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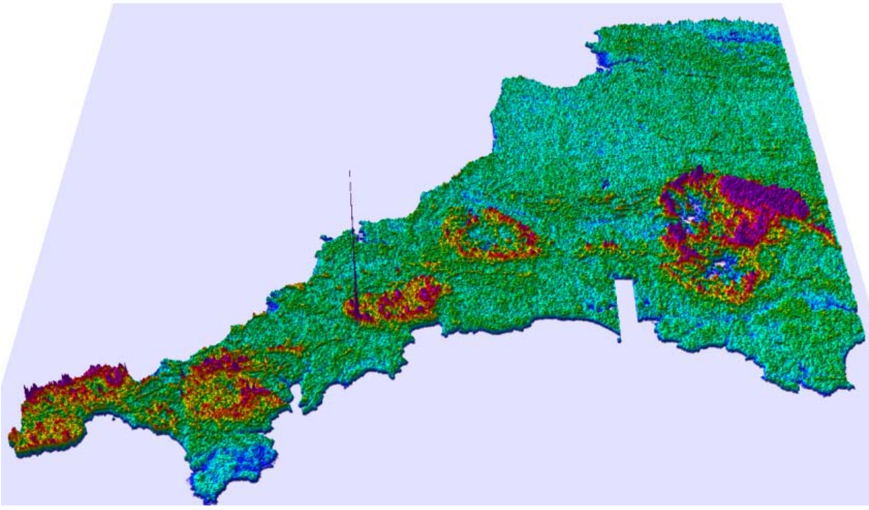
TellusSW: airborne geophysical data and processing report

Geology and Regional Geophysics Programme
British Geological Survey Report OR/14/014



BRITISH GEOLOGICAL SURVEY

Geology and Regional Geophysics Programme

OPEN REPORT OR/14/014

TellusSW: airborne geophysical data and processing report

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Keywords

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Front cover

Uranium distribution across the TellusSW survey area.

Bibliographical reference

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Foreword

This report describes the data and processing of an airborne geophysical survey conducted as part of the Geology and Regional Geophysics Programme. The airborne survey (TellusSW) covered a largely continuous onshore/offshore area in the SW of England primarily across the counties of Cornwall and Devon. The data acquisition was undertaken by the airborne geophysical contractor CGG Airborne Survey (Pty) Ltd (formerly Fugro Airborne Surveys) during the second half of 2013. The contractor delivered final processed data towards the end of February 2014. This report accompanies the release of the final TellusSW data set.

Contents

FIGURES

1 Introduction

The specification for the TellusSW airborne geophysical survey (http://www.tellusgb.ac.uk/) was developed in March 2013. The survey area (10,929 km^2) was centred on the onshore area of SW England and contains an offshore ribbon extension (Figure 1).

Figure 1. TellusSW Survey area (red polygon). Coordinates are British National Grid (m)

Tellus SW is the latest phase of a series of projects that have acquired modern, high resolution airborne geophysical data in the UK and Republic of Ireland. The UK, and recent Irish, surveys flown between 1998 and 2013 are shown in Figure 2. The original HiRES-1 North Midlands survey (Peart et al., 2003) of 1998 was largely acquired at lower spatial resolution (400 m line spacing) and at a higher elevation (90 m) than later surveys.

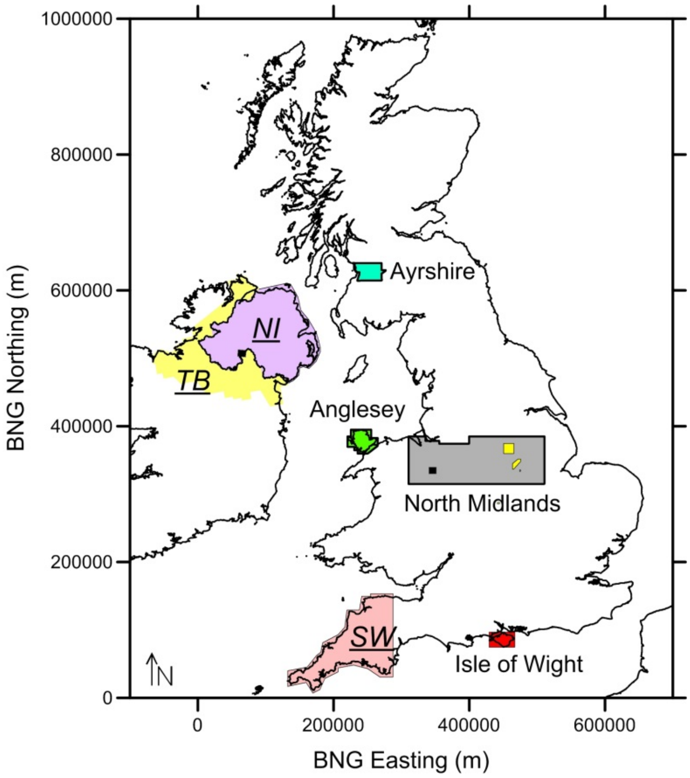

Figure 2. HiRES airborne geophysical surveys in the UK (1998-2013). The 3 Tellus surveys are labelled with italics and underline (NI: Tellus Northern Ireland, TB: Tellus Border, SW: TellusSW).

The 3 Tellus surveys, combining airborne geophysics and ground geochemical sampling, are identified in Figure 2. In contrast to previous Tellus surveys, TellusSW did not acquire airborne electromagnetic (EM) data alongside the standard magnetic and radiometric data. This was largely a result of both time and budget constraints.

The Tellus SW airborne geophysical survey encompasses the county of Cornwall and parts of Devon and Somerset. The survey comprises a high resolution magnetic/magnetic gradient survey combined with a multichannel (256 channel) radiometric survey, with these basic characteristics:

- Line spacing 200m
- Line orientation 0 degrees (N-S)
- Tie-line (E-W) spacing 2000m

The survey plan provided an estimated 60,000 line-km of geophysical data. The survey acquisition production dates were from 1 August 2013 to 02 January 2014, i.e. acquisition was conducted over a 5 month interval. The Appendix provides further details and production rates as supplied in the contractors report. The contractor used a triaxial magnetometer system (wing-tips and tail). This system further provides an estimate of localised measured horizontal gradient using the along- and cross-line gradients. The sampling of the magnetic data was 20 Hz providing an along-line sampling of 3.56 m using the mean survey speed noted later. The sampling of the radiometric data was 1 Hz and this provided a mean along-line sampling of 71 m.

The objective of the airborne survey is to provide high quality data for geological mapping, resource assessment and environmental management. Integrated with the other planned project information (e.g. soil and stream sediment geochemistry, airborne LIDAR), the data will contribute to the promotion of mineral exploration and environmental research and management in the fields of hydrogeology, soil-carbon/peat inventory, natural radioactivity, radon risk and geo-hazards.

The present report summarises the data delivered by the contractor and then provides an Appendix formed from the combined logistics and processing report delivered by the contractor. Since the combined report is highly verbose in terms of logistic detail, we have extracted the information of direct relevance to the delivered, processed data.

2 Data characteristics

All data were supplied in British National Grid (BNG) coordinates. The data coverage of the complete line-based data set is summarised in Figure 2.

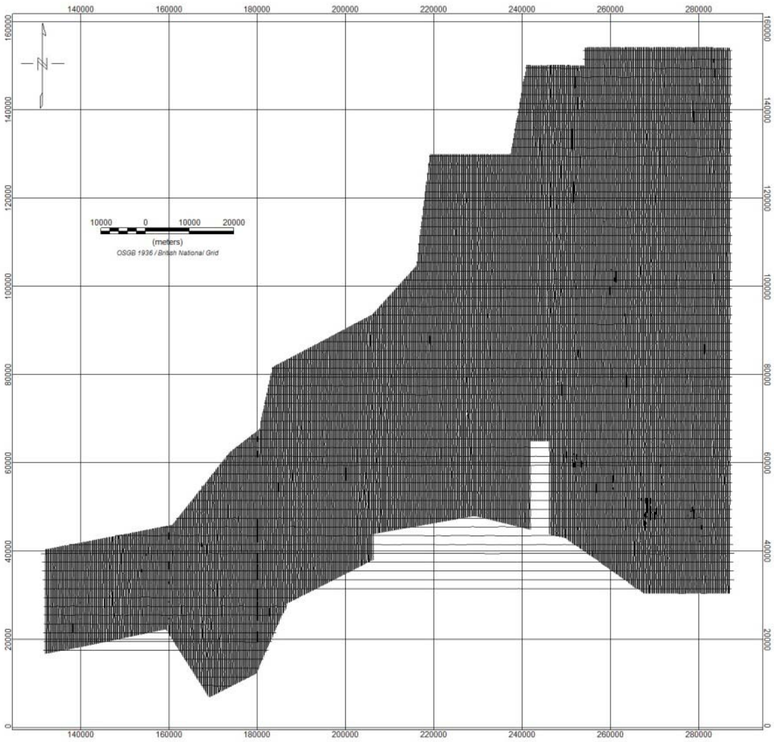

Figure 3. Line plot of delivered data (survey and tie-lines).

It can be seen that a set of offshore E-W tie-lines in the south of the survey area were included in the delivery. Additionally a survey line ‘gap’ exists on the south coast, to the west of Plymouth. This zone of omitted data was approved in the winter of 2013 during a prolonged period of poor weather. The poor weather combined with both onshore and offshore military restriction zones to effectively halt progress across this area. Permissions had been obtained to perform surveying across the controlled airspace above the Devonport naval dockyard however the survey would have been restricted to elevations of 2000 feet and above. This would have entailed long climbs and descents in a N-S direction and provided data of limited resolution.

Due to the poor weather experienced from mid-October onwards, the contractor undertook increasing amounts of partial-line acquisition. During final delivery, repeated requests to remove partial line overlaps in the data set were only partially successful. As a consequence the delivered data set contains a series of localised overlapping line sections.

Although the line-separation quality control was largely adhered to (see Appendix) there are a small number (3) of tall communication-mast 'avoids' within the data set.

The CAA permit for the survey ruled that the aircraft should survey 'at a height of less than 800 feet Minimum Safe Distance (MSD) over congested areas and not less than 260 feet MSD over all other areas.' The two heights referred to are 244 and 79 m respectively. The contractor developed a conventional drape plan, based on topography and aircraft performance (see Appendix). We requested 'over-sea' modifications to this drape plan to avoid climbs and descents over areas with major cliff zones (e.g. along the northern coast of the survey area). The contractor was not able to carry out these modifications due to inflexible software. The CAA requirements then formed visual 'in-flight' modifications to the drape plan.

The final delivered survey elevations range from 10 to 651 m and the pattern of variation is formed by a spatial convolution of the drape plan and locations of conurbations/structures across the survey area. Survey elevations above ground are shown in Figure 4 using a linear colour scale from 80 to 200 m.

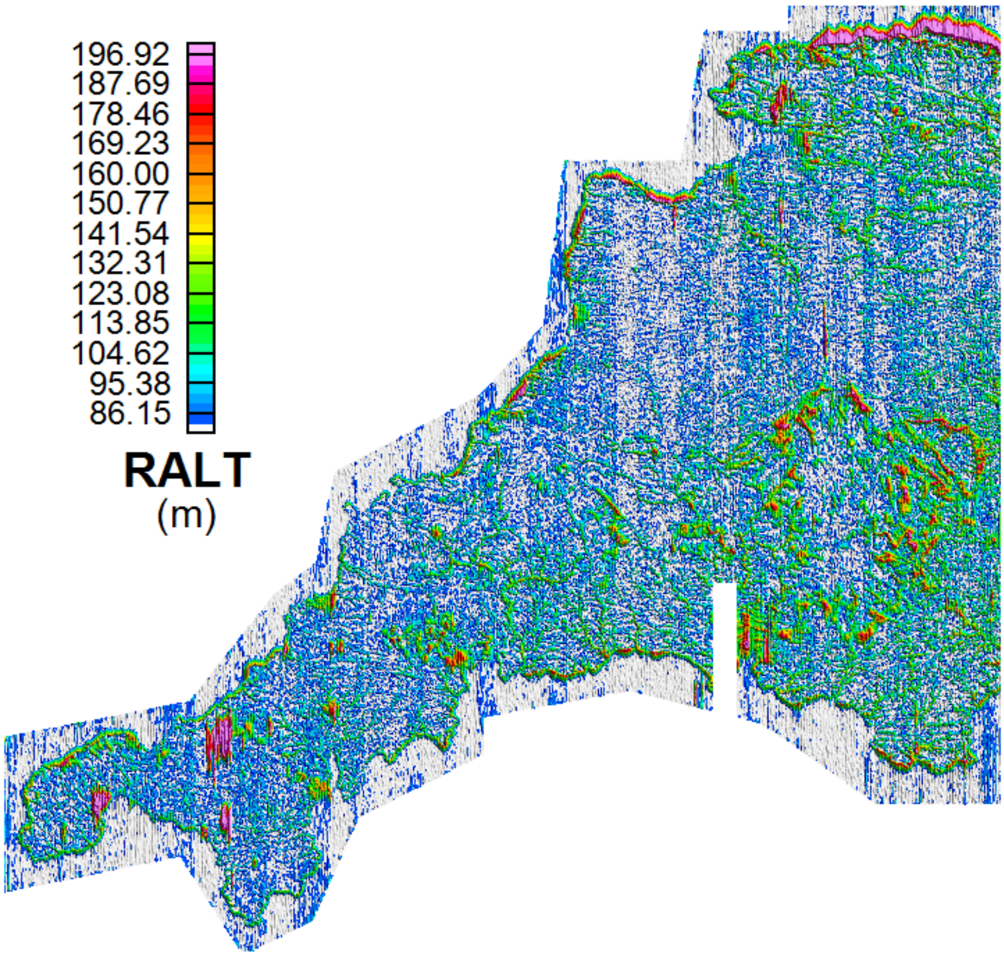

Figure 4. Survey elevations shown using a linear colour scale from 80 to 200 m.

The mean flying height for the TellusSW survey was a somewhat disappointing 91.6 m. Banded zones, presumably due to differing piloting abilities, can be observed in Figure 4.

The contractor delivered data are fully described in the Appendix. The delivered data contain 17,276,495 data points (MAGNETIC) and 855,362 data points (RADIOMETRIC). Some of the data channels contain DUMMY values (as a result of processing) and the available valid data sets effectively contain 17,140,169 data points (MAGNETIC) and 853,322 data points (RADIOMETRIC).

The line-km values within the database are 61,564,801 (MAGNETIC) and 61,896,591 line-km of RADIOMETRIC data. Data assessments shown in Table 1 contain both survey and tie-lines.

Table 1 Data characteristics of the delivered data. RALT refers to radar altitude.

BGS determined data characteristics				
	MIN	MAX	MEAN	Units/comment
FLIGHT NUMBERS	2	97		
SURVEY LINES	1010	8760		number
TIE-LINES	90020	90740		number
GPSZ (gps_height)	45.8	739.7	211.8	(m)
RALT	9.96	650.94	91.55	(m)
speed	45.98	92.84	71.21 (m/s)	256.35 (km/hr)
IGRFCorr_MAG	-1025.3	3009.2	-2.31	nT
Horizontal Gradient MAG	-18.04	39.98	-0.00003	nT/m
Diurnal MAG	48220.6	48595.5	48412.5	nT
IGRFCorr_MAG (4th DIFFERENCE, normalised)*	-3.7966	4.4311	0.0000	
Basemag (4th DIFFERENCE , normalised)	-0.0003	0.0003	0.0000	
Basemag (5nT / 2min)	0.0	2.62	0.20	nT (over 2 min)
Potassium**	-1.0	4.62	1.06	%K
Uranium**	-7.1	84.2	1.5	eU
Thorium**	-4.3	25.8	6.8	eTh
Total**	-395.8	20157.3	1176.3	cps

*There are 25 instances of the IGRFCorr_MAG_4th DIFFERENCE (normalised) having values greater than 0.5. There are 72 instances of the IGRFCorr_MAG_4th DIFFERENCE (normalised) having values greater than 0.1.

**Negative values in ground concentrations arise due to statistical uncertainty in the measurement when very low signal levels are encountered.

3 Data release

The contractor delivered data are to be released, in simplified form, as ASCII comma-separated value (.csv) files. The data format of these files are shown in Tables 2 (Magnetic) and 3 (Radiometric), below.

