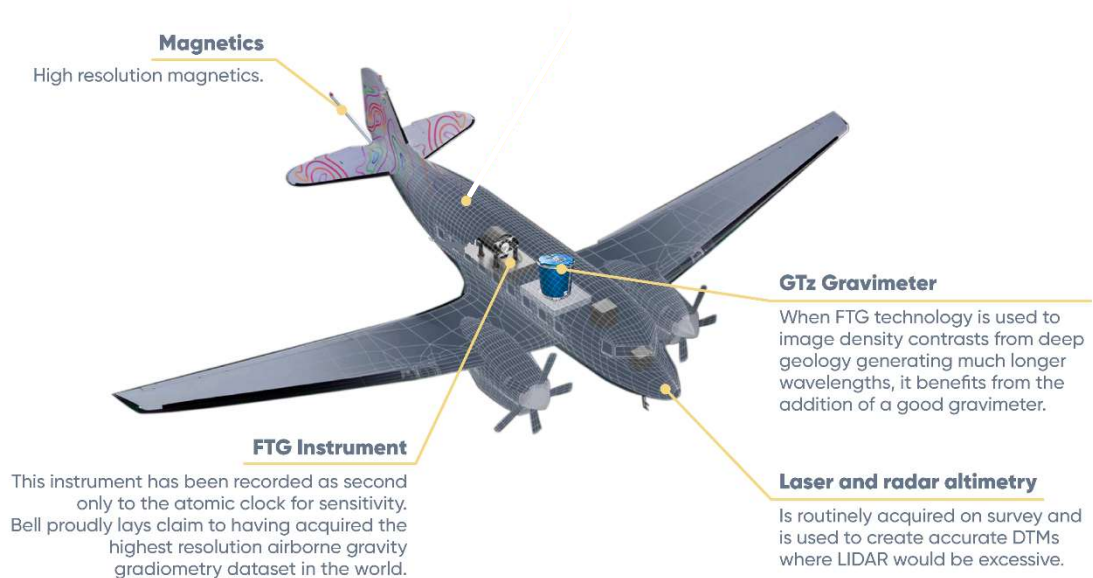


Figure A2.1: Instrument locations on the survey aircraft (top view)

Appendix 3 Air-FTG System and Operating Details

The Full Tensor Gradiometer (FTG) system used on this project is owned by Bell Geospace and manufactured by Lockheed Martin.

Platform and binnacle:

The FTG is comprised of three gravity gradient instruments (GGIs) mounted on a stabilised platform, shown in Figure A3.1. 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.



Figure A3.1: A photograph of the FTG system, with the binnacle cover removed to reveal the roll gimbal.

GGIs and accelerometers:

The three GGIs are mounted in an internal coordinate frame of axis of which the gradiometers are mutually perpendicular and deviate by an equal angle from the vertical, shown in Figure A3.2. Each gradiometer outputs two channels of signal (Cross and Inline) each, totalling six. This is the equivalent of all nine components of the gradient tensor.

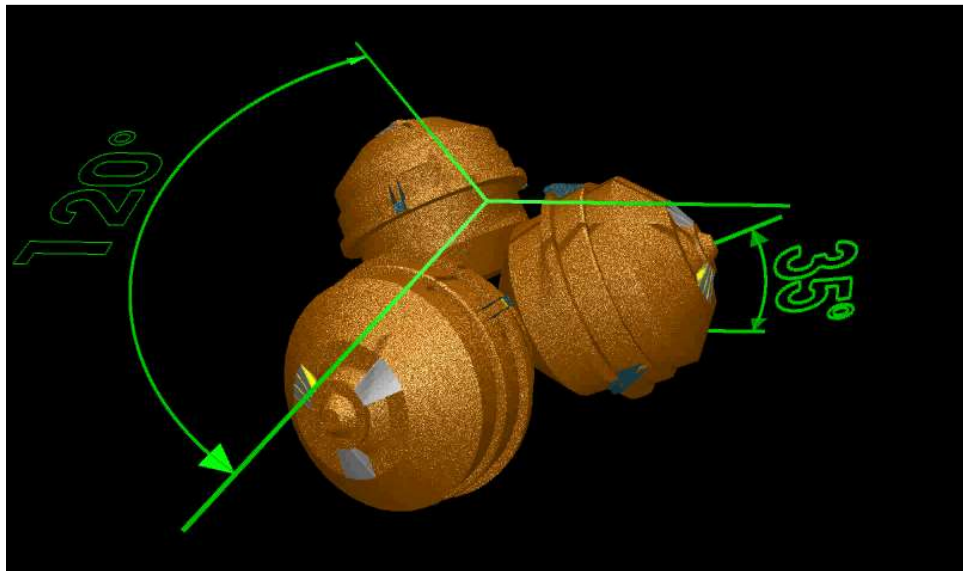


Figure A3.2: A diagram showing the relative positions of the GGIs inside the binnacle.

