



**British
Geological Survey**

NATURAL ENVIRONMENT RESEARCH COUNCIL

The HiRES airborne geophysical survey of Anglesey: Processing Report

Environmental Geoscience Baselines Programme

Open Report OR/10/002



BRITISH GEOLOGICAL SURVEY

ENVIRONMENTAL GEOSCIENCE BASELINES PROGRAMME

OPEN REPORT OR/10/002

The HiRES airborne geophysical survey of Anglesey: Processing Report

J.C. White and D. Beamish

The National Grid and other Ordnance Survey data are used with the permission of the Controller of Her Majesty's Stationery Office.
Licence No: 100017897/ 2010.

Keywords

Report, Anglesey, HiRES, airborne geophysics, geological mapping.

Front cover

View from survey aircraft © Ed Haslam

Bibliographical reference

J.C. WHITE AND D. BEAMISH.
2010. The HiRES airborne geophysical survey of Anglesey: Processing Report. *British Geological Survey Internal Report*, OR/10/002. 44pp.

Copyright in materials derived from the British Geological Survey's work is owned by the Natural Environment Research Council (NERC) and/or the authority that commissioned the work. You may not copy or adapt this publication without first obtaining permission. Contact the BGS Intellectual Property Rights Section, British Geological Survey, Keyworth, e-mail ipr@bgs.ac.uk. You may quote extracts of a reasonable length without prior permission, provided a full acknowledgement is given of the source of the extract.

Maps and diagrams in this book use topography based on Ordnance Survey mapping.

BRITISH GEOLOGICAL SURVEY

The full range of our publications is available from BGS shops at Nottingham, Edinburgh, London and Cardiff (Welsh publications only) see contact details below or shop online at www.geologyshop.com

The London Information Office also maintains a reference collection of BGS publications, including maps, for consultation.

We publish an annual catalogue of our maps and other publications; this catalogue is available online or from any of the BGS shops.

The British Geological Survey carries out the geological survey of Great Britain and Northern Ireland (the latter as an agency service for the government of Northern Ireland), and of the surrounding continental shelf, as well as basic research projects. It also undertakes programmes of technical aid in geology in developing countries.

The British Geological Survey is a component body of the Natural Environment Research Council.

British Geological Survey offices

BGS Central Enquiries Desk

Tel 0115 936 3143 Fax 0115 936 3276
email enquiries@bgs.ac.uk

Kingsley Dunham Centre, Keyworth, Nottingham NG12 5GG

Tel 0115 936 3241 Fax 0115 936 3488
email sales@bgs.ac.uk

Murchison House, West Mains Road, Edinburgh EH9 3LA

Tel 0131 667 1000 Fax 0131 668 2683
email scotsales@bgs.ac.uk

Natural History Museum, Cromwell Road, London SW7 5BD

Tel 020 7589 4090 Fax 020 7584 8270
Tel 020 7942 5344/45 email bgs_london@bgs.ac.uk

Columbus House, Greenmeadow Springs, Tongwynlais, Cardiff CF15 7NE

Tel 029 2052 1962 Fax 029 2052 1963

Forde House, Park Five Business Centre, Harrier Way, Sowton EX2 7HU

Tel 01392 445271 Fax 01392 445371

Maclean Building, Crowmarsh Gifford, Wallingford OX10 8BB

Tel 01491 838800 Fax 01491 692345

Geological Survey of Northern Ireland, Colby House, Stranmillis Court, Belfast BT9 5BF

Tel 028 9038 8462 Fax 028 9038 8461

www.bgs.ac.uk/gsni/

Parent Body

Natural Environment Research Council, Polaris House, North Star Avenue, Swindon SN2 1EU

Tel 01793 411500 Fax 01793 411501
www.nerc.ac.uk

Website www.bgs.ac.uk

Shop online at www.geologyshop.com

Foreword

This report is the published product of a study carried out by the British Geological Survey (BGS). The project is a HiRES airborne geophysical survey carried out by the Geophysical Baselines Team under the Environmental Geoscience Baselines Programme. The survey was intended to form a part of the then current revised mapping being undertaken across the island of Anglesey and part of the north-west coast of Gwynedd.

Acknowledgements

The JAC survey team, including BGS operators, listed in BGS Internal Report IR/09/61 are thanked for their contributions to the successful HiRES survey project.

Contents

Foreword	2
Acknowledgements	2
Contents	3
Summary	7
1 Introduction	8
2 Electromagnetic processing	9
2.1 Prelevelling.....	9
2.2 Levelling.....	10
2.3 Microlevelling	12
2.4 Estimation of apparent conductivity and depth	12
2.5 Further Microlevelling.....	13
2.6 Electromagnetic data delivery	13
3 Magnetic processing	15
3.1 Aircraft correction	15
3.2 Diurnal Correction.....	15
3.3 Lag Correction.....	15
3.4 Heading Correction.....	16
3.5 influence OF Aircraft.....	16
3.6 Data QC and spike removal.....	16
3.7 Levelling magnetic data.....	17
3.8 Microlevelling	17
3.9 Magnetic data delivery	18
4 Radiometric processing	19
4.1 DEAD Time correction	19
4.2 Filtering	19
4.3 Aircraft and Cosmic background correction	19
4.4 Background radon.....	19
4.5 Effective height correction	20
4.6 Stripping correction	20
4.7 Conversion to apparent radioelement concentrations.....	20
4.8 Levelling of radiometric data	20
4.9 Radiometric data delivery.....	21
5 Positional processing and line trimming	23
6 Maps of the survey area	24
6.1 Overview	24
6.2 Signal/Noise features in the data	24
6.3 Images.....	25

7 References40

Appendix 141

 The minimisation of error between the line data and the regional field 41

FIGURES

Figure 1. An example of EMPRELEV applying a non-linear drift correction to the real component of the 912 Hz data. 10

Figure 2. An example of EMPRELEV applying a non-linear drift correction to the imaginary component of the 912 Hz data. 10