Table 2. Contents of ASCII file Magnetic data

Channel	Description	Units
X_BNG	Easting (X) BNG (OSGB 1936)	m
Y_BNG	Northing (Y) BNG (OSGB 1936)	m
Lat	Latitude in WGS84	ddd.mm.ss.ss
Lon	Longitude in WGS84	ddd.mm.ss.ss
flight	Survey flight number	
date	Survey flight date	yyyy/mm/dd
Line	Line number	
Igrf	International Geomagnetic Reference Field	nT
altimeter	Radar altimeter height from surface	m
processed_horizontal_gradient	Measured Horizontal Gradient (processed)	nT/m
levelled_mag	Total Magnetic Intensity (Levelled)	nT
levelled_mag_igrf_corrected	Residual Magnetic Intensity (Levelled)	nT

Table 3 Contents of ASCII file Radiometric data

Channel	Description	Units
X_BNG	Easting (X) BNG (OSGB 1936)	m
Y_BNG	Northing (Y) BNG (OSGB 1936)	m
flight	Survey flight number	
date	Survey flight date	yyyy/mm/dd
Line	Line number	
altimeter	Radar altimeter height from surface	m
processed_total_count	Final corrected total count	cps
processed_potassium	Final corrected potassium	%K
processed_uranium	Final corrected uranium	ppm (eU)
processed_thorium	Final corrected thorium	Ppm (eTh)

Additionally, gridded and georeferenced images of standard geophysical derived parameters are also available. These will be released for download via a BGS TellusSW data portal in the near future. Two of the standard images of the data are shown below.

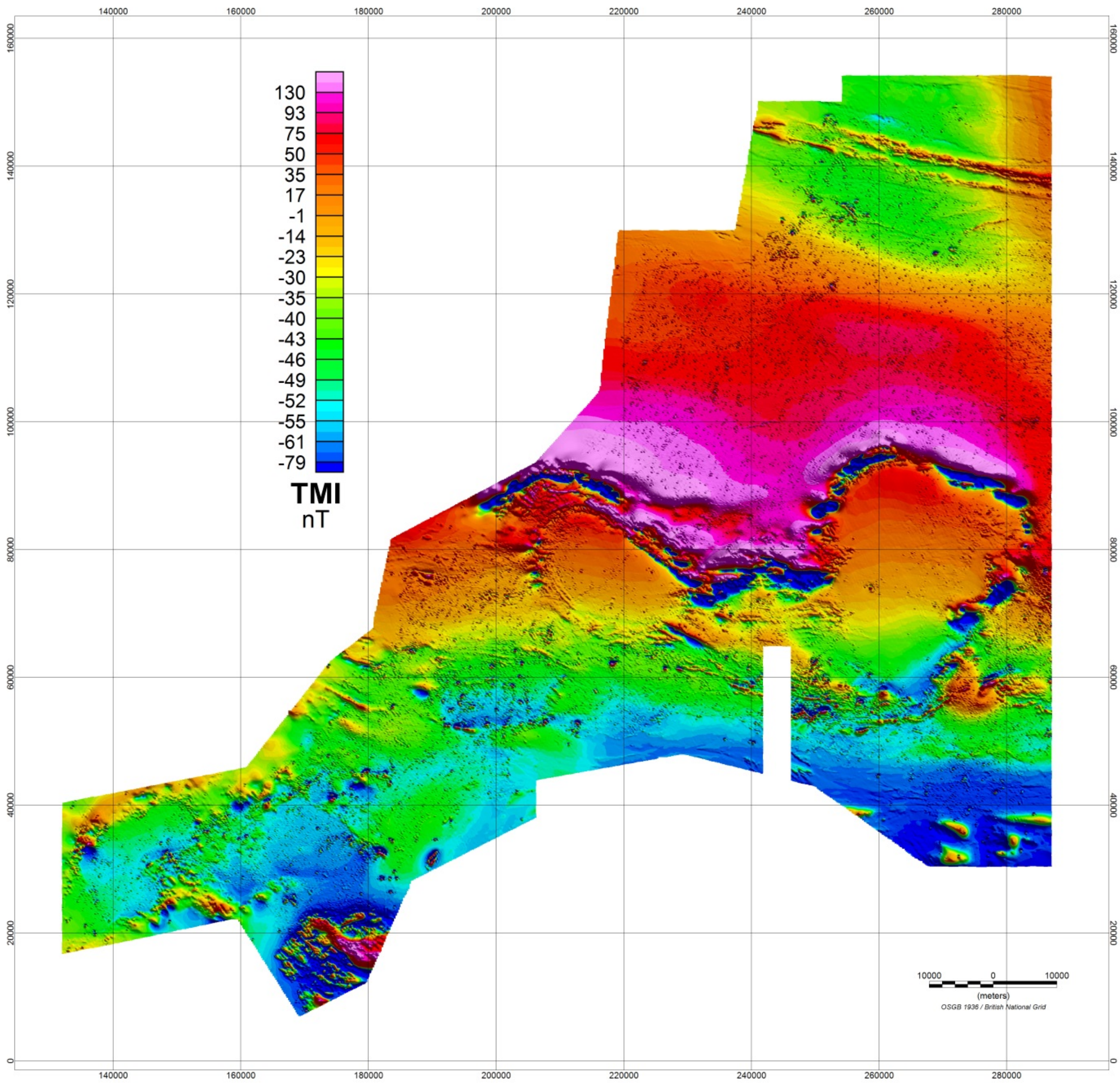

Figure 5. Total Magnetic Intensity (TMI), IGRF corrected to provide the final TMI anomaly data. Equal-area colour normalisation.

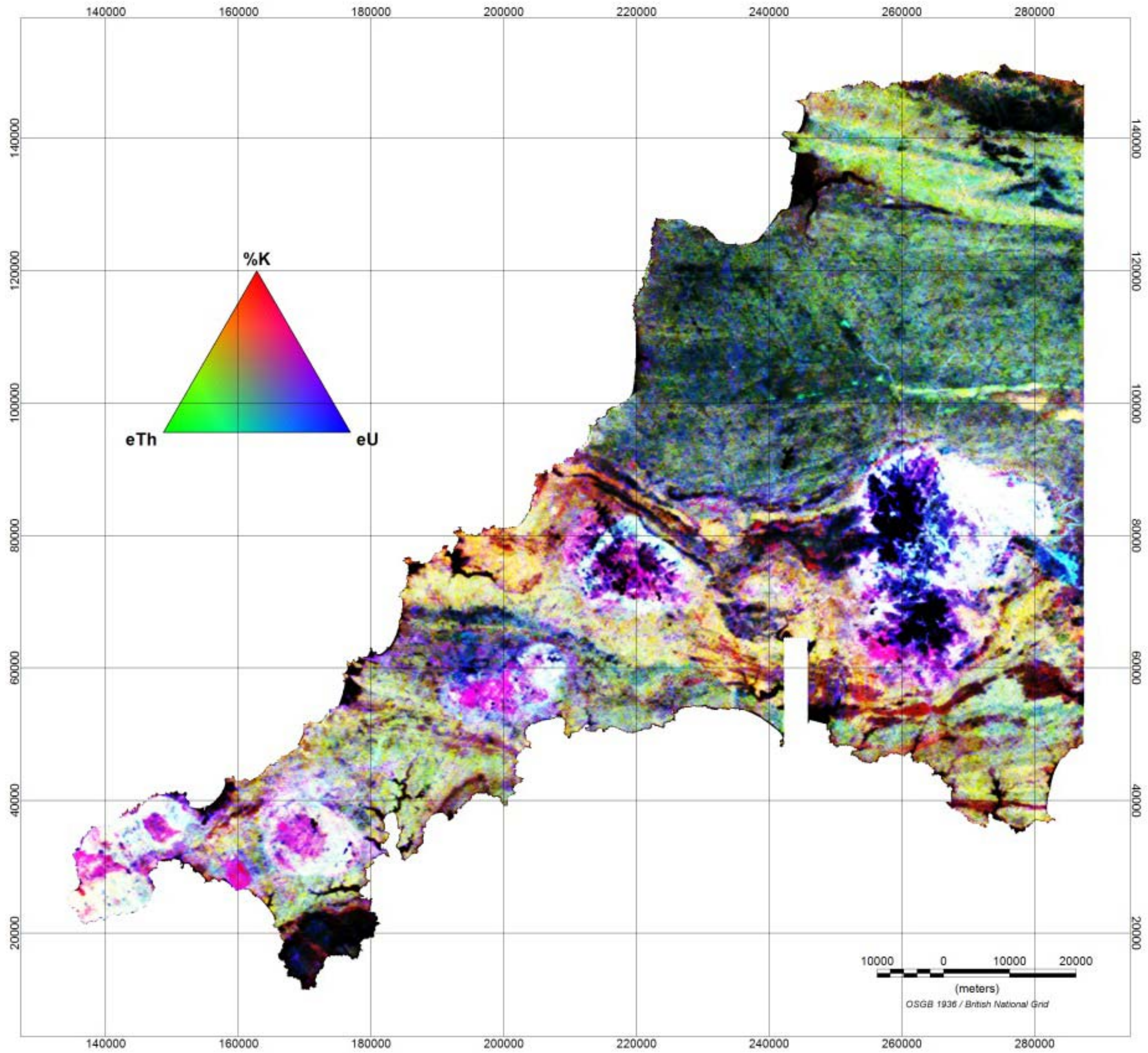

Figure 6. Ternary radiometric image formed from the Potassium (%K), Thorium (eTh) and Uranium (eU) ground concentration estimates.

4 References

British Geological Survey holds most of the references listed below, and copies may be obtained via the library service subject to copyright legislation (contact libuser@bgs.ac.uk for details). The library catalogue is available at: http://geolib.bgs.ac.uk.

PEART, R.J., CUSS, R.J., BEAMISH,D. & JONES, D.G., 2003. The High Resolution Airborne Resource and Environmental Survey- Phase 1 (HiRES-1): background, data processing and dissemination and future prospects. *British Geological Survey Internal Report*, **IR/03/112**. 28pp.

Appendix

The following Appendix is formed from a subset of the combined logistics and processing report delivered by the contractor CGG in February 2014.

PROJECT/LOGISTICS AND PROCESSING REPORT

February 2014

RCUK United Kingdom
United Kingdom

British Geological Survey. [BGS]

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CGG Project Number: **FCR2606**

1 Contents

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1 INTRODUCTION

CGG Airborne Survey used a FMAG system to conduct an airborne magnetic and radiometric survey over the 200 X 2000m Mag/Spec Area near Newquay / Cardiff, United Kingdom on behalf of BGS.
Award of the contract took place on June 2013 and mobilisation took place on 17 July 2013 following granting of the necessary authorisations and completion of on-site inspections.
Acquisition took place between 1 August 2013 and 2 January 2014, with the first production flight taking place on 1 August 2013; the final production flight on 2 January 2014.
The total combined area for production was for 60 323 line kilometres out of the planned 60 323 line kilometres. (Excluding the restricted area mutually agreed)
This report presents, in Part I, survey data, in Part II, logistics information, and, in Part III, processing information.

2 PART I: SURVEY INFORMATION

2.1 SURVEY AREA

The following figures (Figure 7. to **Error! Reference source not found.**) place the survey area in the context of the ONC Chart

Figure 7.: the geographical location as depicted on Google Earth

Figure 8: Survey area over Digital Terrain Map

Figure 9: Survey area over topography (SRTM)