The GGIs are based on pairs of accelerometers mounted 10cm apart on opposite sides of a disk rotating at 0.5Hz, shown in Figure A3.3. 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 marks 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, which are independently measured by the platform gyros, can be isolated 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.

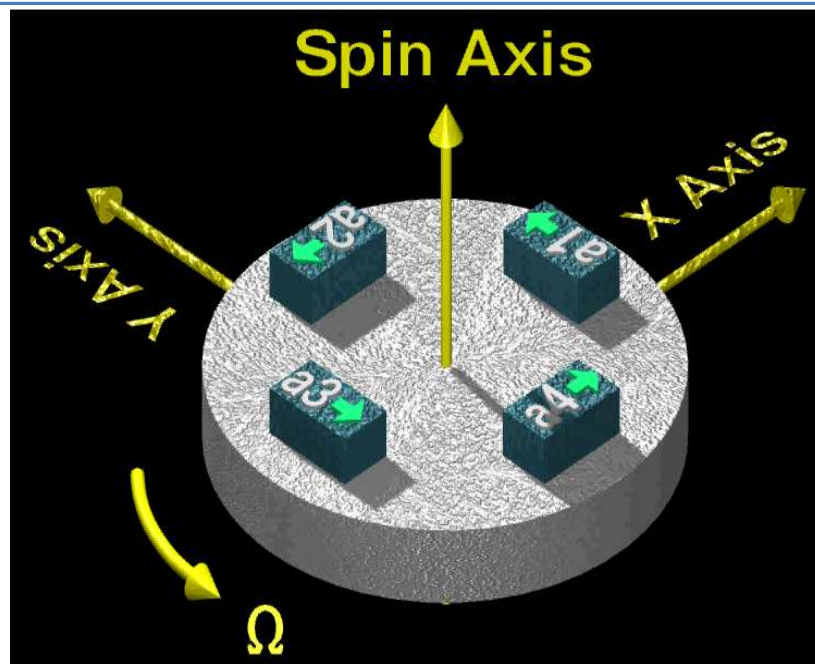


Figure A3.3: A diagram showing the relative positions of the accelerometers inside a GGI.

The matching between the accelerometers is crucial 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.

On-site operations:

The platform is mounted in the centre of the aircraft, minimising the effects of aircraft motion on the readings, as shown in Figure A3.4.

Once set up the FTG runs automatically with the platform stabilisation and GGI tuning handled continually by the circuits and software housed in the electronics cabinet. The user interface is through a computer called the System Control Processor (SCP) that allows the operator to monitor performance and status parameters and change settings such as calibration values. A second passive computer, the online monitor, picks up the data output from the SCP for further analysis and data recording.

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 A3.4: Air-FTG system installed in Basler aircraft

Calibrations:

The FTG platform and inertial navigation system and the GGIs (gravity gradient instruments) were calibrated according to standards set out by the manufacturer, Lockheed Martin. They were performed while the aircraft was immobile. This created a table of calibration factors that was used during data processing to remove the gradient effects of the variations in pitch, roll, and yaw experienced by the aircraft in flight.

The platform calibrations ensured that the FTG platform is correctly oriented and that the accelerometers and gyroscopes used for inertial navigation and platform stabilisation were accurately aligned and scaled. This was 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.

In addition to the static calibrations, GGI control parameters that minimise the FTG's sensitivity to external accelerations and vibrations were calculated from data recorded and processed during dedicated "tweak flights". Tweaks were also determined from routine survey data and were assessed after every flight to ensure that the system was working optimally.

Survey acquisition & recording:

Air-FTG flight planning at Bell Geospace involves three interlaces. Each interlace is made up of every third line of the survey plan. In addition to flying every third line, between each interlace the FTG platform is rotated 120 degrees which is referred to as the carousel angle. For example, the first interlace might have GGI 1 oriented at 000 degrees North, the second interlace might have GG1 at 120 degrees from North, and the third interlace might have GGI 1 oriented at 240 degrees from North. The intention of flying these interlaces and rotating the FTG platform is to help to isolate each GGI's noise characteristics across the survey area as an aid in noise analysis and reduction.