Figure 3. Example of LEVEL32 applied to 3 kHz real component across 5 sequential lines. DC level adjustments are interactively made to each line (current line for adjustment is shown in grey). 11

Figure 4. Real and quadrature sampling covers 19716 points for all four frequencies. 13

Figure 5. The removal of the anomaly cause by aluminium smelting works: left - the acquired data; middle - the blanked region; right - the restored interpolated signal. 17

Figure 6. Digital terrain model. 25

Figure 7. Altitude (RALT). 26

Figure 8. Levelling corrections applied after minimisation to regional field (left wing tip). 26

Figure 9. Levelling corrections applied after minimisation to regional field (nose tip). 27

Figure 10. Levelling corrections applied by decorrugation procedure (left wing tip). 27

Figure 11. Levelling corrections applied decorrugation procedure (nose tip). 28

Figure 12. Total magnetic intensity (left wing tip). 28

Figure 13. Total magnetic intensity (nose tip). 29

Figure 14. Power line monitor. 29

Figure 15. Radar altitude (DALT) less than 100 m (red). 30

Figure 16. EM: Real component, 0.912 kHz. 30

Figure 17. EM: Imaginary component, 0.912 kHz. 31

Figure 18. EM: Real component, 3 kHz. 31

Figure 19. EM: Imaginary component, 3 kHz. 32

Figure 20. EM: Real component, 12 kHz. 32

Figure 21. EM: Imaginary component, 12 kHz. 33

Figure 22. EM: Real component, 24.5 kHz. 33

Figure 23. EM: Imaginary component, 24.5 kHz. 34

Figure 24. EM: Apparent resistivity, 0.912 kHz. 34

Figure 25. EM: Apparent resistivity, 3 kHz. 35

Figure 26. EM: Apparent resistivity, 12 kHz. 35

Figure 27. EM: Apparent resistivity, 24.5 kHz. 36

Figure 28. Radiometric ternary image. 37

Figure 29. Total radiation (shaded relief). 37

Figure 30. Potassium concentration (shaded relief). 38

Figure 31. Thorium concentration (shaded relief). 38

Figure 32. Uranium concentration (shaded-relief). 39

TABLES

Table 1. Heading corrections for the Anglesey magnetic survey.16

Table 2. The recommended (IAEA) energy ranges of the spectral windows. 19

Summary

This report describes the final processing of data acquired during the HiRES airborne geophysical survey of the island of Anglesey and the north-west coastal region of Gwynedd. This report is a companion to the logistics report of Beamish and White (2009). The survey was carried out by the Joint Airborne-Geoscience Capability (JAC) established between the Geological Survey of Finland (GTK) and British Geological Survey (BGS). The project is a HiRES survey carried out by the Geophysical Baselines Team under the Environmental Geoscience Baselines Programme.

1 Introduction

This report describes the final processing procedures performed on the HiRES airborne geophysical survey data acquired over the island of Anglesey and part of the north-west region of Gwynedd, North Wales. This processing work was carried out at the BGS offices at Keyworth in the months following the survey. The report also details the naming conventions employed for the final data sets and includes gridded images of the processed data.

The report is subdivided into sections which focus specifically on the three data sets: electromagnetic, magnetic and radiometric.

2 Electromagnetic processing

This section focuses on the processing procedures applied to the Anglesey electromagnetic data.

2.1 PRELEVELLING

The in-field prelevelling procedure is further refined during the data processing stage and is the principal step in ensuring an accurate and well levelled data set.

At the beginning of each survey flight the zero-level is adjusted to an artificial level to ensure a large enough scale to register both positive and negative anomalies. As such, the recorded values are independent of the real zero-level. This calibration is performed at a high altitude (greater than 300 metres above ground) to provide a true 'out-of-ground' response. The zero-level calibration procedure is repeated at the end of each flight. The level of the EM data is then corrected linearly using these calibration results.

The preliminary automatic zero-level correction gives good results if the drift is linear and low in magnitude. The linear part of the drift is usually less than 100 ppm/hour if there is no temperature gradient. If the flight lines are long the air temperature can sometimes vary significantly during a traverse, and this may introduce a non-linear drift to the zero-level. A temperature variation results in a change in the coil separation and the zero-level may change by about 70 ppm for a temperature variation of one degree centigrade. It would be possible (in theory) to correct this effect, but unfortunately the wings of an airplane cannot be regarded as a totally rigid item. The wings are made of composite materials, meaning the relationship between temperature and wing length variation may be non-linear. There are also other reasons for this drift, such as temperature variation in the coils and in other analogue components, which are never ideal and lead to a non-linear drift.

The non-linear drift is estimated for each EM component during each flight. An interactive JAC Windows program, EMPRELEV, is used for non-linear drift removal. The user interactively provides a set of points which estimate the drift of each component, see Figure 1 and Figure 2. The outside temperature is usually plotted above the EM data to help to determine whether a high temperature gradient exists. The online/offline parameter is used to define the flight lines and turns.

There were additional challenges in handling the Anglesey data since the EM system had developed a habit of introducing erroneous steps into the data. This was most noticeable in the IM25 component but was also seen in the other coupling ratios. The approach adopted for correcting this issue was to attempt to remove the step in EMPRELEV in order to match the data with the response on adjacent lines. One reflight was called as a consequence of these problems but the reflight line also suffered from the same issue and remediation was required.