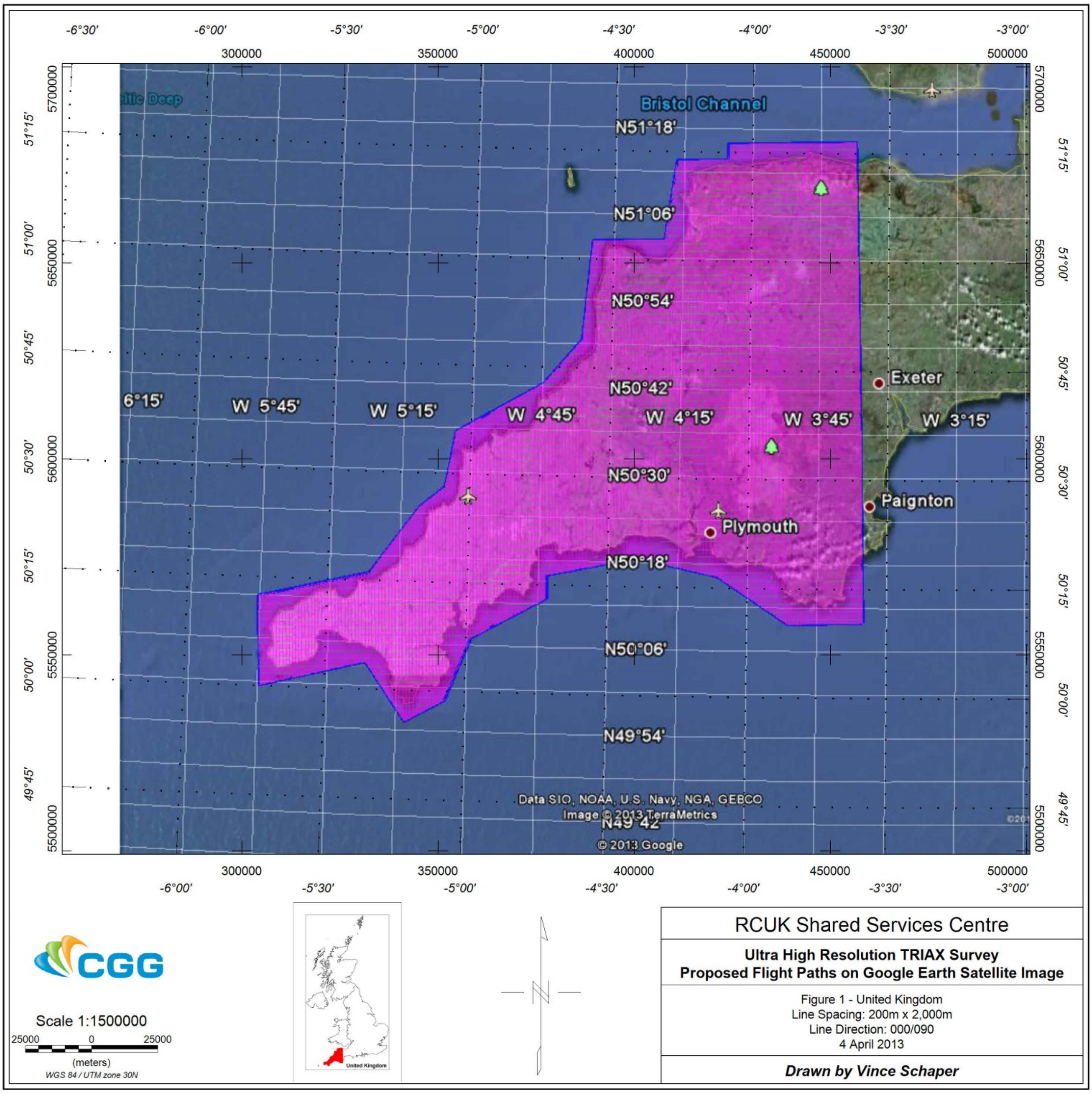


Figure 7. Survey area over Google Earth Satellite Image

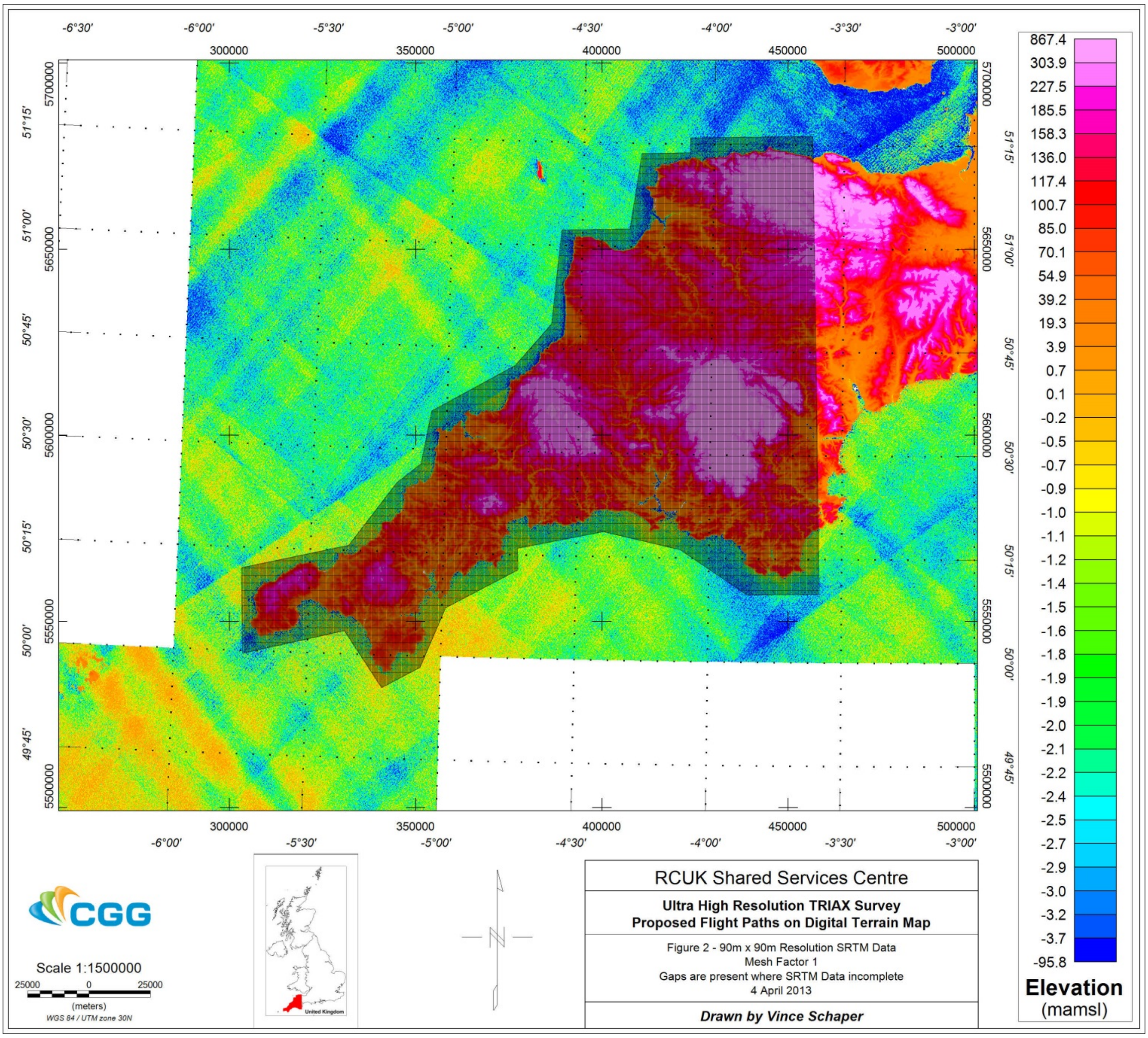


Figure 8. Survey area over Digital Terrain Map

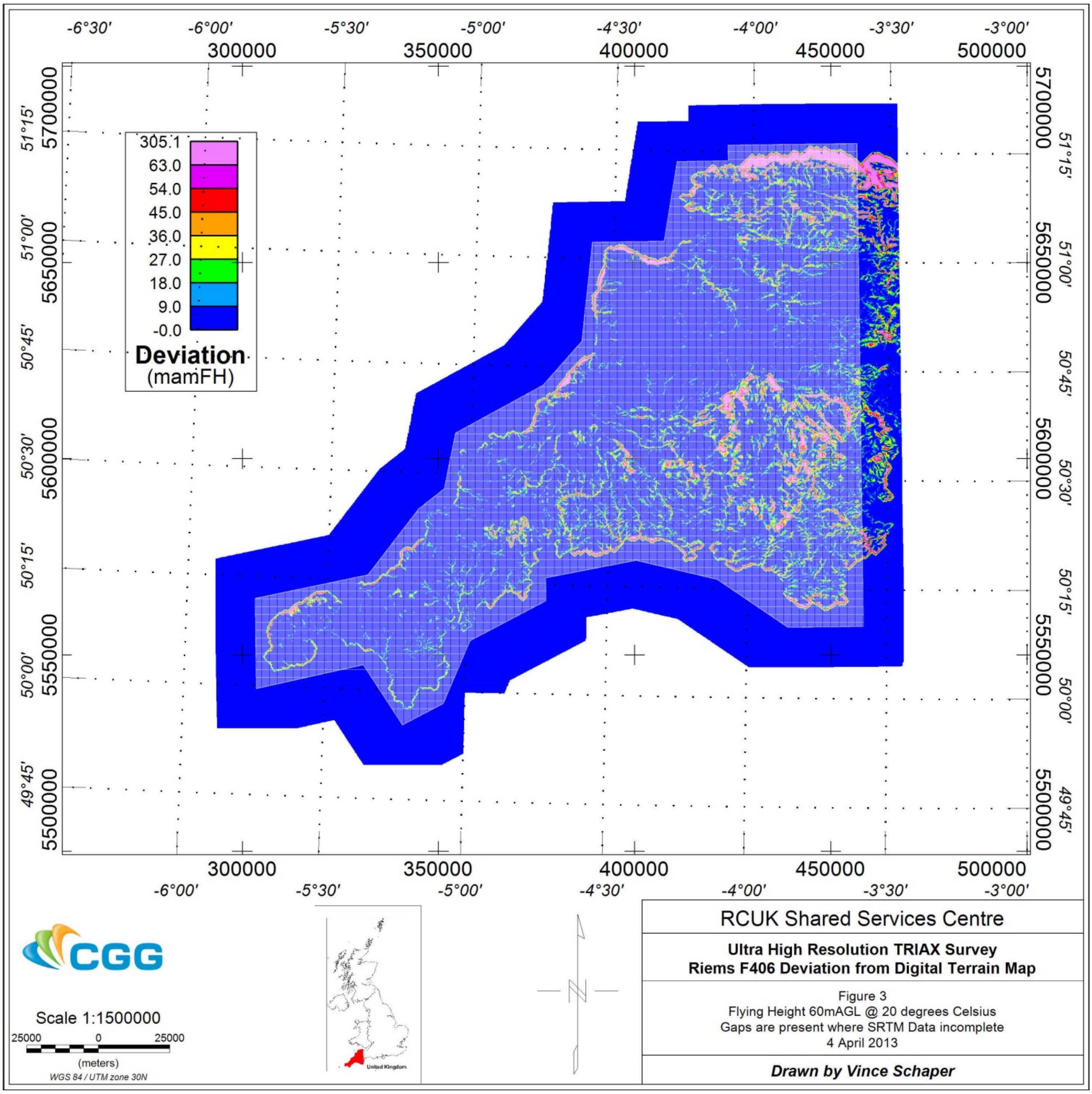


Figure 9: Survey area over topography (SRTM)

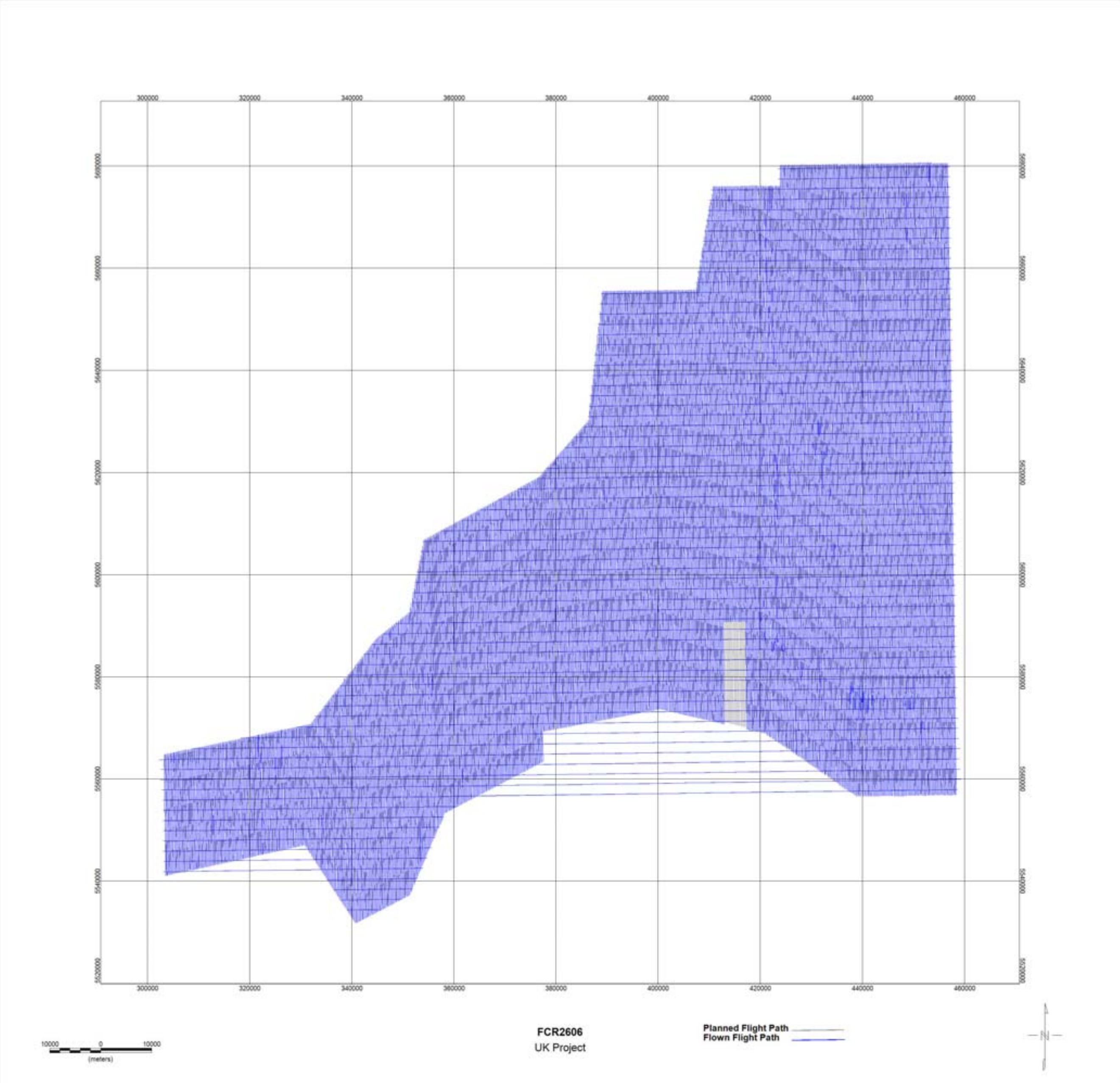


Figure 10: Completed survey lines (flight path trimmed to the survey area)

2.2 GEOGRAPHICAL COORDINATES SYSTEM USED

The data is provided in **[OSGB 1936] (21m) UK - Great Britain; Isle of Man** geographical coordinates system, EPSG code **4277**.

2.3 SURVEY BOUNDARIES

The following coordinates define the survey boundaries (see Figure 10 and Section 2.2).

200 X 2000m Mag_Spec

#	X	Y	LATITUDE DD.MM.SS.ss	LONGITUDE DD.MM.SS.ss

1	458320	5557292	50.09.58.940	-3.35.00.947
2	439047	5557034	50.09.44.579	-3.51.12.188
3	421015	5569274	50.16.13.139	-4.06.30.058
4	400371	5574101	50.18.38.135	-4.23.57.208
5	377342	5569674	50.15.59.238	-4.43.15.870
6	377421	5563812	50.12.49.588	-4.43.05.057
7	358031	5553650	50.07.05.158	-4.59.09.206
8	351180	5537610	49.58.20.110	-5.04.31.548
9	340831	5532212	49.55.15.845	-5.13.02.698
10	330857	5547499	50.03.20.538	-5.21.46.691
11	303562	5541422	49.59.33.816	-5.44.26.688
12	303254	5564404	50.11.56.704	-5.45.24.728
13	332029	5570398	50.15.42.525	-5.21.24.161
14	344980	5587224	50.24.59.650	-5.10.55.444
15	351447	5592322	50.27.50.609	-5.05.35.248
16	354291	5606491	50.35.31.613	-5.03.31.016
17	376682	5618701	50.42.25.304	-4.44.47.420
18	386517	5629897	50.48.34.835	-4.36.38.626
19	389247	5655149	51.02.13.922	-4.34.46.800
20	407519	5655397	51.02.33.582	-4.19.09.114
21	410822	5675665	51.13.31.420	-4.16.37.605
22	423879	5675843	51.13.43.989	-4.05.24.724
23	423825	5679840	51.15.53.328	-4.05.30.570
24	456658	5680287	51.16.20.192	-3.37.16.756

2.4 SURVEY PARAMETERS

Line spacing	:	200
Tie line spacing	:	2000
Line direction	:	0°
Tie line direction	:	90°
Total number of lines	:	776
Total number of tie lines	:	73
Total line kilometres	:	54704
Total tie line kilometres	:	5972

Sensor clearance
Magnetic : ~80 metres

The survey was flown to a drape surface.

2.5 REFLIGHT SPECIFICATIONS

Parameter	Data Specification
Diurnal:	Diurnal variation in excess of 5 nT per 2 minutes
Positional:	Line spacing should not exceed 1.25 times and not be less than 0.75 times the nominal line spacing for distances greater than 3.0 km along the flight path
Altitude:	In excess of 15m deviation for 5,000 metres or more dependent upon safety

On-line magnetic data:	The noise envelope of each sensor will remain below 0.2 nT outside zones where there are a pronounced magnetic gradient.

3 PART II: SURVEY LOGISTICS

3.1 AIRCRAFT AND EQUIPMENT

3.1.1 Aircraft and Geophysical On-Board Equipment

Aircraft	:	Reims F406
Operator	:	CGG AIRBORNE SURVEY
Registration	:	ZS-SSC
Survey Speed	:	140 knots
Magnetometer (x3)	:	Scintrex CS-3 single cell caesium vapour, wing pod(s) and/or tail stinger installation, sensitivity = 0.01 nT , sampling rate = 0.5 s, ambient range 20,000 to 100,000 nT. The general noise envelope was kept below 0.5 nT.
Digital Acquisition	:	FASDAS
Radar Altimeter	:	Honeywell KRA405B
Camera	:	Digital camera.
Electronic Navigation	:	Novatel OEMV-3 & Omnistar DGPS

3.1.2 Base Station Equipment

Magnetometer	:	Scintrex CS-3 single cell caesium vapour, mounted in a magnetically quiet area, measuring the total intensity of the earth's magnetic field in units of 0.01 nT at intervals of 0.5 sec, within a noise envelope of 0.20 nT.
GPS Receiver	:	NovAtel OEM4, measuring all GPS channels, for up to 12 satellites.
Computer	:	Laptop, Pentium model.
Data Logger	:	CF1, SBBS (single board base station).

3.1.3 Data Processing Equipment

Computer	:	Laptop computer.
Printer	:	Portable inkjet printer.
DVD writer Drive	:	Internal DVD+RW format.
Hard Drive	:	1024 GB Removable hard drive.