Data was acquired continuously throughout a flight, usually at ground speeds of around 215 km/hr. The system generates approximately 400 megabytes of data per hour, which is stored on a computer hard drive and backed up to external hard disk drives. Much of this data is high-rate motion data that is used to calculate compensated gradients in post-processing and other information such as environmental status is monitored and recorded continually. After processing and exportation of the gradient and navigation data at 1Hz sample rate, 1GB of data will compress to around 2MB.

Gradiometer data was 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 was 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.

Appendix 4 Positioning and Gravimeter details

Global Positioning System (GPS):

GPS data (position and Coordinated Universal Time) was acquired from a Novatel ProPak LB receiver system connected to a combined L1/L2/RTCM antenna. TerraSTAR's XP service was used to provide real-time differential corrections to the GPS data, enhancing the accuracy to approximately 0.1m for 95% of positions.

Transparent Earth Geophysics GTz (GT-3A):

The GTz (GT-3A) is a highly modified and re-designed version of the industry standard GT-2A airborne gravimeter. The GTz (GT-3A) modifications were designed and engineered by Transparent Earth Geophysics in Australia, and Transparent Earth Geophysics are the exclusive operators of this highly advanced system.

The GTz (GT-3A) was designed with a focus on size and weight reduction, in addition to improvements in the vibration isolation and thermal control - as compared to the GT-2A.

The installation weight of the GTz (GT-3A) is 60kg, compared to approximately 200kg for the GT-2A.

The operating temperature range of the GTz (GT-3A) is -30°C to +50°C, with internal "ambient" temperature controlled to within +/-1°C.

The core technology of the GT-2A has been preserved in designing the GTz (GT-3A), and this technology is described below;

The GTz (GT-3A) gravimeters are vertical sensor, GPS-INS, scalar gravimeters with a Schuler-tuned three-axis inertial platform. The vertical accelerometer, or gravity sensing element (GSE) has an axial design with a reference mass on a spring suspension, a photoelectric position pickup and a movingcoil force feedback transducer. The GSE suspension design minimises the effect of cross-coupling, an undesirable effect which contaminates gravity measurements with components of horizontal accelerations induced by aircraft motion. This feature allows the gravimeters to collect data in the presence of

large horizontal accelerations, such as during aircraft turns or during periods of high turbulence.



Figure A5.1: Image of GTz (left) and GT-2A (right) Airborne Gravimeters

The GSE, with a bandwidth of 100 Hz, is installed on the gyro-stabilised platform contained in a double-axis gimbal suspension. The platform also holds two horizontal accelerometers, a dynamically tuned gyro with a vertical angular momentum, a fibre optic gyro for azimuth control, and two gravimeter calibration devices. The latter are designed to calibrate the gravimeter by means of inclination without dismounting the GSE.

The gravimeters also contain a microprocessor, input/output interfaces, and secondary power supplies, all within the electronics bay. The GSE is placed in a double-loop constant-temperature environment on the inertial platform. The other elements installed on the platform, plus the current regulator of the code-to-current converter within the gyro control circuit, are individually temperature controlled.

Automated Operation

The gravimeters are fully automated – no operator is required on board the aircraft while collecting data on survey lines. All systems including stabilisation servo systems, temperature control systems and gyroscopic correction systems are controlled by the built-in microprocessor. The computer also takes control of actuation, reference measurements, balancing, and measurements during survey mode. A vertical gyro correction system using GPS-derived information on latitude and aircraft speed provides vertical gyro stability. An optimal Kalman filter is implemented in control algorithms for

both the stabilisation servo system and the vertical gyro correction system.

Dynamic range

The gravimeters have a dynamic range of $\pm 1,000$ Gals (1.0 g), allowing for acquisition in turbulent conditions.

Data is acquired through short periods of accelerometer saturation in extreme turbulence by the automatic application of a reduced-order Kalman filter, enabling platform misalignment to be computed and hence controlled. This feature, combined with high dynamic range, provide an extremely high tolerance to turbulence.

Internal software

The internal microprocessor carries out a large number of measurement and control functions. Measurements of platform orientation, rotation rates and accelerometer outputs are taken at 300 Hz, the same rate at which critical platform control and other internal functions are carried out. The high sampling rate eliminates aliasing of the high frequency vibrations encountered in most survey vehicles. This data is passed through an anti-aliasing filter and is subsequently processed and recorded at a rate of 18.75 Hz. The main control loop also runs at this frequency. Velocity and latitude data from the GPS receiver provide GPS-aided platform levelling, significantly improving the platform level during flight.



Figure A5.2: GTz (GT-3A) Gravimeter installed in a survey aircraft

Operating software

The gravimeters are operated by programs running on the GDAS-II. The easy-to-use

menu-based programs include calibration and diagnostic functions in addition to the normal data logging capability.