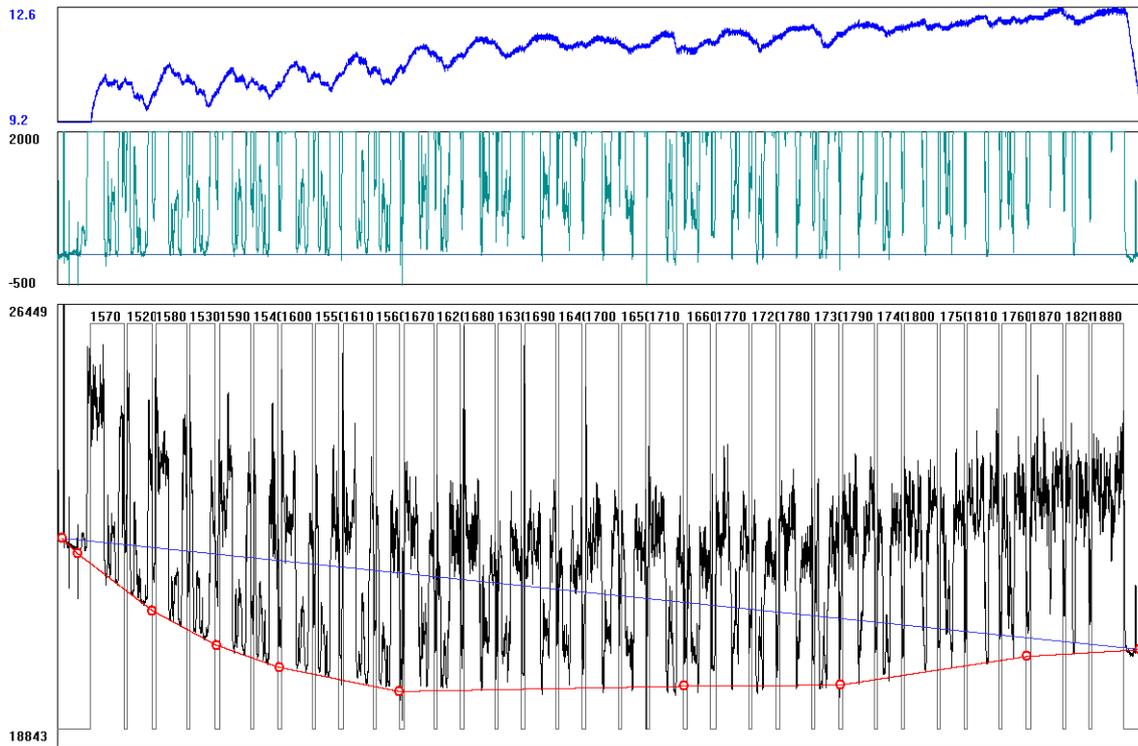


Figure 1. An example of EMPRELEV applying a non-linear drift correction to the real component of the 912 Hz data.

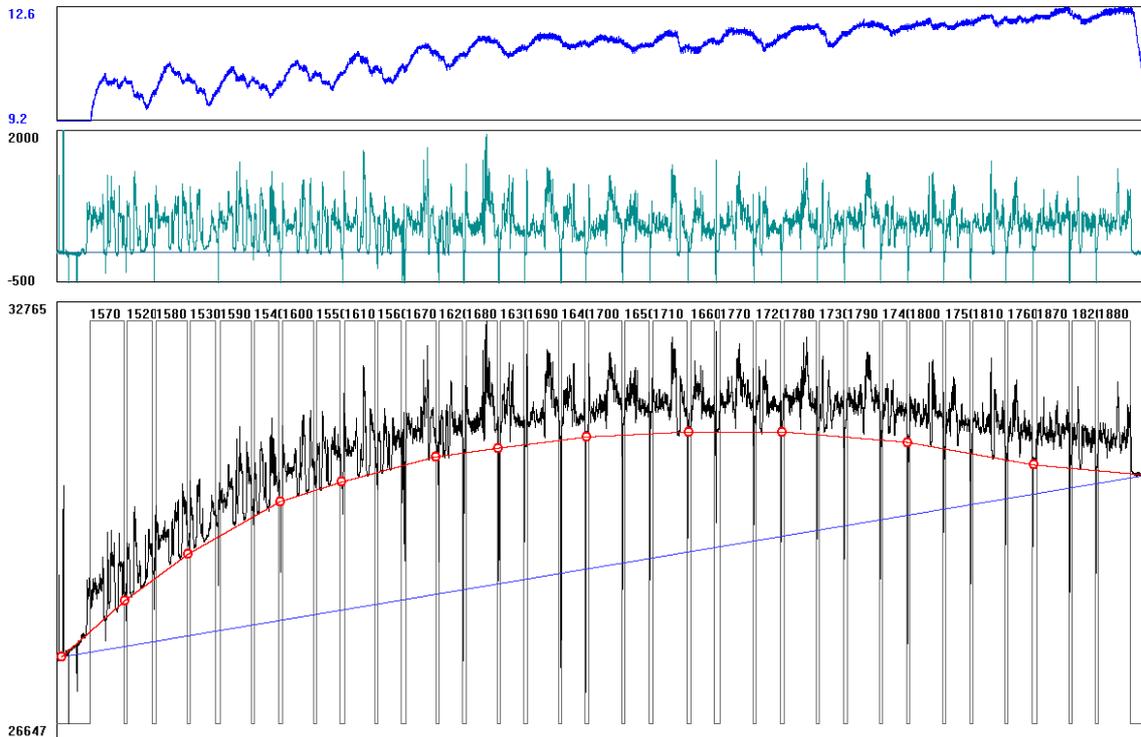


Figure 2. An example of EMPRELEV applying a non-linear drift correction to the imaginary component of the 912 Hz data.

2.2 LEVELLING

The pre-levelling is followed by further line-by-line adjustment (if required) of the zero levels for each component of each line of data. A JAC graphical Windows program, Level32 is used

for this purpose. An example of this program is presented in Figure 3. A variable number of profiles of a specific EM component can be presented simultaneously in a window. Lines are sorted, so adjacent profiles are compared to provide information about line-to-line behavior of the zero level. For each line, the user provides a set of points, which determine the revised zero-level. Usually two points are enough to determine any residual small drift curve for correction. However, in regions of rapid drift three or more points might be used.

The above procedures work on EM data from individual lines and enable de-trending procedures (linear and non-linear) and residual offset removal to be applied where necessary. Since these procedures are line-based they do not perturb the EM data anomalies that have an expected wavelength much less than the line length. The data generated are the most appropriate data for use in quantitative procedures (e.g. modeling/inversion) that require minimum filtering/distortion of individual anomalies.