3.2 SURVEY ACQUISITION PROGRESS

PROJECT ACQUISITION FIGURES	
Total survey line kilometres Accepted	60 323
Total Flying Hours	415.2

Table 4 Project Acquisition Progress

PROJECT DOWNTIME FIGURES	
Total days flown	44
Lost days due to Weather Influence	77.25

Lost days due to Excessive Diurnal activity	0
Lost days due to Aircraft Mechanical Issues	15.25
Lost days due to Electronical Issues	1
Lost days due to Data / System Noise	0.5
Lost days due to sickness, injuries or other HSEQ Incidents	0
Lost days due to mandatory Pilot Down Days	0
Lost days due to Logistics (Permits, security, fuel shortages, unrest)	4.25 *(2 Days Total Invoice able)*
Lost days due to 3rd Party Influence	0

Table 5 Project Downtime Figures

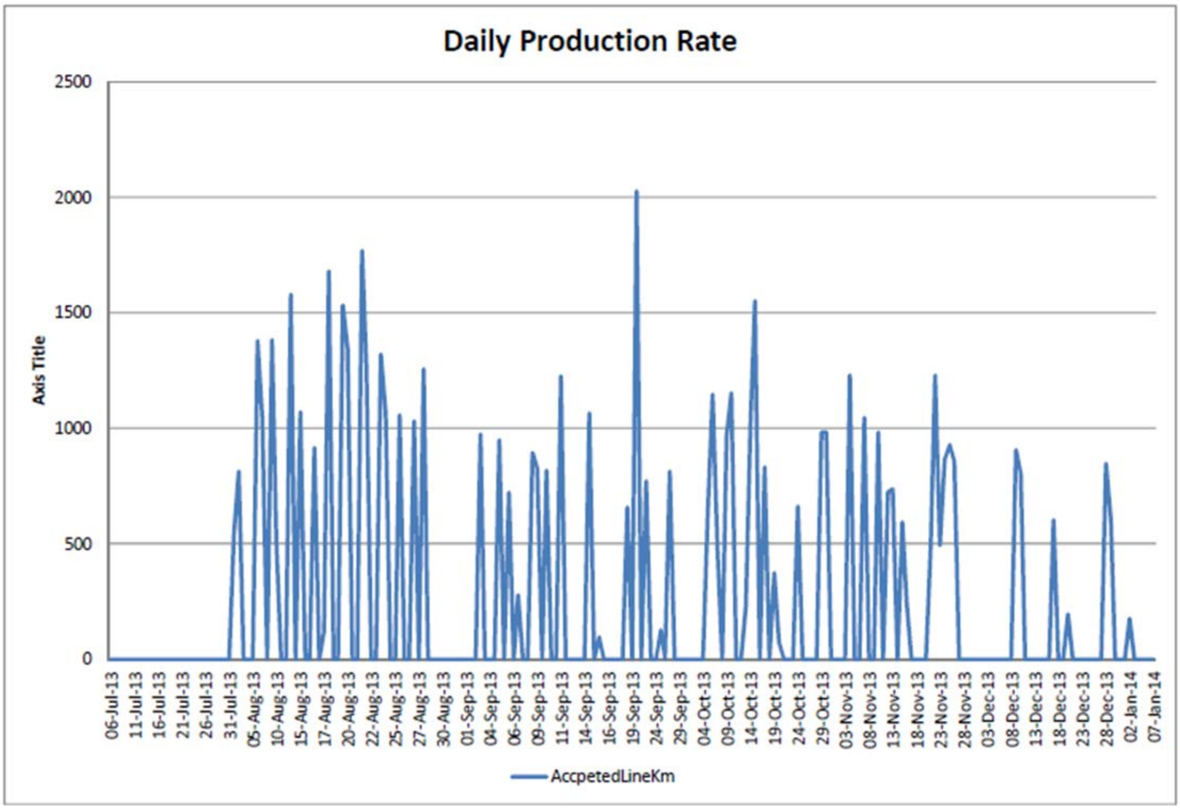


Figure 11: Production

3.3 AIRBORNE SYSTEM

Figure 12: Airborne system

3.4 TESTS AND CALIBRATIONS

Important checks were performed before, during and after the data acquisition stage to ensure that the data quality was in keeping with the survey specifications. The following outlines the Quality Control measures conducted throughout the acquisition phase of the survey.

3.4.1 System Lag

The difference between the time a reading is taken and the time it is stored, due to computer processing time and position of the different sensors relative to the GPS antenna was determined in the field. See Appendix 3 for the lag value of the different geophysical systems.

3.4.2 Magnetic Tests and Calibrations

3.4.2.1 MAGNETOMETER COMPENSATION (FOM)

The compensation procedure involved the flying, at altitude, over a magnetically quiet area, undertaking aircraft manoeuvres, rolls ± 10°, pitches ± 5° and yaws ± 5°, along headings parallel to the traverse and control line trends. A fluxgate magnetometer monitored these manoeuvre noise effects and the compensator accumulated the results. The compensator returned a Figure of Merit (FOM) value, results of which are presented in Appendix 3.

3.4.2.2 PARALLAX CONTROL

Before the commencement of the survey several lines were flown at standard speed and flying height in opposite directions over a suitable, well controlled magnetic anomaly to establish the parallax of the system (spatial relationship between GPS and magnetometer readings).

The system noise was measured and recorded at the project site before the survey started, see Appendix 3.

3.4.2.3 HEADING TEST

The results of the heading test are presented in Appendix 3.

3.4.3 Altimeter Calibration

The radar altimeter was calibrated at the start of the survey. See tabulated results in Appendix 3.

3.5 QUALITY CONTROL OF PRODUCTION DATA

3.5.1 Initial field QC

At the completion of each day's flying an initial review of the data was performed in the field. This process was primarily to ensure all the equipment was functioning properly and enables the crew to immediately ascertain that production can resume the following day. This process does not necessarily determine if the data were within specifications. Priority was given to getting the data back to the office where a more thorough analysis of the data was performed. A list of the steps of the initial field review of the data follows:

1) All digital files were confirmed to be readable and free of defects.
2) The integrity of the airborne data was checked through statistical analysis and graphically viewed in profile form. Any null values or unreasonable noise levels were identified.
3) All altimeter and positional data were checked for any inconsistency, invalid values and spikes.
4) The base station files were examined for validity and continuity. The data extent was confirmed to cover the entire acquisition period.
5) The diurnal data were examined for any noise events or spiking.
6) Flight path video files were visually checked for quality and to confirm the full coverage for the survey flight.
7) Duplicate backups of all digital files were created.

3.5.2 Data Checking and Editing

All acquired data were thoroughly checked at each field base prior to delivery to the Johannesburg processing centre, including checking of line and flight numbers and spike checking in all major data channels. Upon receipt of the data in Johannesburg, these procedures were repeated, beginning again from the raw (untouched) data and providing a backup check of data quality.

The line data was checked for noise, flight path separation, height deviation, gaps and spikes using in-house CGG ATLAS software. The magnetic diurnal was checked and later corrected as described in section 4.1.2 below.

All lines passed the basic QC check.

3.5.3 Line Spacing Control

Standard quality control routines were applied to highlight deviations from the planned flight path that exceed survey specification. These are accepted if a valid safety or other acceptable reason for the deviation is given in the flight log.

3.5.4 Height Control

The survey was acquired on a drape surface. The figure "Map of the height deviation from planned drape" in Appendix 3 presents the deviation from the planned drape.

4 PART III: DATA PROCESSING

Processing is currently performed in CGG ATLAS.

4.1 MAGNETIC DATA PROCESSING

The magnetic data is first de-spiked and decimated to 20 Hz.

4.1.1 Removal of System Parallax and Heading

The instruments recording magnetic intensity, magnetic gradient and various altitude parameters are at physically different locations to the instrument recording the aircraft position. In addition, each instrument requires a slightly different amount of time to process its raw inputs (frequency, voltage, etc.) and compute the raw data recorded by the acquisition system. The cumulative result of these effects is that data readings are recorded at a different time position to that at which they were actually acquired. As a result, the position with which they are recorded is offset in time from the position at which they were acquired. In order to correct for this discrepancy, a time offset is applied to the data readings to restore them to their correct time and thus location. The required offsets for each aircraft and each instrument are determined in field tests as described in Section 3.4 above.

Parallax corrections were applied to the data as per the tests carried out and detailed in Section 3.4.2.2 above.

Heading corrections were applied to the data as per the tests carried out and detailed in Section 3.4.2.3 above.

4.1.2 Correction for Temporal Magnetics ("Diurnal") Variation

Diurnal base station values were corrected for secular variation by removing the International Geomagnetic Reference Field (IGRF) field value at the base station location, computed at the time of measurement. This method is more effective than subtracting a simple constant since the regional field at any location is varying with time. The corrected (residual) diurnal field values were then subtracted from the interpolated and compensated magnetic data.

4.1.3 Correction for Regional Magnetic Variation (IGRF)

Regional effects of the earth's magnetic field were removed by subtracting from each reading the value computed from the IGRF 2010 model. IGRF was computed at each survey data point using the actual time that that point was surveyed.

GPS height is also used in IGRF computation as the large variations in height above sea level encountered in the project area yield significant variation in computed IGRF values. Failure to use actual aircraft height (above the spheroid) in such cases has been seen to cause additional levelling problems in regions of complex terrain.

Since IGRF removal is a regional field subtraction, no base value is applied to the result. Consequently, corrected values are true residuals in the sense that they range from negative to positive values. The computed IGRF values subtracted are provided in the final data.

4.1.4 Levelling

After correction for diurnal magnetic variations, residual levelling errors remain in the data. These result from the difference between diurnal activity measured at the base station and diurnal activity at the aircraft position. Errors also result from residual aircraft heading errors and imprecision in measuring aircraft position (vertical and horizontal).

A three stage procedure is then applied to the data to produce the final levelled magnetic data.

4.1.5 Gridding

Levelled data were then gridded to produce 2D maps of the data.

Refer to Table A5.1 in Appendix 4 for gridding parameters.

4.1.6 Residual Magnetic Intensity

The residual magnetic intensity (RMI) is calculated from the total magnetic intensity (TMI), the diurnal, and the regional magnetic field. The TMI is measured in the aircraft, the diurnal is measured from the ground station and the regional magnetic field is calculated from the International Geomagnetic Reference Field (IGRF). The first step is to remove the low frequency component of the diurnal from the TMI which is extracted from the filtered ground station data. The average of the diurnal is then added back in to obtain the resultant TMI. Next, we tie line level and micro-level the TMI data. The regional magnetic field, calculated for the specific survey location and time using the IGRF model, is removed from the resultant TMI to obtain the RMI.

4.1.7 Magnetic First Vertical Derivative

The first vertical derivative (1VD) was calculated in the frequency domain from the final grid values to enhance subtleties related to geological structures.

4.1.8 Reduction to the Pole

The residual magnetic intensity was reduced to the pole using a 2-D frequency domain operator, working from the gridded values of the levelled magnetic data. The calculation, assuming all induced magnetization, was based on the following magnetic field parameters:

- Magnetic declination: 2.5°W.
- Magnetic field inclination 65.5°N.

4.1.9 Analytic Signal of Magnetics

To improve on the definition of the magnetic structures, the analytic signal was calculated from the residual magnetic values. The analytic signal calculation is the Pythagorean sum (square root of the sum of the squares) of the three derivatives x, y and z. This was calculated in the frequency domain by using a 2-D operator working from the gridded values of the levelled magnetic data.

4.1.10 Calculated Horizontal Gradient

The calculated horizontal gradient was derived from the residual magnetic intensity grid to enhance the high frequency content of the data and attenuate the low frequency background. It was normalized to nanoteslas per metre based on the cell size.

4.1.11 Horizontal Gradient Gridding

The levelled anomalous magnetic field grid are generated from measured lateral and calculated longitudinal gradients as follows:

The lateral gradient was levelled to correct for DC offsets from line to line, that are caused by hysteresis, by computing the average lateral gradient for each line.

A horizontal gradient grid was then computed from the measured lateral and computed longitudinal gradients and the forward transform computed.

The frequency domain grid for the total field was computed by use of the transfer function below:

$$fft(TF) = \left(\frac{-i}{k^2}\right)(kx\ \ fft(gx) + ky\ \ fft(gy))$$

where kx and ky were the wave numbers in the x and y directions and k2 was $\sqrt{kx^2 + ky^2}$. This transform was computed for every point in the frequency domain except kx=ky=0. This point represented the DC value of the total field, which was computed by calculating the average total field value for the survey area.

The reverse FFT was then computed for the above frequency domain grid and the DC value above added.

5 Radiometric Processing

5.1 ENERGY CALIBRATION

Energy recalibration, dead time correction and region of interest selection were performed in field during the field tape extraction process. A peak position statistics file is generated. This is used in the extraction process to select the appropriate channel (fractional) range for calculation of the standard channels, using Specdrift (Proprietary CGG Airborne Survey software).

.1.1 ROI	Channel	KeV	Label
1	34 – 224	404 – 2805	Tc
2	115 – 131	1369 – 1574	K
3	139 – 155	1652 – 1863	U
4	202 – 233	2415 – 2812	Th
5	-	-	-
6	-	-	-

7	-	-	-
8	139 - 155	1652 – 1863	UP

Cs-137 was windowed from the 256 channel data using the limits below.

	Energy Limits		Channel Limits	
	Lower	**Upper**	**Lower**	**Upper**
Cs-137	**648**	**732**	**54.08**	**61.09**

5.2 DEAD TIME CORRECTION

The calculated standard windows were time normalized to counts per second. This is done by dividing the count rate by the live time. In the case of the cosmic channel which has different counting circuitry with minimal dead time, the channel was normalised by dividing by the sample time. This is also done during the extraction process.

The extracted file was loaded into the database where subsequent radiometric processing was performed.

5.3 COSMIC AND AIRCRAFT BACKGROUND REMOVAL

Before the radiometric processing below was performed, the data was filtered to reduce statistical noise. The filtering applied was typically as follows:

- Potassium, Uranium, Thorium, Total count channels were filtered with a Gaussian low pass filter with filter length of 5 samples to reduce statistical noise.
- Radar altitude channel was filtered with a 5 point Gaussian cut off filter so that the altimeter response time matches that of the radiometric data.
- Cosmic channel was filtered with a running average of 20 terms. Due to the increased volume of upward crystal the number of terms for uranium up may be decreased. This was decided after examination of data statistics.

The time normalized and filtered channels were corrected as follows:

$$Kbg = K_F - KACBG - K\underline{COS\_F} * Cosmic$$

$$Ubg = U_F - UACBG - U\underline{COS\_F} * Cosmic$$

$$Thbg = Th_F - ThACBG - Th\underline{COS\ F} * Cosmic$$

$$TCbg = TC_F - TCACBG - TC\underline{COS\ F} * Cosmic$$

$$UCAVbg = U_{av} - UACBG - UCOS\_F * Cosmic$$

$$THAVbg = TH - ThACBG - ThCOS\_F * Cosmic$$

where KF, UF, ThF, TCF, UUPF are time normalised filtered potassium, uranium, thorium, uranium up and cosmic channels; KACBG, UACBG, ThACBG, TCACBG are the aircraft backgrounds for potassium, uranium, thorium, total count; Uav and Thav are the channels filtered by means of a running average.

5.4 RADON BACKGROUND REMOVAL

The radon correction was then computed using Minty's method.

Minty's method (1992) is a technique for estimating the background atmospheric (radon) radiation in Airborne Gamma-ray Spectrometry.

The method uses the observations that:

in modern airborne spectrometric systems the resolution of the detectors at the 214Bi photopeaks at 0.609 MeV (from atmospheric radiation) and 1.76 MeV (from uranium in the ground) is well resolved above the Compton continuum, and;

due to the differences in spectral shapes between the two 214Bi photopeaks it is possible to differentiate low energy airborne 214Bi signals (at 0.609 MeV) from the higher energy terrestrial ones (from uranium, at 1.76 MeV): the low energy 214Bi photopeak at 0.609 MeV is less attenuated than the 214Bi peak at 1.76 MeV;

those photopeaks can then be used to estimate the contributions of radon and uranium to the observed spectrum because thorium and potassium sources do not contribute appreciably to these peak count rates.

The technique of determination of background by full spectrum analysis is applied after the aircraft and cosmic backgrounds are removed from the observed spectrum. It involves computing the radon contribution and the uranium contribution to the low energy (0.609 MeV) and high energy (1.76 MeV) peak count rates using the observed count rates in those energy peaks and the computation of three constants determined from the radon and uranium spectra. In turn, the radon contribution to the background in the standard uranium window is computed and added to the aircraft and cosmic backgrounds to get the total uranium channel background. And finally the computed uranium background is used to estimate the total count and potassium backgrounds. Thorium background is computed independently from the aircraft and cosmic backgrounds.

Reference:

Minty, B.R.S., 1992, Airborne gamma-ray spectrometric background estimation using full spectrum analysis. Geophysics, Vol 57, No. 2, PP. 279-287.

The radon correction values were then removed from the filtered background and cosmic corrected values Kbg, Ubg, Thbg and Tcbg

5.5 CALCULATION OF EFFECTIVE HEIGHT

The height from the filtered height channel was then converted to effective height at standard temperature and pressure as per the following formula:

$$h_e = \frac{273hP}{1013(T+273)}$$

Where:

h = the observed radar altitude in metres.

T = the measured air temperature in degrees Celcius.

P = the barometric pressure in millibars.

5.6 SPECTRAL STRIPPING

The background corrected count rates in the three windows must be stripped to give the counts in the potassium, uranium and thorium windows that originate solely from potassium, uranium and thorium. The stripping ratios α, β, γ, a and g must be determined from measurements over calibration pads. The three principal stripping ratios (α, β, and γ) increase with altitude above the ground as shown in Table 2.The background corrected data is then stripped. Before stripping the coefficients are corrected for variation from height as follows:

Where:

The background corrected data was then stripped.