The calibration program has two modes for carrying out automatic GSE calibration. A 3-hour measurement period provides GSE calibration coefficients, while over a period of 5 hours, the program determines the above coefficients plus the non-perpendicularity angles between the GSE and the platform surface. This program is normally run once prior to each survey project and does not need to be run at the completion of the survey.

The diagnostic program maintains a running check on the serviceability of all gravimeter subsystems. Warnings regarding data quality are presented to the pilot through a remote light: flashing red means turbulence is approaching upper limits for the acquisition of high quality data; and solid red means high quality data cannot be recovered from the data being collected under present flight conditions.

Post-processing software

The gravimeters come with several programs for processing the GPS and gravimeter data collected to derive z-component, scalar, and relative gravity values. All programs are seamlessly integrated into Seequent Oasis Montaj for ease of use.

Quality Control is the first operation which must be carried out on the raw data files from the GPS receivers (rover and base) and the gravimeter. The QC program ensures that all data meets specifications for noise, offsets, and drift, and that high quality gravity data can be computed from the raw data.

The second stage operation is to compute delta-g values using a suite of programs. Operations are semi-automatic, with the operator having to arrange the raw data files as input to the various processes. Filters must be optimised to the flight conditions and target size, and the output files have clearly marked headers identifying each computed value.

Drift

The gravimeter's GSE design provides a highly linear drift which is easily compensated by recording a reference measurement at the same location immediately prior to and

following each flight. These reference measurements are then used to remove drift from data collected during the flight using linear interpolation. Four internal temperature monitors are recorded and are also used during postprocessing to correct the accelerometer's inherent drift to within 0.03 mGals/day.

Spatial Resolution

The gravimeters provide a wide range of spatial resolutions through the application of filters with varying cut-off frequencies.

Filters are chosen on the basis of aircraft ground speed, flight conditions and target dimensions. Filters might vary from 60 to 110 seconds or longer for more turbulent flights, which provides halfwavelength spatial resolutions of 1.5 and 2.75 km respectively with an aircraft ground speed of 50 m/sec. A helicopter flying at half this speed would provide resolutions of 750 m and 1.4 km respectively with 60 and 110-second filters.

System Precision

The gravimeters have a base-level sensitivity of 0.2 mGal under all test conditions. Combined with GPS in an airborne application, the basic noise level rises to approximately 0.6 mGal on repeat-line measurements based on RMS error from the mean. This noise level depends on the filters applied during post-processing and in turn this depends on flight conditions and aircraft speed. The following repeat line profiles detail typical performance under a range of flight conditions with a survey speed of 60 m/sec:

Appendix 5 Air-FTG Data Quality Control

Bell Geospace has developed numerous methods over the course of its history to monitor and evaluate the quality of acquired Air-FTG data, both on and off field.

Real time QC:

Accelerations measured by the instrument during data acquisition were closely monitored along with many other indicators of instrument performance. On the main screen, the operators visually inspected 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 were closely monitored and whenever an error was detected, the acquisition was interrupted with appropriate action taken. Many other factors were also monitored that would help alert the operator to any unusual performance of the FTG system. These included strip charts, coefficient tables and on-site off-line analysis of the data.

Besides monitoring physical characteristics such as temperature, humidity and power draws, the operator watched instrument position, rotation rates and other parameters that would indicate data problems. Individual GGI signals were also observed on the scope for indicators of quality deterioration.

Office based QC:

As well as visual inspection of the Air-FTG data for noise content, the following numerical analytic criteria were applied:

- › Vertical Acceleration (Vacc) – This assesses accelerations from standalone accelerometers that were in the system but not used to measure the gradient. This gave indication of the induced (non-gravity related) accelerations that the system was being exposed to which may add noise to the signal.
- › Inline Sum – By definition, the in-line energy of the data should sum to zero since it is a Laplacian Tensor. Practically, this is unachievable, thus threshold limits were determined that indicated if there was too much noise. For this, an alternative method for evaluating the inline sum noise was derived. It is the

normalised sum of the in-line energy ($= \text{sum}(\text{Inline}) / \sqrt{3}$), band=pass filtered at 0.033 – 0.1 Hz with a filter length of 256.

- › Line to Line QC – During processing, the lines are compared to their neighbours. Since 3D-FTG is a truly three-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 neighbouring lines. By gridding neighbouring lines and comparing we can get an indication of noise. Bell Geospace has a patented system (Auto Evaluate) that does this automatically and provides a numerical analysis of the results which we compare to a determined threshold.