In practice Level32 was not used significantly in the processing of the Anglesey survey as it failed to yield significantly improved results. The majority of the level error was corrected using EMPRELEV. The Anglesey data proved to be very difficult to level satisfactorily, the low frequency response across the island was highly variable and did not improve with zero (and in some cases first) order adjustment. A virtual tie line method was utilised in an effort to improve the levelling but offered no improvement.

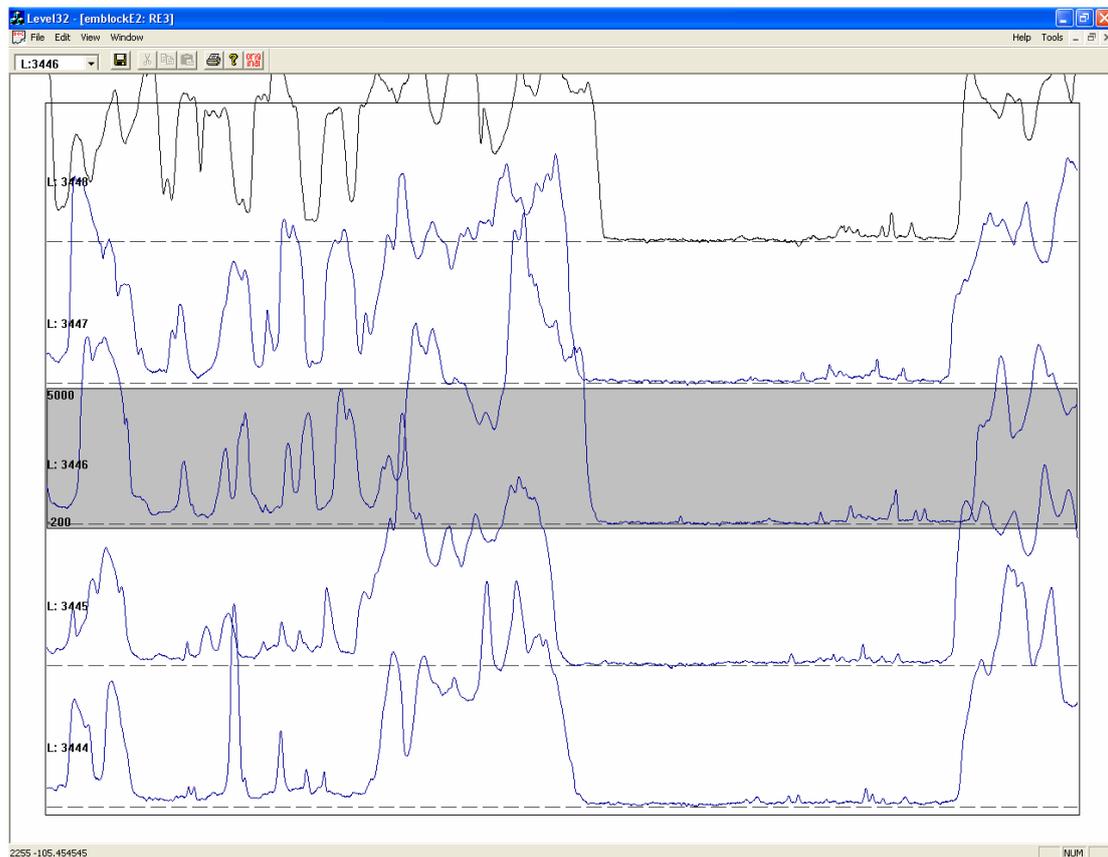


Figure 3. Example of LEVEL32 applied to 3 kHz real component across 5 sequential lines. DC level adjustments are interactively made to each line (current line for adjustment is shown in grey).

At this stage initial plots of apparent conductivity and depth revealed that there appeared to be a significant calibration error associated with the 912 Hz data. Inversion and chi-square tests were undertaken on a 5 x 5 km region of sea and a decision to amend the 912 Hz components was made. The real component was shifted by -76 ppm and the imaginary component by 79 ppm across the whole data set.

2.3 MICROLEVELLING

When the EM data are gridded, small residual line-to-line levelling errors may become apparent. These effects are often referred to as ‘corrugations’ or ‘streaks’; such features are common to all the airborne survey data components. Microlevelling procedures are used to remove such features prior to the production of final grids. Microlevelling procedures apply filters and spatial averages across multiple lines but these methods have limitations and are capable of distorting data. The application of such procedures depends on a set of control parameters (e.g. those associated with filter lengths and spatial wavelengths) for each data set; a level of judgment is required to minimize distortion and provide acceptable microlevelled grids.

For the EM coupling ratio data, JAC uses a microlevelling technique called the Floating Median Difference (FMD) method. Originally developed by Liukkonen (1996), a more recent use of the technique is described by Muring and Kihle (2006). The microlevelling program EMLEV uses an along line radius (1000 m was used for the Anglesey survey) and an across-line radius that controls the number of lines involved in estimating the result at a particular point. An across-line value of 500 m was employed during this study meaning 5 lines were used in the procedure; given the flight line spacing of 200 m.

The leveling routine will not remove features that are shorter in wavelength than the along line radius. This leaves high frequency features intact. It does, however, adjust all line data to some extent. The amount of filtering this procedure performs is seen as being a good balance between leveling and smoothing. Many procedures exist that would create a much more aesthetically pleasing result, but these all overly smooth data. The FMD routine does have some characteristics that are worth noting. In situations where data levels change rapidly, such as a step, the FMD routine can create large negative spikes on a down-step. Therefore caution has to be taken when deciding which dataset to use for visual presentation of data (microlevelled) or for modeling (non-levelled).