Before stripping the coefficients were corrected for variation from height as follows:

αe = α + 00049 * he

βe	=	β	+	00065	*	he
γe	=	γ	+	00069	*	he

Table 6 – Stripping Ratios

Where:

he is equivalent height above ground at STP.

α, β and γ are the stripping ratios calculated at ground level.

αe, βe and γe are the corresponding co-efficients at height he and,

a, b, g are the reverse stripping co-efficients derived from the PAD calibrations.

Stripping is then applied as follows:

$$N_{K,K} = [N_{TH}(\alpha e \gamma e - \beta e) + N_u(a\beta e - \gamma e) + N_K(1 - a\alpha e)]/A$$
$$N_{U,U} = [N_{TH}(g\beta e - \alpha e) + N_u(1 - b\beta e) + N_K(b\alpha e - g)]/A$$
$$N_{TH,TH} = [N_{TH}(1 - G\gamma e) + N_u(b\gamma e - a) + N_K(ag - b)]/A$$

Where:

A = 1 - g γe - a (αe - g βe) - b (βe - αe γe).

NK = Observed potassium counts corrected for background.

NU = Observed uranium counts corrected for background.

NTH = Observed thorium counts corrected for background.

NK,K = Stripped counts in K.

NU,U = Stripped counts in U.

NTH,TH = Stripped counts in Th, and,

αe, βe, γe are stripping coefficients derived from the pad calibration,

and a, b, g are coefficients as described above.

5.7 HEIGHT CORRECTION

The background corrected and stripped count rates are corrected for variations in the altitude of the detector using the following equation:

$$N_{corr} = N_{obs} e - \mu(h_o - h)$$

Where:

Ncorr = the count rate normalised to the nominal survey altitude, h0.

Nobs = the background corrected, stripped count rate at STP height h and

μ = the attenuation coefficient for that window.

5.8 CONVERSION TO CONCENTRATIONS

The corrected window count rate data will be converted to ground concentrations of potassium, uranium and thorium using the following expression:

$$C = \frac{N}{S}$$

Where:

C = concentration of the radioelement (K%, U ppm or Th ppm).
S = broad source sensitivity for the window; and,
N = count rate for each window, after dead-time, background, stripping and height correction.

5.9 LEVELLING

Some leveling was required after radiometric correction. This was done using proprietary tie-line leveling and micro-leveling software routines where required.

5.10 NOISE ADJUSTED SINGULAR VALUE DECOMPOSITION (NASVD)

Noise adjusted singular value decomposition (NASVD) was used to considerably enhance low signal to noise regions of the survey.

The technique is an enhancement of the principal component (PC) technique commonly used in Remote Sensing for processing of Landsat and Spot images. The PC technique is a linear transformation of multiband data that generates uncorrelated components.

Each successive component contributes successively less variance to the total response. The first PC can be considered the spectral shape that contributes most to the overall response.

This technique is enhanced by adjusting the variances to fit that expected for a Poisson distribution. This yields components that have physical meaning.

5.11 PRODUCTS DELIVERED

The following products have been delivered. It is noted that all products are digital and have been presented in the project coordinates reference system (See Section 2.2).

5.11.1 Geosoft Grids

Magnetic Grids

▪ tmi.grd	Total Magnetic Intensity (TMI) - nT
▪ tmi_hg_enhanced.grd	TMI with Horizontal Gradient enhancement (nT)
▪ tmi_igrf.grd	IGRF Correcxted TMI (nT)
▪ tmi_igrf_1VD.grd	First Vertical Derivative of TMI (nT/m)
▪ tmi_igrf_analytical_signal.grd	Analytical Signal of TMI-(nT/m)
▪ tmi_igrf redp.grd	Reduction to the Pole of TMI (nT)

Radiometric Grids

▪ Potassium masked.grd	Processed Potassium with offshore data masked out (%)
▪ Potassium.grd	Processed Potassium (%)
▪ Thorium masked.grd	Processed Thorium with offshore data masked out (ppm)
▪ Thorium.grd	Processed Thorium (ppm)
▪ Total Count masked.grd	Processed Total Count with offshore data masked out (cps)
▪ Total Count.grd	Processed Total Count (cps)
▪ Uranium masked.grd	Processed Uranium with offshore data masked out (ppm)
▪ Uranium.grd	Processed Uranium (ppm)

Other Grid

- Terrain.grd Digital Terrain Model (m)

5.11.2 Final Databases

FORMAT OF GEOSOFT MAGNETIC DATABASE

Channel	Description	Units
X	Easting (X) in WGS84 UTM Zone 30N	m
Y	Northing (Y) in WGS84 UTM Zone 30N	m
X_BNG	Easting (X) OSGB 1936	m
Y_BNG	Northing (Y) OSGB 1936	m
Lat	Latitude in WGS84	ddd.mm.ss.ss
Lon	Longitude in WGS84	ddd.mm.ss.ss
fid	Fiducial number	
flight	Survey flight number	
date	Survey flight date	yyyy/mm/dd
humidity	Humidity	Degrees C
Fluxgate X	Fluxgate X	millisecs
Fluxgate Y	Fluxgate Y	millisecs
Fluxgate Z	Fluxgate Z)	millisecs
Igrf	International Geomagnetic Reference Field	nT
diurnal	Magnetic Ground Base Station	nT
diurnal_igrf	IGRF Corrected Magnetic Ground Base Station	nT
gps_time	Time in seconds after midnight	seconds
gps_height	Altitude above WGS84 Datum	metres
altimeter	Radar altimeter height from surface	metres
pressure	Outside air pressure	mb
temperature	Outside air temperature	Degrees C
compensated_mag_left_sensor	Total Magnetic Intensity (compensated)	nT
compensated_mag _right_sensor	Total Magnetic Intensity (compensated)	nT
compensated_mag _tail_sensor	Total Magnetic Intensity (compensated)	nT
raw_horizontal_gradient	Horizontal Gradient (compensated)	nT
processed_horizontal_gradient	Horizontal Gradient (processed)	nT/m
levelled_mag	Total Magnetic Intensity (Levelled)	nT
levelled_mag_igrf_corrected	Residual Magnetic Intensity (Levelled)	nT
inclination	Magnetic Inclination	degrees
declination	Magnetic Declination	degrees
terrain	Calculated digital terrain model	m
srtm_data	SRTM	m

FORMAT OF GEOSOFT RADIOMETRIC DATABASE

Channel	Description	Units
X	Easting (X) in WGS84 UTM Zone 30N	m
Y	Northing (Y) in WGS84 UTM Zone 30N	m
X_BNG	Easting (X) OSGB 1936	m
Y_BNG	Northing (Y) OSGB 1936	m
fid	Fiducial number	
flight	Survey flight number	
date	Survey flight date	yyyy/mm/dd
STime	Sample time	millisecs
LTime	Live time	millisecs
gps_time	Time in seconds after midnight	seconds
gps_height	Aircraft height above geoid	metres
altimeter	Radar altimeter height from surface	metres
pressure	Outside air pressure	mb
temperature	Outside air temperature	Degrees C
cosmic	Cosmic radiation	counts
uranium_up	Upward looking Uranium	counts
normalised_total_count	Total count (normalised)	counts
normalised_total_count_nasvd_processed	NASVD corrected total count (normalised)	counts
processed_total_count_nasvd	Final corrected total count	cps
normalised_potassium_nasvd	Potassium (normalised)	counts
normalised_potassium_nasvd_processed	NASVD corrected potassium (normalised)	counts
processed_potassium_nasvd	Final corrected potassium	%

normalised_uranium	Uranium (normalised)	counts
normalised_uranium_nasvd_processed	NASVD corrected uranium (normalised)	counts
processed_uranium_nasvd	Final corrected uranium	ppm
normalised_thorium	Thorium (normalised)	counts
normalised_thorium_nasvd_processed	NASVD corrected thorium (normalised)	counts
processed_thorium_nasvd	Final corrected thorium	ppm
raw_256_down	Downward looking radiometric spectra	
raw_256_up	Upward looking radiometric spectra	

FORMAT OF GEOSOFT TESTLINE DATABASES

Channel	Description	Units
X	Easting (X) in WGS84 UTM Zone 30N	m
Y	Northing (Y) in WGS84 UTM Zone 30N	m
Lat	Latitude in WGS84	ddd.mm.ss.ss
Lon	Longitude in WGS84	ddd.mm.ss.ss
fid	Fiducial number	
flight	Survey flight number	
date	Survey flight date	yyyy/mm/dd
gps_time	Time in seconds after midnight	seconds
gps_height	Aircraft height above geoid	metres
altimeter	Radar altimeter height from surface	metres
pressure	Outside air pressure	mb
temperature	Outside air temperature	Degrees C
STime	Sample time	millisecs
LTime	Live time	millisecs
TC_nasvd	Total count (normalised)	counts
K_nasvd	Potassium (normalised)	counts
U_nasvd	Uranium (normalised)	counts
Th_nasvd	Thorium (normalised)	counts
TC_processed	Final corrected total count	cps
K_processed	Final corrected potassium	%
U_processed	Final corrected uranium	ppm
Th_processed	Final corrected thorium	ppm
raw_256_down	Downward looking radiometric spectra	
raw_256_up	Upward looking radiometric spectra	

6 CONCLUSIONS

CGG Airborne Survey used a FMAG system to conduct the airborne magnetic only survey over the 200 X 2000m Mag_Spec Area near Newquay / Cardiff, United Kingdom on behalf of BGS.

No major HSE incidents or accidents have been reported during the duration of the survey.

A total of 60 646 line kilometres was successfully acquired.

Submitted by:

Nigel Stack

APPENDICES

APPENDIX 3: TESTS AND CALIBRATIONS RESULTS

APPENDIX 4: GRIDDING PARAMETERS

APPENDIX 5: RADIOMETRIC SPECTRAL INDEX FIGURES

APPENDIX 6: CALIBRATION REPORT AIRCRAFT ZS-SSC

APPENDIX 3: TESTS AND CALIBRATIONS RESULTS

Figure of Merit

– Refer to Section 3.4.2.1

PORT

Line Number	Direction	ROLL (nT)		PITCH (nT)		YAW (nT)		FOM
77110	0	-0.0435	-0.0716	-0.0391	-0.0778	-0.0209	-0.0289	0.178
		0.0281		0.0387		0.0080		
77110	270	-0.0515	-0.0813	-0.0375	-0.0811	-0.0359	-0.0674	0.230
		0.0298		0.0436		0.0315		
77110	180	-0.0203	-0.0545	-0.0268	-0.0491	-0.0439	-0.0926	0.196
		0.0342		0.0223		0.0487		
77110	90	0.0041	-0.0169	-0.0618	-0.0994	-0.0196	-0.0658	0.182
		0.0210		0.0376		0.0462		
						TOTAL		**0.786**

STARBOARD

Line Number	Direction	ROLL (nT)		PITCH (nT)		YAW (nT)		FOM
77110	0	-0.0273	-0.0691	-0.0405	-0.0676	-0.0099	-0.0170	0.154
		0.0418		0.0271		0.0071		
77110	270	-0.0301	-0.0623	-0.0760	-0.1115	-0.0309	-0.0609	0.235
		0.0322		0.0355		0.0300		
77110	180	-0.0952	-0.2326	-0.0513	-0.0446	-0.0662	-0.1545	0.432
		0.1374		-0.0067		0.0883		
77110	90	-0.0473	-0.0697	-0.0372	-0.0365	-0.0044	-0.0217	0.128
		0.0224		-0.0007		0.0173		
						TOTAL		**0.948**

TAIL

Line Number	Direction	ROLL (nT)		PITCH (nT) -0.0375		YAW (nT)		FOM
77110	0	-0.0150	-0.0375	-0.0404	-0.0767	-0.0268	-0.0557	0.170
		0.0225	-0.0575	0.0363		0.0289		
77110	270	-0.0267	-0.0575	-0.1177	-0.1449	-0.0546	-0.0904	0.293
		0.0308	-0.0583	0.0272		0.0358		
77110	180	-0.0048	-0.0583	-0.0792	-0.1502	-0.0468	-0.0847	0.293
		0.0535	-0.0208	0.0710		0.0379		
77110	90	-0.0160	-0.0208	-0.0241	-0.0596	-0.0361	-0.0667	0.147
		0.0048		0.0355		0.0306		
						TOTAL		**0.903**

Figure of Merit – 29-July-2013

PORT

Line Number	Direction	ROLL (nT)		PITCH (nT)		YAW (nT)		FOM
77110	0	-0.1088	-0.0904	0.0059	-0.0183	-0.0715	-0.0810	0.190
		-0.0184		0.0242		0.0095		
77110	270	-0.1538	-0.0273	0.0151	-0.0427	-0.0051	-0.0797	0.150
		-0.1265		0.0578		0.0746		
77110	180	-0.0806	-0.0705	-0.0301	-0.0230	-0.0163	-0.0533	0.147
		-0.0101		-0.0071		0.0370		
77110	90	0.0106	-0.0201	-0.0358	-0.0340	-0.0505	-0.0635	0.118
		0.0307		-0.0018		0.0130		
						TOTAL		**0.604**

STARBOARD

Line Number	Direction	ROLL (nT)		PITCH (nT)		YAW (nT)		FOM
77110	0	-0.1413	-0.1432	-0.0908	-0.0763	-0.0021	-0.0605	0.280
		0.0019		-0.0145		0.0584		
77110	270	-0.0262	-0.0635	-0.1139	-0.0704	-0.0649	-0.0521	0.186
		0.0373		-0.0435		-0.0128		
77110	180	-0.0967	-0.0636	-0.0327	-0.0675	-0.0419	-0.0617	0.193
		-0.0331		0.0348		0.0198		
77110	90	-0.0554	-0.0536	-0.0404	-0.0542	0.0243	-0.1066	0.214
		-0.0018		0.0138		0.1309		
						TOTAL		**0.873**

TAIL

Line Number	Direction	ROLL (nT)		PITCH (nT)		YAW (nT)		FOM
77110	0	-0.0464	-0.0717	-0.0499	-0.0604	-0.0571	-0.1423	0.274
		0.0253		0.0105		0.0852		
77110	270	-0.0090	-0.0234	0.0002	-0.0456	-0.0525	-0.0369	0.106
		0.0144		0.0458		-0.0156		
77110	180	-0.0131	-0.0283	0.0106	-0.0154	-0.0495	-0.0287	0.072
		0.0152		0.0260		-0.0208		
77110	90	-0.0310	-0.0411	0.0011	-0.0384	-0.0305	-0.0909	0.170
		0.0101		0.0395		0.0604		
						TOTAL		**0.623**

Figure of Merit – 13-October-2013

PORT

Line Number	Direction	ROLL (nT)		PITCH (nT)		YAW (nT)		FOM
77110	0	-0.0801	-0.1677	-0.0217	-0.0340	-0.059	-0.1273	0.329
		0.0876		0.0123		0.0683		
77110	270	-0.0277	-0.0697	-0.0446	-0.0867	-0.0382	-0.0555	0.212
		0.042		0.0421		0.0173		
77110	180	-0.0912	-0.1590	-0.0532	-0.1065	-0.0745	-0.1244	0.390
		0.0678		0.0533		0.0499		
77110	90	-0.0358	-0.0604	-0.0224	-0.0575	-0.047	-0.1178	0.236
		0.0246		0.0351		0.0708		
						TOTAL		**1.167**

STARBOARD

Line Number	Direction	ROLL (nT)		PITCH (nT)		YAW (nT)		FOM
77110	0	-0.0021	-0.0220	-0.0343	-0.1082	-0.0661	-0.1516	0.282
		0.0199		0.0739		0.0855		
77110	270	-0.0274	-0.0690	-0.0945	-0.1400	-0.038	-0.0623	0.271
		0.0416		0.0455		0.0243		
77110	180	-0.0876	-0.1307	-0.0325	-0.0874	-0.0566	-0.1165	0.335
		0.0431		0.0549		0.0599		
77110	90	-0.0196	-0.0330	-0.0095	-0.0621	-0.0946	-0.1660	0.261
		0.0134		0.0526		0.0714		
						TOTAL		**1.149**