2.4 ESTIMATION OF APPARENT CONDUCTIVITY AND DEPTH

The primary EM in-phase and quadrature components can be transformed to apparent resistivity and apparent depth using a half-space model (Fraser, 1978; Suppala *et al.*, 2005). The method returns apparent resistivity and apparent depth at each measured frequency and no misfit error is provided (Beamish, 2002). The transformation is performed using the JAC program TRANSAEM07. The program employs minimum limits on the real and imaginary coupling ratios to identify the noise level in the coupling ratios. Figure 4 shows the applicable ranges for the coupling ratios.

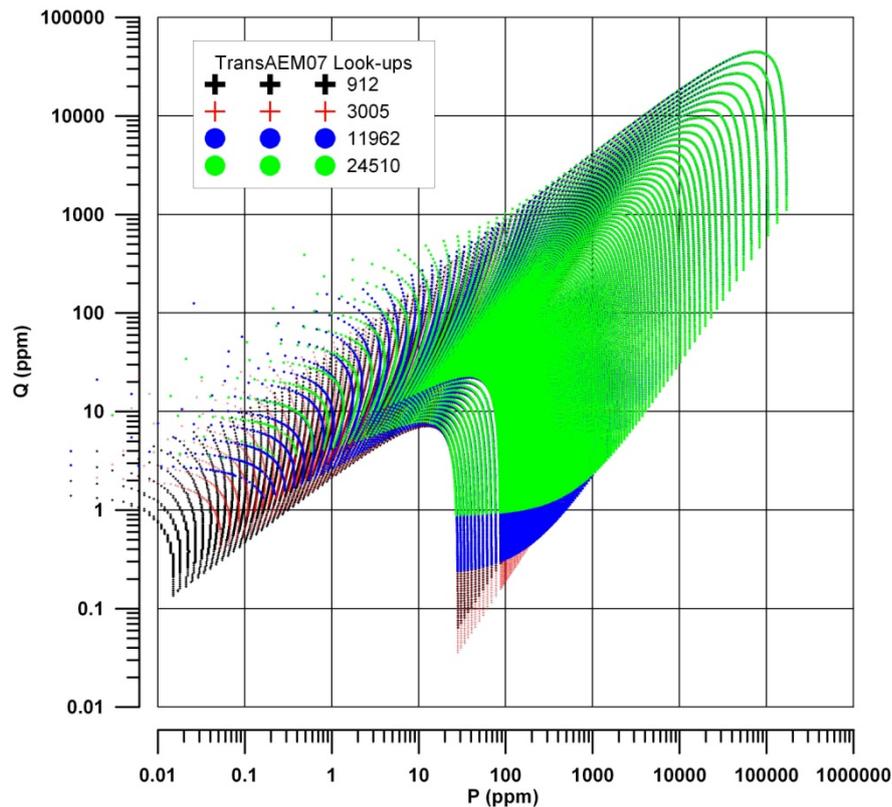


Figure 4. Real and quadrature sampling covers 19716 points for all four frequencies.

In conditions of variable flight elevation, the levels of signal/noise may also vary (signal decreases with increasing elevation). Such effects decrease with increasing frequency and are thus most pronounced in the 912 Hz data.

The apparent resistivity and apparent depth data are an application of a half-space model and should be considered as such. The appropriateness of this model must be ascertained before an interpretation is made. Final detailed interpretation (e.g. modeling, inversion) should be carried out using the original in-phase and quadrature data (i.e. data obtained prior to microlevelling).

2.5 FURTHER MICROLEVELLING

The apparent resistivity and depth data sets can be further microlevelled using a similar method to EMLEV. Once again along and across line radii are required in order to ascertain the two dimensional background level. The level of correction is controlled during the levelling, ensuring that low values, which have a greater relative accuracy, are not corrected as heavily as high values. The along line radius should be selected such that EM anomalies are shorter than this value. For the Anglesey processing the along and across line radii were 1000 m and 1000 m respectively.

2.6 ELECTROMAGNETIC DATA DELIVERY

The final electromagnetic data is contained in a series of files. The levelled in-phase and quadrature components are summarized in EMraw_adj.xyz. The microlevelled version of this data is EM_PROLEV_ADJ.xyz. The transformed apparent resistivity and depth data is AP_PROLEV_ADJ.xyz, whilst the microlevelled equivalent is AP_PROLEV_ASDJ.xyz. EMAP_PROLEV_adj_FINAL.xyz is a combined dataset of microlevelled coupling ratios and apparent resistivities, conductivities and depths. A READ_ME file is included in the processed data folder and the final data set includes:

e.g. for EMAP_PROLEV_adj_FINAL.xyz

X_BNG

Grid Easting (m) – British National Grid

Y_BNG	Grid Northing (m) – British National Grid
Z	GPS altitude (m) above geoid (WGS84)
PITCH	Pitch (degrees)
ROLL	Roll (degrees)
HEADING	Heading (degrees clockwise)
FLIGHT	Flight number
DAY	Day number (Julian)
TIME	Time (HHMMSS)
DIR	Flight direction (degrees clockwise)
RALT_LP	Radar altitude (m) – low passed at 5 fiducials
LALT	Laser altitude (m)
DTM	Digital Terrain Model (m)
PLM	Power line monitor
RE09_adj	Real (in-phase) component at lowest frequency 912 Hz (ppm)
IM09_adj	Imaginary (quadrature) component at lowest frequency 912 Hz (ppm)
RE3	Real (in-phase) component at low frequency 3005 Hz (ppm)
IM3	Imaginary (quadrature) component at low frequency 3005 Hz (ppm)
RE12	Real (in-phase) component at high frequency 11962 Hz (ppm)
IM12	Imaginary (quadrature) component at high frequency 11962 Hz (ppm)
RE25	Real (in-phase) component at highest frequency 24510 Hz (ppm)
IM25	Imaginary (quadrature) component at highest frequency 24510 Hz (ppm)
AR09_adj	EM apparent resistivity at lowest frequency 912 Hz (Ohm m)
AD09_adj	EM apparent depth at lowest frequency 912 Hz (Ohm m)
AR3	EM apparent resistivity at low frequency 3005 Hz (Ohm m)
AD3	EM apparent depth at low frequency 3005 Hz (Ohm m)
AR12	EM apparent resistivity at high frequency 11962 Hz (Ohm m)
AD12	EM apparent depth at high frequency 11962 Hz (Ohm m)
AR25	EM apparent resistivity at highest frequency 24510 Hz (Ohm m)
AD25	EM apparent depth at high frequency 24510 Hz (Ohm m)

3 Magnetic processing

This section describes the processing procedures applied to the Anglesey magnetic data. The standards used in airborne magnetic processing are well established and documented (e.g. Luyendyk, 1997).

In practice, although in-field processing of the magnetic data was undertaken, all the survey data was reprocessed in the office to provide validated (uniformly correct calibration factors for each season) data sets. The main magnetic software package used in these procedures is MAGCOR.

A full description of the standard processing applied to the JAC magnetic data is given by (Hautaniemi *et al.*, 2005). A review of the procedures for the Anglesey data is provided below.

3.1 AIRCRAFT CORRECTION

The aircraft is a magnetised metallic body moving in the Earth's magnetic field. The resultant magnetic effect depends on flight direction (heading) and the movement of the aircraft (pitch, roll, and yaw). These properties also vary with time. The magnetic effects depend on time and place within the Earth's magnetic field, so the calibrations have to be made separately for each survey area, and have to be repeated in cases of prolonged surveying. The procedures for calibration are described by Beamish and White (2009). Data from the aircraft logging system include raw magnetic data and compensated magnetic data. This allows magnetic compensation to be re-calculated post flight, although in practice this was not necessary.

3.2 DIURNAL CORRECTION

Short time variations of the Earth's magnetic field are removed by using a magnetic base station. The magnetic base station is established near the survey area. The magnetic variation during the survey flight has to be small enough so that it can be considered that the magnetic variation has minimum time difference between survey aircraft and the base station. Suitable limits of variation are defined according to local magnetic anomaly level, required accuracy and quality and possible cost and time limits of the survey. Both short and long time variation limits were defined; 12 nT over any 3 minute chord or 2 nT over any 30 second chord. All line data that exceeded these limits would have been rejected in the field and reflown. The data was also checked for significant micro-pulsation activity. None of these conditions were met during the survey. MAGCOR performs the diurnal correction. Base station data are filtered using a default median filter of 24 seconds and mean filter of 16 seconds. Filters of different lengths can be applied either specifying different filter lengths in MAGCOR or when viewing the magnetic base station in Mag32. In practice it was not necessary to adjust the default values.

3.3 LAG CORRECTION

A lag test is performed to verify the recording delay. Due to the real time RMS compensation, it's pre-filtering, and delays in network data transmission, a small lag exists in the recording of the data. This is verified by repeating a flight line in opposite directions above a sharp but sideways wide magnetic anomaly source like a railway or thin magnetic dyke. Comparing these repeated measurements, the exact lag is then determined. When flight lines are rejected due to QC considerations the re-flight is always in the opposite direction so as to confirm the lag correction. A lag correction of -0.7 seconds is applied to the data by MAGCOR. Following additional analysis in Geosoft using line 180 (flown in both directions) a further correction of 0.1 seconds was applied; although the determination of the true lag is difficult as there are no cross-cutting anomalies perpendicular to the flight line direction.

3.4 HEADING CORRECTION

The aircraft is a magnetised metallic body moving in the Earth's magnetic field. As such, different magnetic values recorded in the two opposing flight line directions. Heading corrections for the Anglesey survey were as follows:

Direction	Left magnetometer	Nose magnetometer
0	-0.58 nT	-4.73 nT
180	-0.78 nT	-10.83 nT

Table 1. Heading corrections for the Anglesey magnetic survey.

The heading correction applied by Geosoft is a simple DC shift of line data based simply on the direction of travel.

The heading correction is one of the most common sources of levelling error during data processing. Heading corrections are not always stable with time or may vary when objects are taken from or placed within the aircraft. The heading correction can be determined by examining the statistics of the entire survey. The calculation of the mean for the two different flight directions can show the error in heading correction.

3.5 INFLUENCE OF AIRCRAFT

The aircraft has a number of mission-critical systems on board which create a magnetic source that can result in small errors in the magnetic data. A typical disturbance with the Twin Otter aircraft is the effect of the hydraulic pump. The hydraulic pump causes a 1 – 2 nT anomaly which lasts up to two seconds during its operation. The hydraulic pump is mission critical and has been shielded as much as possible but its operation is necessary after long periods of significant rudder and ailerons use, common in mountainous regions. When the pump is operated, the duration is recorded and the magnetic data is then removed automatically. Re-flying is not possible as repeat operation of the pump is often observed as the same flying conditions are experienced on the re-flight.

Other sources of magnetic noise include windscreen wipers and the VHF communication system. The former is short period; otherwise the flight line is abandoned. The Anglesey survey also specified that flying would not occur during any periods of rain, therefore windscreen wipers were not in operation during this survey. The latter source of noise is not normally a problem in surveying. Communication between the aircrew and Air Traffic Control is coordinated so that it only occurs during turning, i.e. off of survey line. However, there are times when the aircrew are called on-line and they are obliged to respond. This did not occur during this survey.

3.6 DATA QC AND SPIKE REMOVAL

After data processing using the MAGCOR program, the data are imported into Geosoft Oasis montaj and thoroughly checked. At this stage, all residual remaining errors (such as spikes, VHF communications, etc.) are corrected if observed.

The primary processing assignment with the Anglesey magnetic data related to the response from the aluminium plant on Holy Island, in the western region of Anglesey. The anomaly measured over this smelting works was larger than any response previously recorded during the HiRES program. The signal completely dominated the geological response and the decision was made to subtract the anomaly from the data set. The method involved the careful removal of the signal from the nose and left data and before sparse gridding (at 700 m) and resampling back to original spatial positions for the missing data. The maximum and minimum values recorded over the smelting works were 99191 nT and 16723 nT respectively.