TAIL

Line Number	Direction	ROLL (nT)		PITCH (nT)		YAW (nT)		FOM
77110	0	-0.0099	-0.0948	-0.0521	-0.1077	-0.0553	-0.1207	0.323
		0.0849		0.0556		0.0654		
77110	270	-0.0659	-0.1319	-0.0509	-0.0958	-0.0636	-0.1630	0.391
		0.066		0.0449		0.0994		
77110	180	-0.0448	-0.0931	-0.0049	-0.0141	-0.051	-0.0575	0.165
		0.0483		0.0092		0.0065		
77110	90	-0.006	-0.0132	-0.0084	-0.0115	-0.0024	-0.0722	0.097
		0.0072		0.0031		0.0698		
						TOTAL		**0.976**

Figure of Merit – 09-December-2013

PORT

Line Number	Direction	ROLL (nT)		PITCH (nT)		YAW (nT)		FOM
77110	0	-0.0232	-0.0800	-0.0994	-0.1782	-0.0239	-0.0472	0.305
		0.0656		0.0788		0.0233		
77110	270	-0.0704	-0.0935	-0.1156	-0.1838	-0.0469	-01003	0.378
		0.0231		0.0682		0.0534		
77110	180	-0.0612	-0.0696	-0.0606	-0.1050	-0.0589	-0.1227	0.297
		0.0084		0.0444		0.0638		
77110	90	-0.0496	-0.0785	-0.0705	-0.1227	-0.0585	-0.0997	0.301
		0.0295		0.0522		0.0412		
						TOTAL		**1.281**

STARBOARD

Line Number	Direction	ROLL (nT)		PITCH (nT)		YAW (nT)		FOM
77110	0	-0.0766	-0.1709	-0.0689	-0.0552	-0.0561	-0.0848	0.311
		0.0933		-0.0137		0.0288		
77110	270	-0.1596	-0.3075	-0.0845	-0.1668	-0.0555	-0.1049	0.579
		0.1479		0.0828		0.0494		
77110	180	-0.0055	-0.0435	-0.0572	-0.0837	-0.0799	-0.1386	0.266
		0.0491		0.0265		0.0587		
77110	90	-0.0187	-0.0996	-0.0774	-0.1300	-0.0386	-0.0938	0.323
		0.0809		0.0526		0.0558		
						TOTAL		**1.479**

TAIL

Line Number	Direction	ROLL (nT)		PITCH (nT)		YAW (nT)		FOM
77110	0	-0.0137	-0.1850	-0.0047	-0.1232	-0.0453	-0.1054	0.414
		0.1713		0.1185		0.0601		
77110	270	-0.1080	-0.0886	-0.0496	-0.1359	-0.0726	-0.1243	0.349
		0.0194		0.0863		0.0517		
c77110	180	-0.0468	-0.1087	-0.0281	-0.1212	-0.0588	-0.1173	0.347
		0.0627		0.0931		0.0585		
77110	90	-0.0485	-0.1116	-0.0413	-0.1163	-0.0386	-0.0656	0.294
		0.0631		0.0751		0.0278		
						TOTAL		**1.403**

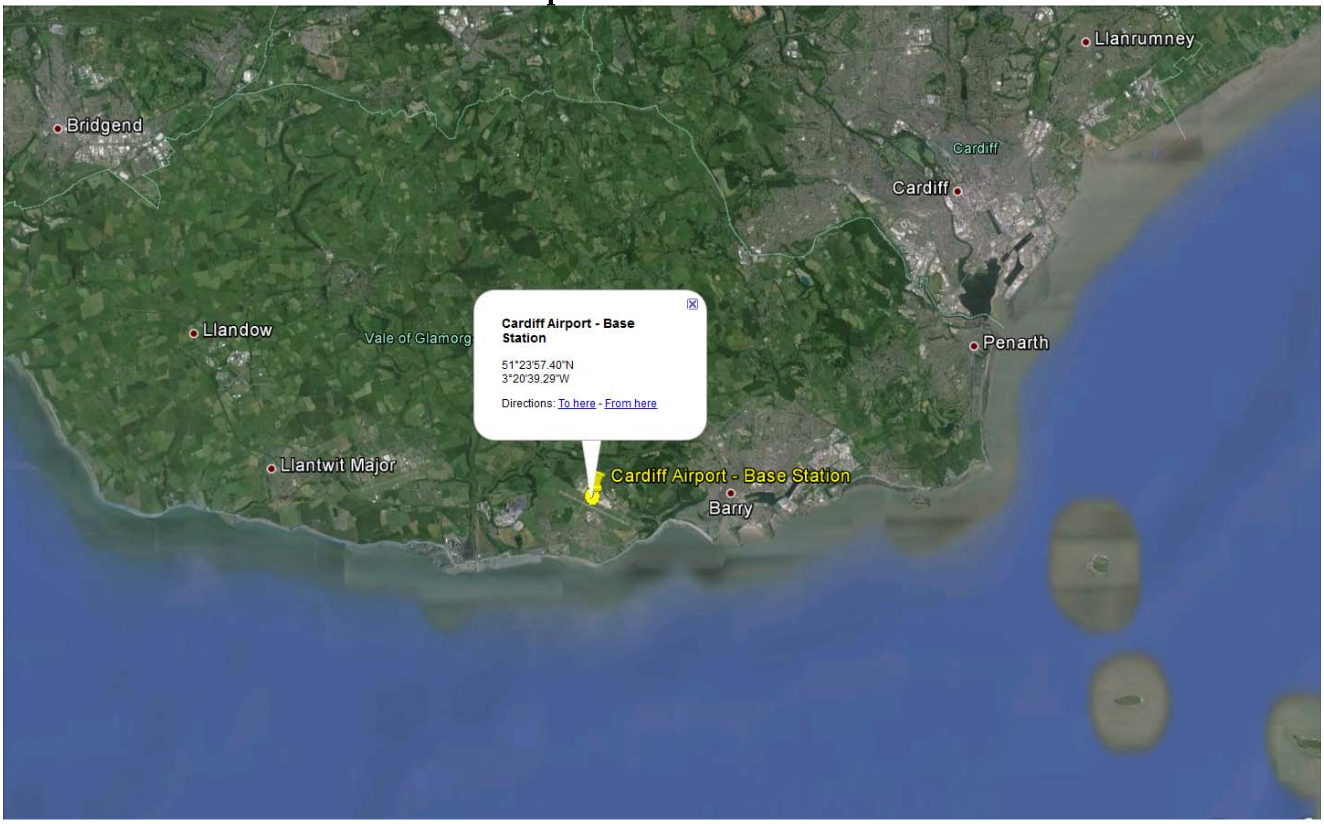
Figure of Merit – -02-January-2014

Lag correction:

Lag correction value for the magnetic system used for survey : 1.0 s

Newquay Base Station

Cardiff Airport – Base Station



Heading Test

– Refer to Section 3.4.2.3

Censor Aft

Line	Direction	Mag Reading	Heading	Error
76010	0	48408.550	0 -180	**-0.030**
76020	180	48408.580		
76030	270	48403.470	90 - 270	**-1.560**
76040	90	48405.030		

Censor Port

Line	Direction	Mag Reading	Heading	Error
76010	0	48409.000	0 -180	**0.200**
76020	180	48408.800		
76030	270	48403.600	90 - 270	**-2.480**
76040	90	48406.080		

Censor Starboard

Line	Direction	Mag Reading	Heading	Error
76010	0	48404.970	0 -180	**1.320**
76020	180	48403.650		
76030	270	48399.170	90 - 270	**-2.340**
76040	90	48401.510		

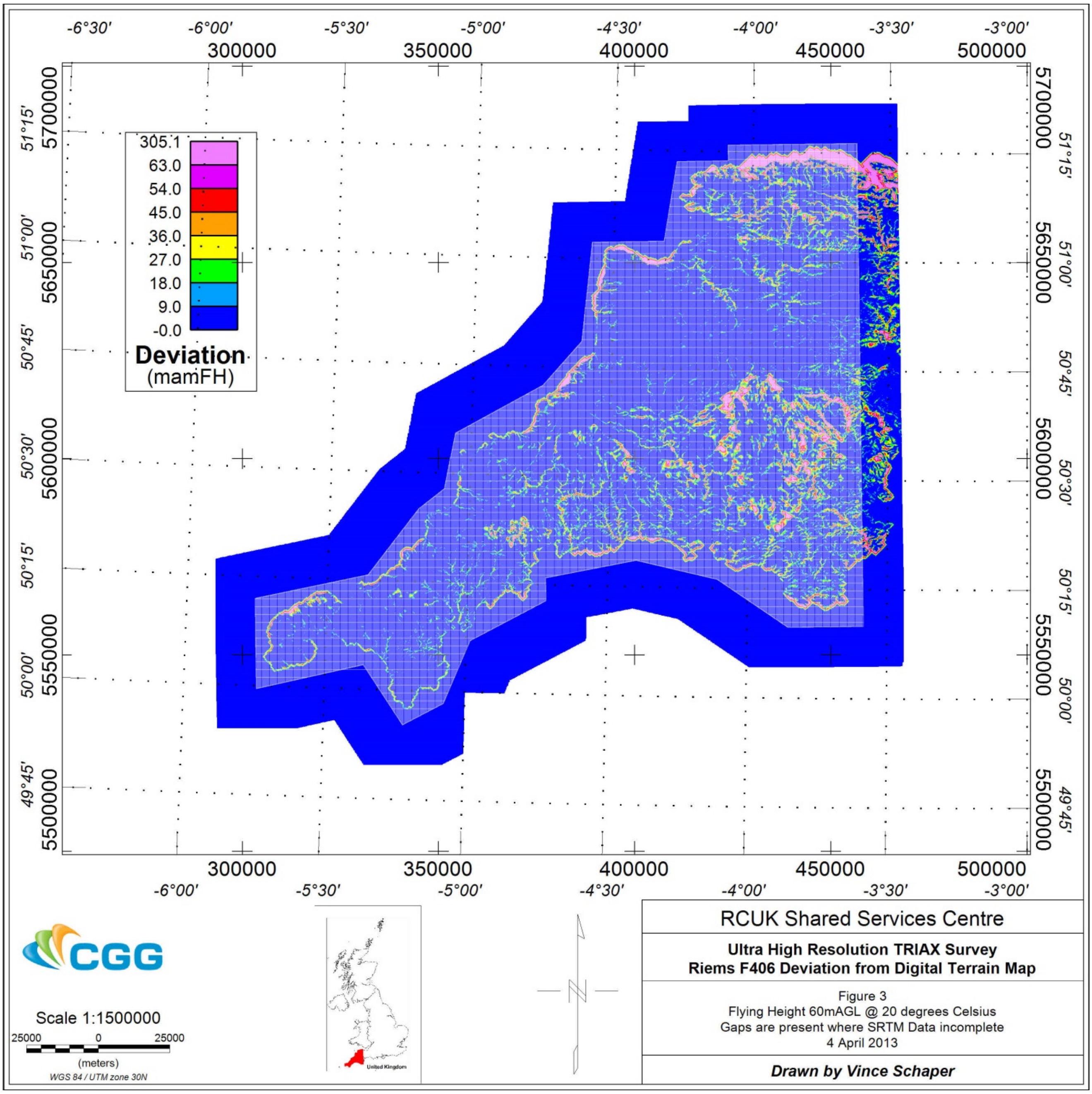
Altimeter Calibration

– Refer to Section 3.4.3

```
Number of observations on runway = 153

Temp (min, avg, max) = 0.000000 0.000000 0.000000
Baro (min, avg, max) = 0.000000 0.000000 0.000000
GpsH (min, avg, max) = 115.967000 116.708144 117.669000
Knee: ADC1_1 = -968922.037468
    Height AGL = 48.039069

Linear regression below knee: Height AGL = -0.000050 * ADC1_1 +0.017044
Correlation coefficient = 0.999602
Standard error         = 0.979880
Number of observations  = 154

Linear regression above knee: Height AGL = -0.000049 * ADC1_1 +0.691082
Correlation coefficient = 0.999794
Standard error         = 0.457766
Number of observations  = 81

Height    Height          ADC          ADC
(feet)    (metres)        linear       non-linear

   0       0.00          108410          344
 100      30.48          113359      -614647
 200      60.96          118309     -1233349
```

Height Control

– Refer to Section 3.5.4



Map of the height deviation from planned drape

APPENDIX 4: GRIDDING PARAMETERS

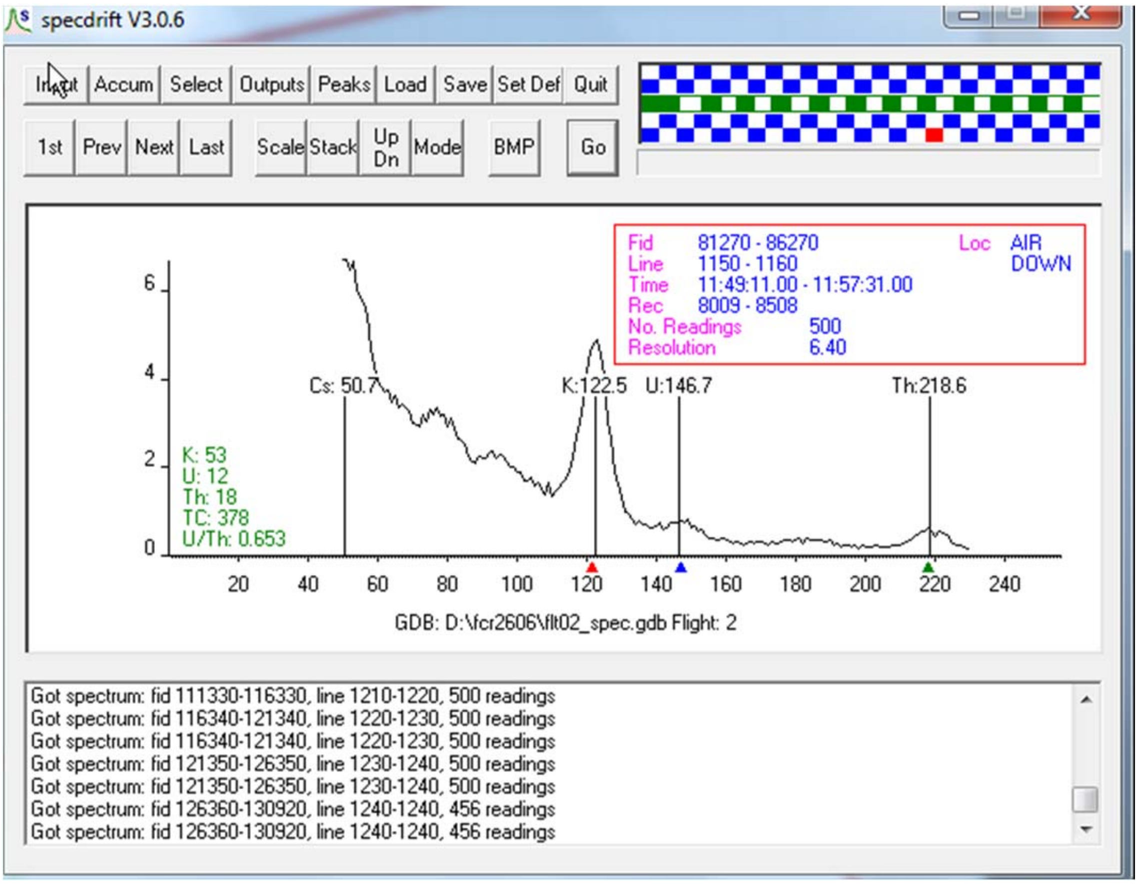
	Magnetic
Gridding method	Bi-Cubic Spline
Grid type	Square
Grid cell size	40 m

Table A5.1: Gridding parameters

	Radiometric
Gridding method	Minimum Curvature
Grid type	Linear
Grid cell size	40 m

APPENDIX 5: RADIOMETRIC SPECTRAL INDEX FIGURE

Example



APPENDIX 6: CALIBRATION REPORT AIRCRAFT ZS-SSC

CALIBRATION REPORT

AIRCRAFT ZS-SSC

Prepared by:

CGG Airborne Survey

Date: July 2013

Aircraft ZS-SSC (Reims F406)

1. Equipment Installed

Radiometric Equipment Serial Numbers	
Description	**Serial Number**
Exploranium GR820 Console	8253

GPX 1024/256 Detector Pack A	3022
GPX 1024/256 Detector Pack B	2651

2. Pad Calibration Procedure

The Pad calibrations were performed at Lanseria Airport using the CGG Airborne Survey portable pads on the 4th of July 2013. The following procedure was used:

- The Spectrometer system was allowed to stabilize on thorium for two hours prior to the calibration.
- The aircraft was positioned out of the way of any traffic for the duration of the tests.
- The "hand sources" (Caesium, Uranium and Thorium) were stored in a lead box at 10 meters away from the aircraft when not used.
- The four pads, background pad (B-pad), Potassium pad (K-pad), Uranium pad (U-pad) and thorium pad (Th-pad) were stored at 15 meters away from the aircraft when not used.
- Each detector pack was calibrated separately.
- After the stabilization period the outputs from the pack not being calibrated were physically disconnected. The inputs from the pack not being calibrated were switched off in the GR820 console. Power however was maintained to the pack not being calibrated to ensure its stabilization. The above method ensures that only the response from the pack being calibrated is recorded.
- Standard background and thorium source tests were performed using aircraft jigs prior and post pad calibrations.
- The response from the B-pad was then recorded for a period of 10 minutes. This was repeated for the K-pad, U-pad and Th-pad. After the Thorium pad the response from the B-pad was again recorded. Following this the standard post calibration background and thorium source test was carried out.
- This procedure was then repeated for the other pack.
- The statistics for the data were then calculated and the stripping coefficients were calculated with the routines from Jens Hovgaard's program "*padwin*".