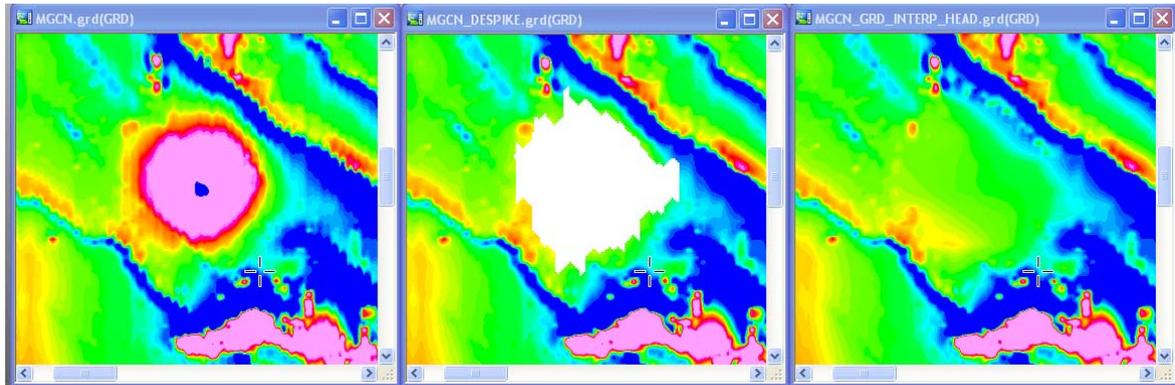


Figure 5. The removal of the anomaly cause by aluminium smelting works: left - the acquired data; middle - the blanked region; right - the restored interpolated signal.

3.7 LEVELLING MAGNETIC DATA

Further levelling of the magnetic data is still required after the corrections described above. Residual errors can be introduced from incomplete diurnal corrections since magnetic base stations are always situated at some distance from the survey aircraft and the transient field varies in both time and space. These errors are generally small but can be seen in high resolution measurements over magnetically flat areas. There are also other possible error sources, for example incomplete compensation and heading correction. The aim in applying any correction is to eliminate errors in the data that have an effect on the true magnetic intensity of the Earth; to be avoided is the application of corrections, which have the sole objective of producing smooth and beautiful maps. If the original measured data is poor in quality, acceptable corrections may not be able to bring it to a high quality level.

JAC do not normally fly tie lines. Tie line corrections are generally ineffective due to low survey altitude and typically strong gradients of anomaly field. The error on intersection points between normal lines and tie lines is very often bigger than the expected accuracy for present high-resolution magnetic surveys. This problem is made worse in areas with high degrees of cultural magnetic noise, where a large proportion of intersection points cannot be used due to excessive gradients.

Normally, JAC uses the virtual tie line approach to level magnetic data but for the Anglesey survey a different approach was adopted. This method develops the approach described by Huang (2008). The technique removes the necessity to level with virtual tie lines and is a quick and easy method that requires minimal user interaction.

The scheme relies upon the long wavelength component of the individual lines capturing the regional field. Taking the unlevelled, but despiked, data the regional field is computed by:

- Gridding the data using Geosoft's bi-directional gridding method, whilst applying a low pass filter of 1600 m to generate a grid of the regional field and levelling errors.
- Regridding the grid with the same low pass filter to isolate the regional field and any high frequency noise.
- Removing the high frequency noise by application of a Hanning (3x3 convolution) filter.
- Resampling the grid back to the original flight line sampling.

The BGS program `Mag_to_regField.exe` is then utilised to minimise the difference between the line data and the regional field, see Appendix 1 for details.

3.8 MICROLEVELLING

The microlevelling approach undertaken for the Anglesey magnetic survey is to utilise the 'decorr.gx' available from PGW Geophysics through Geosoft Oasis Montaj. The scheme

requires a single corrugation cut-off wavelength, in this case 1000 m, and generates a decorrugation noise grid that is removed from the original data.

The more conventional approach of using Geosoft's own bi-directional microlevelling scheme was rejected after tests revealed significant 'run-off' artefacts at almost all cut-off wavelengths.

3.9 MAGNETIC DATA DELIVERY

The final magnetic data sets are ANG_MGCL.xyz and ANG_MGCN.xyz. The region within the polygon $x_{\min}=224650$, $y_{\min}=378550$, $x_{\max}=229050$, $y_{\max}=383250$ should not be used for interpretation as the response of an aluminium smelting works has been removed a simple interpolation performed to fill the missing gap. The data was also subjected to an IGRF correction. A READ_ME file is included in the 'processed' folder and the final data sets include:

X_BNG	Grid Easting (m) – British National Grid
Y_BNG	Grid Northing (m) – British National Grid
Z	GPS altitude (m) above geoid (WGS84)
PITCH	Pitch (degrees)
ROLL	Roll (degrees)
HEADING	Heading (degrees clockwise)
FLIGHT	Flight number
DAY	Day number (Julian)
TIME	Time (HHMMSS)
DIR	Flight direction (degrees clockwise)
RALT	Radar altitude (m)
LALT	Laser altitude (m)
DTM	Digital Terrain Model (m)
BASE	The base station magnetic data
RAW_MGCL/N	The raw recorded magnetic data
DESPIKE_MGCL/N	The despiked raw magnetic data
REGION_MGCL/N	The highly filtered regional magnetic field
CORRECTED MGCL/N	The magnetic data corrected to the regional field
FINAL MGCL/N	The final microlevelled magnetic data

4 Radiometric processing

This section describes the processing procedures applied to the radiometric data. The standards used in airborne radiometric processing stem from procedures described in AGSO and IAEA reference manuals (Grasty and Minty, 1995; IAEA, 1991).

In practice, although in-field processing of the radiometric data was undertaken, all the survey data was reprocessed in the office to provide validated (uniformly correct calibration factors) data sets. The main radiometric software package used in these procedures is RADCOR.