3. PAD CALIBRATION RESULTS

Refer to **Appendix A** for observed results.

3.1 RESULTS OF PACK S/N 3022

Stripping Constants	Constants	Std Devn
Alpha	0.2432	0.0039
Beta	0.4311	0.0072
Gamma	0.7755	0.0111
.a	0.0586	0.0041
.b	-.0065	0.0018
.g	0.0045	0.0019

3.2 RESULTS OF PACK S/N 2651

Stripping Constants	Constants	Std Devn
Alpha	0.2285	.0028
Beta	0.3945	.0051
Gamma	0.7359	.0085
.a	0.0487	.0033
.b	0.0027	.0016
g	0.0027	.0016

3.3 *AVERAGES*

Stripping Constants	Constants
Alpha	0.2359
Beta	0.4128
Gamma	0.7577
.a	0.0537
.b	0.0046
.g	0.0036

4. Height Attenuation Tests

Height attenuation tests were conducted at the Namibian Geological Survey Dynamic Calibration Range at Henties Bay Namibia on 10th July and 11th July 2013. The first attenuation calibration was rejected as it was found that there was a temperature inversion layer at approximately 130m. For the second calibration there was no wind and the sky was clear.

The spectrometer system was run for two hours prior to the attenuation flight to allow it to stabilize. Standard pre-flight test background and thorium source checks were recorded for three minutes. The aircraft was flown low level to the attenuation site to maintain stabilization.

Each portion over land and water was flown sequentially at ground clearances of 900, 750, 680, 610, 540, 460, 390, 320, 250 and 180 feet. All crystals were checked during the flight to be sure of proper stabilization.

The observed data for each level was then background corrected by subtracting the mean of the background observed over water at that level. After this Compton stripping was performed. The co-efficients used were those determined at Lanseria airport. The altimeter was then corrected for standard temperature and pressure. For each channel a regression was performed between the mean STP altitudes and the natural logs of the background corrected, stripped data.

The results are shown in Appendix B.

4.1 THE ATTENUATION CO-EFFICIENTS DETERMINED ARE:

TOTC: -0.0077

KCNT: -0.0099

UCNT: -0.0089

TCNT: -0.0078

5. Sensitivity Calibration

The concentrations at the base point of the Geological Survey of Namibia (GSN) Dynamic Calibration Range at Henties Bay were measured to determine if there were any significant differences in concentrations as measured by the GSN and as measured for the current survey. The measurements are attached in Appendix C. The concentration differences were less than 1 standard deviation and therefore the GSN concentrations for the DCR concentrations were used. These are for potassium, uranium and thorium 3.79 percent, 4.37 ppm, 16.7 ppm respectively.

From the equations of the lines for potassium, uranium and thorium determined by the above regressions the average response at ground level and 80 meters was determined in counts per second for potassium, uranium and thorium. The count rates for each channel at ground level and 80 meters respectively were divided by the respective average concentrations of the test range to give the sensitivity.

5.1 AT GROUND LEVEL

Exposure: 46.93 CPS/nG/hr

Potassium: 192.74 CPS/pct

Uranium : 18.11 CPS/ppm

Thorium : 9.86 CPS/ppm

At 80 meters

Exposure : 26.70 CPS/nG/hr

Potassium: 87.31 CPS/pct

Uranium : 8.89 CPS/ppm

Thorium : 5.28 CPS/ppm

5.2 AT HEIGHT (H)

Exposure : exp(-0.0077 * h) * 49.4260

Potassium: exp(-0.0099 * h) * 192.7146

Uranium : exp(-0.0089 * h) * 18.114

Thorium : exp(-0.0078 * h) * 9.8568

6. COSMIC CALIBRATION

Cosmic calibrations were carried out on the 9th and 13th of July 2013 offshore from Swakopmund Namibia. The first calibration was rejected as it was affected by the presence of radon. The on shore wind was very light. The second calibration was carried out approximately 200 km out to sea. There were onshore winds of approximately 10 knots.

The spectrometer was allowed to stabilize for two hours prior to the calibration flight to ensure stability. The standard pre-flight calibrations background and thorium were performed and recorded. En route to the area the air in aircraft was flushed. Each altitude was flown at a constant height and for duration of 15 minutes. The following height levels were flown 13,000 ft, 12000 ft, 11000 ft, 10,000 ft, 9000 ft, and 8000 ft. Tests were flown from the highest to lowest altitude.

The results are as follows:

Region Of Interest	Cosmic Stripping	Aircraft Background	R2
Total Count	0. 6602	190.49	.9943
Potassium	0. 0380	23.99	.9748
Uranium	0. 0267	9.89	.9952
Thorium	0. 0334	1.52	.9987
Upward	0. 0061	2.61	.9892

The graphs are shown in Appendix D

7. Summary

The calibration was carried out according to the procedures recommended in a "Guide to the Technical Specifications for Airborne Gamma-Ray Surveys" by R.F GRASTY and BRS MINTY "Record 1995/60.

The pre and post thorium source test results for the attenuation and cosmic calibrations are less than the recommended maximum of 3 % for annual calibrations. The goodness of fit coefficients, R squared, are all close to 1.

APPENDIX A

Pad Calibration Calculations

Pack S/N 3022

CALIBRATION OF K-U-TH ROI COUNTS FROM PAD MEASUREMENTS

Pad Concentration file = c:\padcal\Lanseria_Pad _Concentrations.txt

****

CalibrationPadName = TRANSPORTABLE TEST PADS (HANGER, LANSERIA)

****

NumberOfPads = 4

BackgroundPad_K = 0.290 (0.010)
BackgroundPad_U = 1.100 (0.020)
BackgroundPad_Th = 3.330 (0.070)

PotassiumPad_K = 5.795 (0.180)
PotassiumPad_U = 1.140 (0.030)
PotassiumPad_Th = 3.370 (0.060)

UraniumPad_K = 0.449 (0.010)
UraniumPad_U = 37.150 (0.390)
UraniumPad_Th = 4 .160 (0.090)

ThoriumPad_K = 0.316 (0.010)

ThoriumPad_U = 6.550 (0.040)

ThoriumPad_Th = 89.590 (1.420)

NUMBERS IN PARENTHESES ARE ESTIMATED STANDARD DEVIATIONS.

==

Processing Crystal Pack 1 (ID = S/N 3022)

Background Pad line : L71003:1 21600.00 27780.00

Potassium Pad line : L71006:1 47920.00 54180.00

Uranium Pad line : L71005:1 38950.00 45040.00

Thorium Pad line : L71004:1 30100.00 37050.00

Background Pad line (2) : L71007:1 55930.00 61970.00

ROI COUNTS FOR PADS

	Potassium	**Uranium**	**Thorium**	**#Samples**	**Time (Sec)**
Background pad	98546.33	25616.45	22096.35	619	619.00
Potassium pad	208663.44	26577.14	21734.93	627	627.00
Uranium pad	140973.61	76681.82	25426.45	610	610.00
Thorium pad	152670.81	56608.91	103056.24	696	696.00
Background pad(2)	98011.64	25179.30	21631.77	605	605.00

STRIPPING RATIOS:

TH into U (A23/A33): Alpha = 0.2432 (0.0039)

TH into K (A13/A33): Beta = 0.4311 (0.0072)

U into K (A13/A33): Gamma = 0.7755 (0.0111)

U into TH (A32/A22): a = 0.0586 (0.0041)

K into TH (A31/A11): b = -0.0065 (0.0018)

K into U (A21/A11): g = 0.0045 (0.0019)

BACKGROUND COUNT RATES:

K ROI : 147.6763 (0.6136)

U ROI : 37.8499 (0.2162)

TH ROI : 31.3260 (0.2280)

NUMBERS IN PARENTHESES ARE ESTIMATED STANDARD DEVIATIONS.

2013/07/05, 13:31:56 - Log Ended.

THORIUM SOURCE TEST RESULTS	**CPS**	**SDEV**
TOTAL THORIUM RESPONSE:	99.39	9.8
BACKGROUND RESPONSE:	40.32	5.5
THORIUM RESPONSE:	59.07	

THORIUM SOURCE TEST RESULTS	**CPS**	**SDEV**
TOTAL THORIUM RESPONSE:	100.12	9.8

BACKGROUND RESPONSE:	39.91	5.5
THORIUM RESPONSE:	60.21	

PRE & POST DIFFERENCE: 1.930%

PACK S/N 2651

CALIBRATION OF K-U-TH ROI COUNTS FROM PAD MEASUREMENTS

Pad Concentration file = c:\padcal\Lanseria_Pad _Concentrations.txt

****

CalibrationPadName = TRANSPORTABLE TEST PADS (HANGER, LANSERIA)

****

NumberOfPads = 4

BackgroundPad_K = 0.290 (0.010)
BackgroundPad_U = 1.100 (0.020)
BackgroundPad_Th = 3.330 (0.070)

PotassiumPad_K = 5.795 (0.180)
PotassiumPad_U = 1.140 (0.030)
PotassiumPad_Th = 3.370 (0.060)

UraniumPad_K = 0.449 (0.010)
UraniumPad_U = 37.150 (0.390)
UraniumPad_Th = 4.160 (0.090)

ThoriumPad_K = 0.316 (0.010)
ThoriumPad_U = 6.550 (0.040)
ThoriumPad_Th = 89.590 (1.420)

NUMBERS IN PARENTHESES ARE ESTIMATED STANDARD DEVIATIONS.

==

Processing Crystal Pack 1 (ID = S/N 2651)

Background Pad line : L72003:1 95360.00102180.00
Potassium Pad line : L72006:1 120280.00126320.00
Uranium Pad line : L72005:1 112430.00118470.00
Thorium Pad line : L72004:1 104340.00110460.00
Background Pad line (2) : L72007:1 128110.00134140.00

ROI COUNTS FOR PADS

	Potassium	Uranium	Thorium	#Samples	Time (Sec)

Background pad	117354.26	30142.29	27747.93	683	683.00
Potassium pad	243520.78	27366.97	24641.00	605	605.00
Uranium pad	165563.77	102664.05	29736.21	605	605.00
Thorium pad	162184.52	65484.70	142534.95	613	613.00
Background pad(2)	107260.35	27087.48	25348.23	604	604.00

A-MATRIX FROM NONLINEAR REGRESSION:

41.389866 (1.365360)
2.547291 (0.038825)
0.870513 (0.018000)
0.110524 (0.064823)
3.461555 (0.040665)
0.504181 (0.010275)
-0.112955 (0.068226)
0.168695 (0.011712)
2.206679 (0.037153)

INVERSE A-MATRIX:

0.024192 (0.000799)
-0.017533 (0.000646)
-0.005538 (0.000213)
-0.000964 (0.000463)
0.292839 (0.003460)
-0.066528 (0.001333)
0.001312 (0.000753)
-0.023284 (0.001542)
0.457972 (0.007739)

STRIPPING RATIOS:

TH into U (A23/A33): Alpha = 0.2285 (0.0028)
TH into K (A13/A33): Beta = 0.3945 (0.0051)
U into K (A13/A33): Gamma = 0.7359 (0.0085)
U into TH (A32/A22): a = 0.0487 (0.0033)
K into TH (A31/A11): b = -0.0027 (0.0016)
K into U (A21/A11): g = 0.0027 (0.0016)

BACKGROUND COUNT RATES:

K ROI : 156.8219 (0.7376)
U ROI : 38.9489 (0.2302)
TH ROI : 33.7547 (0.2912)

NUMBERS IN PARENTHESES ARE ESTIMATED STANDARD DEVIATIONS.

===

Average stripping coefficients

===

Alpha	:	0.228479
Beta	:	0.394490
Gamma	:	0.735881
a	:	0.048734
b	:	-0.002729
g	:	0.002670

==

2013/07/05, 14:30:08 - Log Ended.

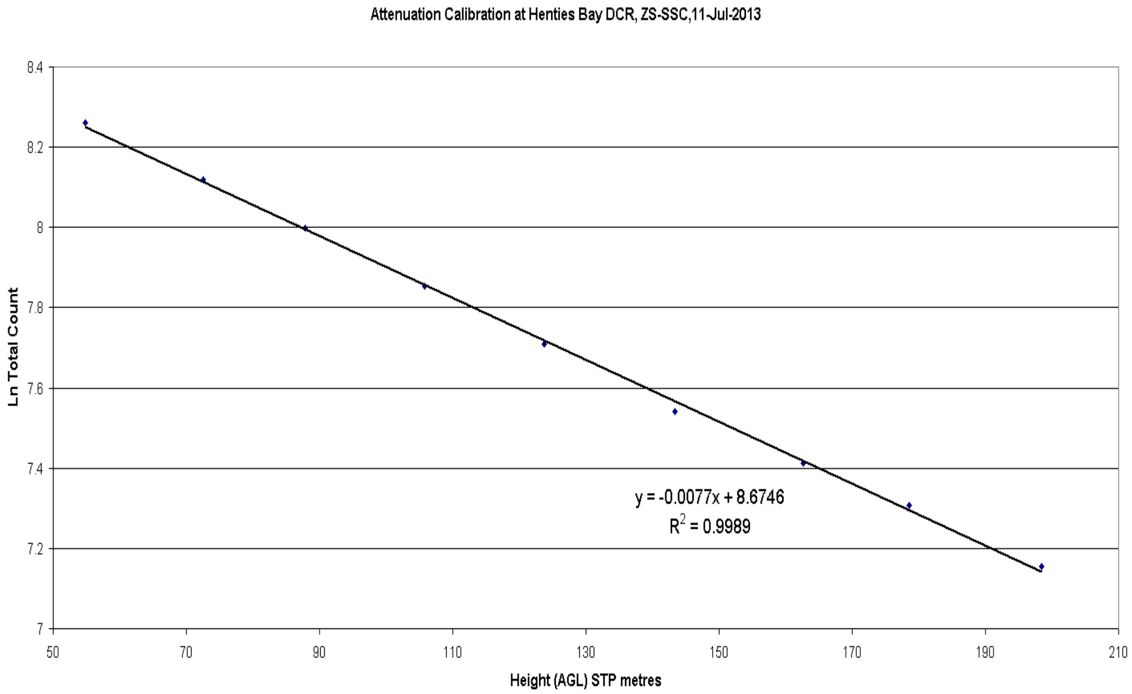
THORIUM SOURCE TEST RESULTS	**CPS**	**SDEV**
TOTAL THORIUM RESPONSE	111.56	11.29
BACKGROUND RESPONSE:	47.56	6.62
THORIUM RESPONSE:	64	

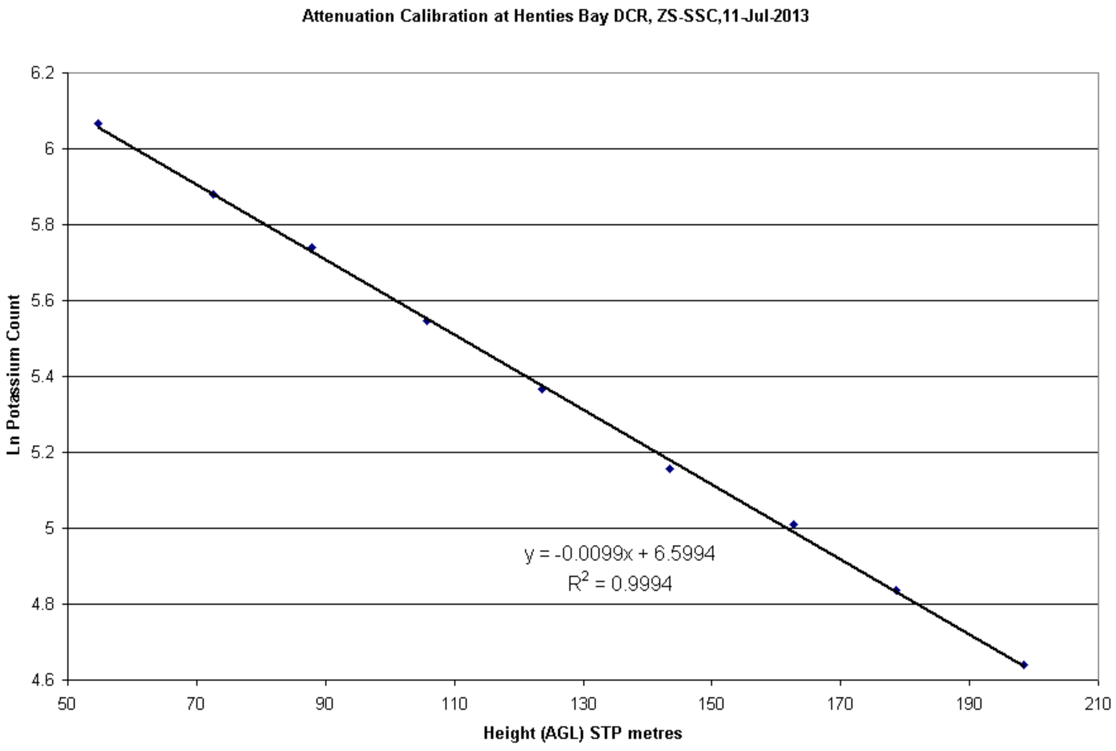
THORIUM SOURCE TEST RESULTS	**CPS**	**SDEV**
TOTAL THORIUM RESPONSE:	112.03	11.52
BACKGROUND RESPONSE:	46.82	7.76
THORIUM RESPONSE:	65.21	

PRE & POST DIFFERENCE: **1.891%**

APPENDIX B

Graphic Representation of Results





Thorium Source Test Results

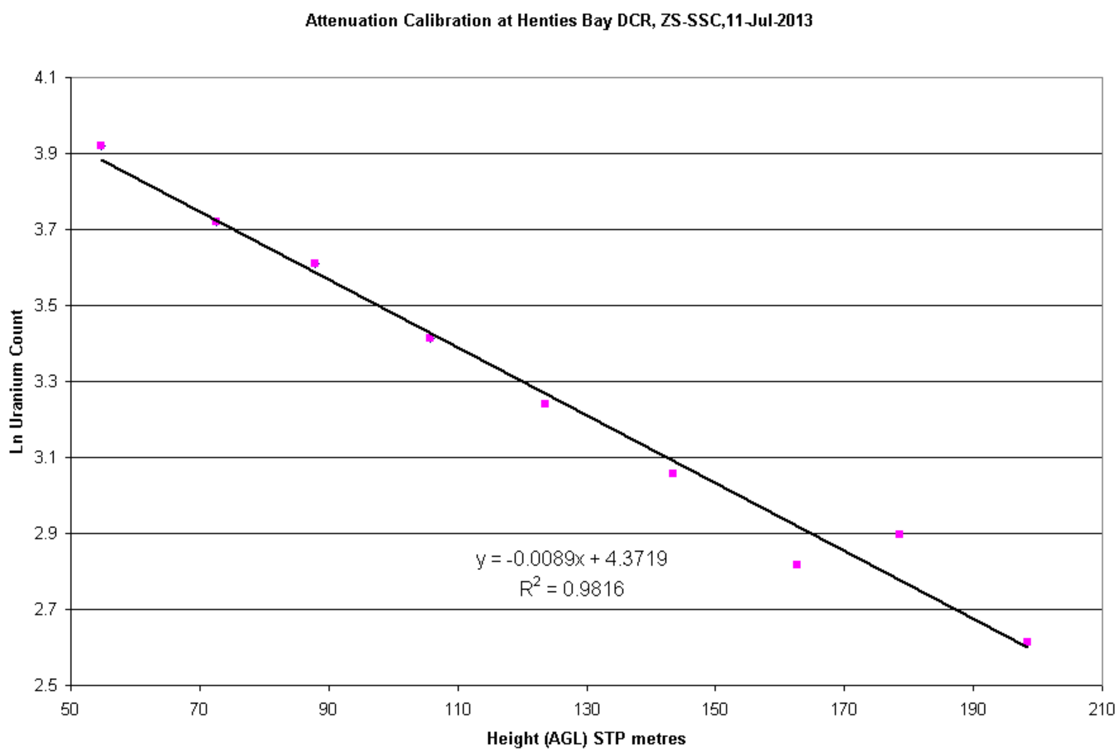
Pre Calibration Results:

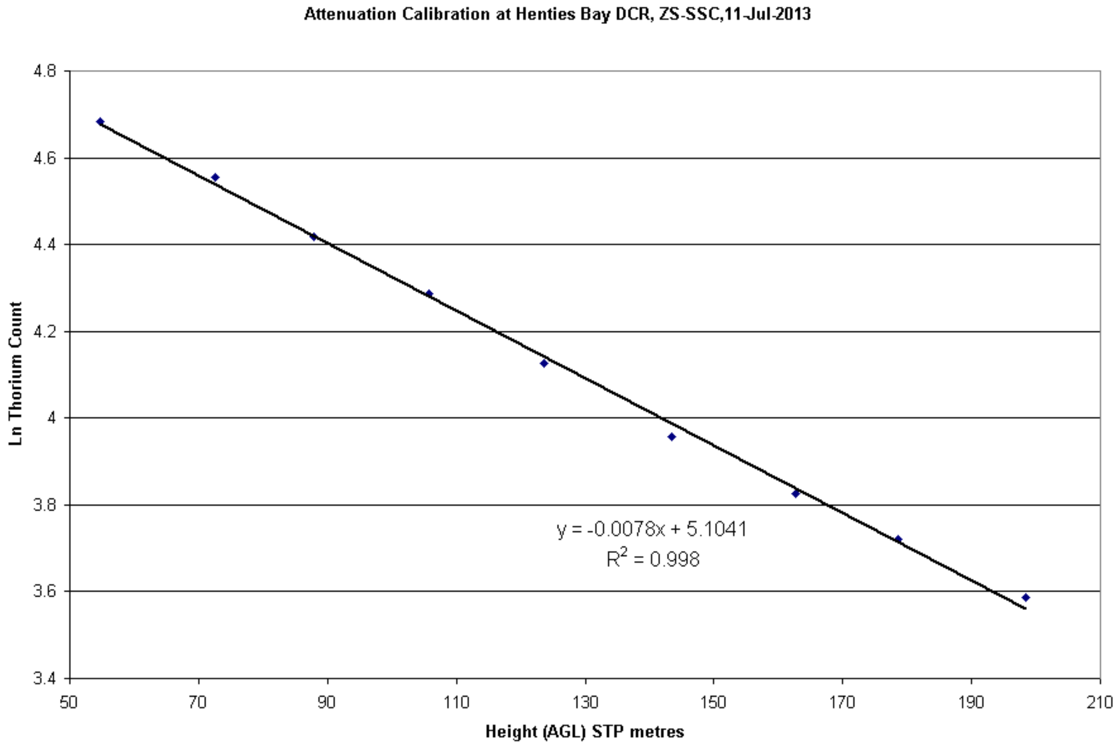
Total Thorium Response	261.3 cps (18.2
Background Response	117.2 cps (12.3)
Thorium Response	144.1 cps

Post Calibration

Total Thorium Response	264.94 cps (17.97)
Background Response	117.2 cps (12.3)
Thorium Response	143.65 cps

Pre & Post difference: 1.03 cps, 0.72 pct





Attenuation Calibration at Henties Bay DCR, ZS-SSC,11-Jul-2013
Ln Thorium Count
4.8
4.6
4.4
4.2
4
3.8
3.6
3.4
y = -0.0078x + 5.1041
R2 = 0.998
50
70
90
110
130
150
170
190
210
Height (AGL) STP metres

APPENDIX C

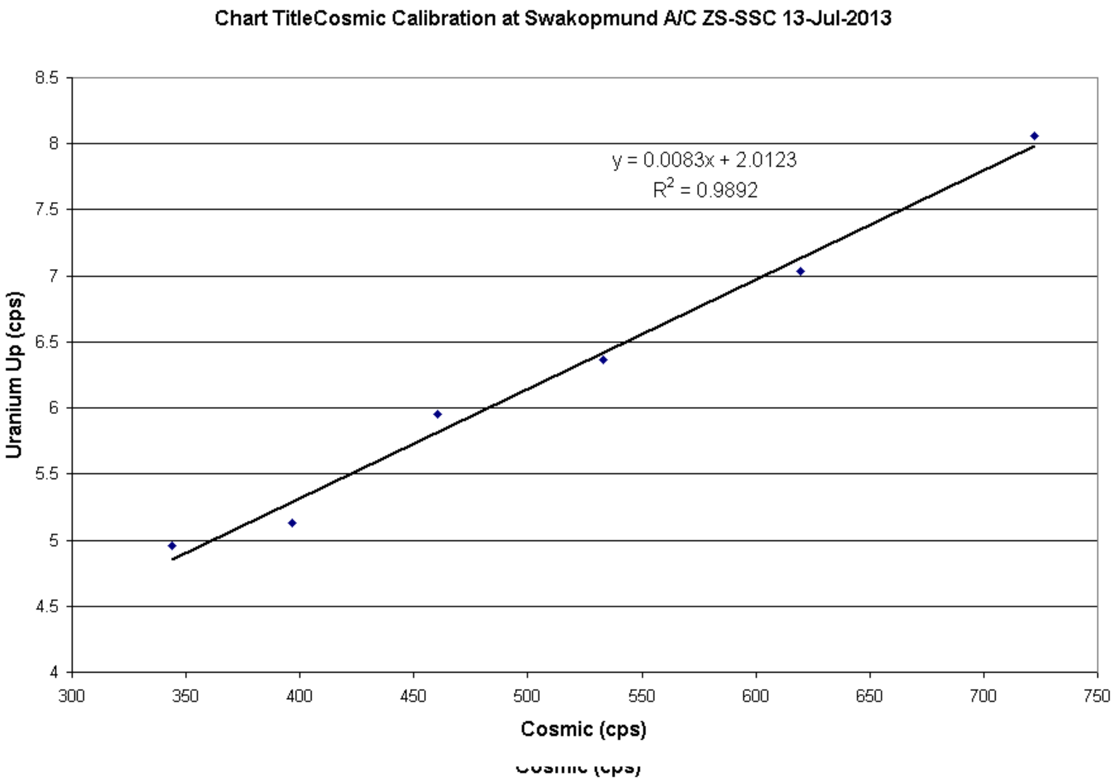
Tabular Representation of Results

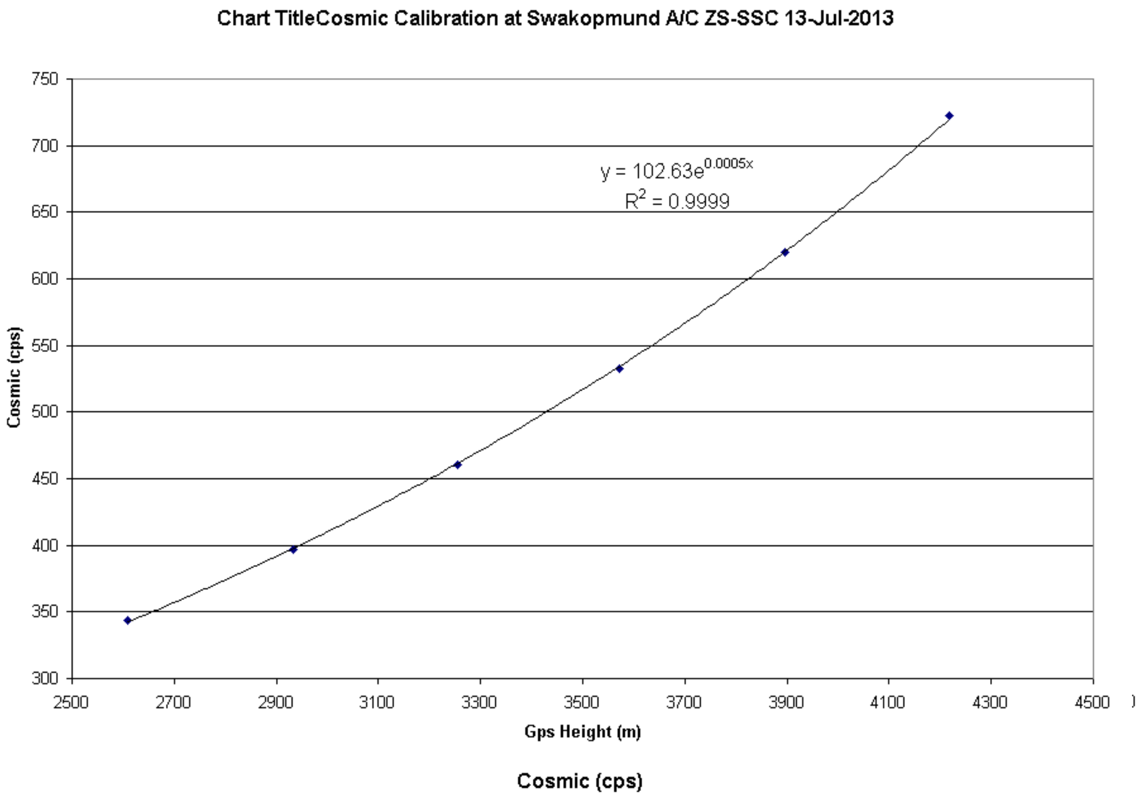
			ZS-SSC 2013-07-10							
Peg/Position	Sample	Time	TOT	K %	U ppm	Th ppm	Tot counts	K counts	U counts	Th ppm
1	5min	10:00	32.3	3.4	4.3	18.8	4072	961	179	179
2	5min	10:07	30.2	3.2	3.4	18.3	3803	893	158	173
3	5min	10:13	32.4	3.6	4.0	18.5	4077	993	172	176
4	5min	10:19	30.2	3.8	3.7	13.9	3800	1014	142	132
5	5min	10:28	33.9	3.6	4.6	19.7	4272	1011	190	187
6	5min	10:34	30.9	3.6	3.7	15.9	3895	978	153	151
7	5min	10:40	32.3	3.6	4.0	18.4	4070	1006	172	175
8	5min	10:46	30.4	3.6	3.9	15.6	3836	968	156	149
9	5min	10:52	32.0	3.4	4.0	19.1	4072	956	174	180
10	5min	10:58	31.1	3.5	4.3	16.2	3919	958	164	154
11	5min	11:04	30.3	3.4	3.7	16.1	3820	942	154	153
12	5min	11:10	29.4	3.6	3.5	14.4	3702	967	141	137
		Averages	31.3	3.5	3.9	17.1	3944.8	970.6	162.9	162.2
		Std Devn	1.3	0.2	0.4	1.9	166.0	33.9	14.9	18.3
Pier 1	15min	12:18	1.5	0.0	0.5	0.0	185	4	10	1
Pier 2	15min	12:35	1.4	0.0	0.2	0.0	171	4	5	1
		Averages	1.45	0	0.35	0	178	4	7.5	1
		Pier adjustment	-2.92	-0.4	-0.51	-2.12				
		Total correction	-1.47	-0.4	-0.16	-2.12				
Background Corrected base station concentrations			**32.8**	**3.9**	**4.1**	**19.2**				

APPENDIX D

Cosmic Calibration Graphs

Thorium Source Test Results





Pre Calibration

Total Thorium Response: 262.57 cps (18.06)

Background Response: 118.88 cps (12.5)

Thorium Response: 143.69 cps

Post Calibration

Total Thorium Response: 263.1 cps (17.54)

Background Response: 118.8 cps (11.44)

Thorium Response: 144.3 cps

Pre & Post difference: 0.61 cps, 0.43 pct