A full description of the processing applied to the JAC radiometric data is given by Hautaniemi *et al.* (2005). The recommended (IAEA) energy rates of the windows used to deliver the Anglesey radiometric data are shown in Table 2:

Window	Energy range (MeV)
Thorium	2.41 – 2.81
Uranium	1.66 – 1.86
Potassium	1.37 – 1.57
Total	0.41 – 2.81

Table 2. The recommended (IAEA) energy ranges of the spectral windows.

A review of the main processing procedures is provided below.

4.1 DEAD TIME CORRECTION

The spectrometer needs a short time to process each pulse and as such has some difficulty observing any subsequent pulse arriving while the first one is being processed. This time is referred to as the dead time. The dead time correction is carried out using electronically measured dead time data for each window.

4.2 FILTERING

Digital filters are applied to the radar altimeter data and applied to the processing of the radiometric data. The filtering is used to smooth sudden jumps that can arise when flying over steep terrain. These sudden shifts/spikes in the data, if uncorrected, can cause problems when height correcting the data later. The spectrometer's cosmic channel (see below) is also filtered to reduce statistical noise.

4.3 AIRCRAFT AND COSMIC BACKGROUND CORRECTION

The aircraft has a background radiation component for each of its radiation windows. The background radiation of the aircraft is constant for each window as long as there are no changes made to the aircraft and its contents. Cosmic background radiation increases with height and is proportional to the number of radiation pulses in the high-energy cosmic window (3 – 6 MeV). The determination of the aircraft and cosmic background count rates for each spectral window has been described in IAEA Technical Report 323 (IAEA 1991), and is described for this survey by Beamish and White (2009, Section 3.2.1).

4.4 BACKGROUND RADON

Radon gas makes it difficult to measure uranium concentrations accurately. Since it is not always evenly distributed in the air; eliminating it from background radiation is not simple.

Determination of the constants necessary for the correction of the background radon requires several steps and utilizes the upward detectors. The procedure outlined in IAEA (1991) is generally correct, but more recent studies have refined the process. The first step, determining the contribution of atmospheric radon to the various spectrometry windows, is best achieved through a series of test flights over water. The method of least squares allows the constants in equations 4.9 to 4.12 (IAEA, 1991) to be determined. The next step is to determine the response of the upward looking detector to radiation from the ground (equation 4.13, IAEA, 1991). The procedure recommended by Grasty and Hovgaard (1996) is more reliable than that in IAEA (1991) for the second step.

Examination of the upward looking data and the Uranium result for the Anglesey survey suggests that there is not a problem with Radon during this survey. The problems radon creates are usually highly localized and may not be consistent from flight line to flight line. This usually results in flight lines that appear "out-of-level".

4.5 EFFECTIVE HEIGHT CORRECTION

The count rates depend on the density of air and thus on the temperature and pressure of the air. The filtered radar altimeter data is used in adjusting the stripping ratios, for altitude corrections and also to correct for the attenuation of the radioactivity at nominal height. The filtered radar altimeter data is converted to effective height at standard temperature and pressure (STP). The radiometric results are then corrected to a nominal height to remove the effect of varying survey altitude. The background corrected total count and stripped count rates vary exponentially with aircraft altitude.

4.6 STRIPPING CORRECTION

The spectra of K, U and Th overlap and so one radioelement will also contain some effect from the other two radioelements. This channel interaction must be corrected to produce pure concentration values. The stripping ratios α , β , γ , a , b and g are determined over calibration pads as described in Chapter 4 of IAEA 1991 and are discussed by Beamish and White (2009, Section 3.2.2). The dimensions of our transportable calibration pads are $1\text{m} \times 1\text{m} \times 30\text{cm}$ and the weight of each one of them is approximately 660 kg. The principal ratios α , β , and γ vary with standard temperature and pressure (STP) and altitude above the ground and are usually adjusted before stripping is carried out. Using the six stripping ratios, the background corrected count rates in the three windows can be stripped to give the counts in the potassium, uranium and thorium windows that originate solely from potassium, uranium and thorium. These stripped count rates are given by equations 4.44 to 4.47 in the IAEA 1991.

4.7 CONVERSION TO APPARENT RADIOELEMENT CONCENTRATIONS

The fully corrected count rate data is used to estimate the concentrations in the ground of each of the three radioelements; potassium, uranium and thorium. The procedure determines the concentrations that would give the observed count rates, if uniformly distributed in an infinite horizontal slab source. Because the U and Th windows actually measure ^{214}Bi and ^{208}Tl respectively, the calculation implicitly assumes radioactive equilibrium in the U and Th decay series. The U and Th concentrations are therefore expressed as equivalent concentrations, eU and eTh.

4.8 LEVELLING OF RADIOMETRIC DATA

As noted previously, the Total count and Uranium results, following the application of the above procedures, were judged adequate in relation to the potential effects of radon. No further levelling of the radiometric data was undertaken.

4.9 RADIOMETRIC DATA DELIVERY

The final radiometric data set is ANG_RAD.xyz. A READ_ME file is included in the processed folder and the final data sets include:

X_BNG	Grid Easting (m) – British National Grid
Y_BNG	Grid Northing (m) – British National Grid
Z	GPS altitude (m) above geoid (WGS84)
LINE	Line number
PITCH	Pitch (degrees)
ROLL	Roll (degrees)
HEADING	Heading (degrees clockwise)
FLIGHT	Flight number
DAY	Day number (Julian)
TIME	Time (HHMMSS)
DIR	Flight direction (degrees clockwise)
BALT	Barometric altitude (m)
TOUT	External temperature (°C)
DTM	Digital Terrain Model (m)
RALT	Radar altitude (m)
LALT	Laser altitude (m)
D_KAL	Potassium (%K)
D_THO	Thorium (ppm, eTh)
D_TOT	Total counts (Ur units)
D_URA	Uranium (ppm, eU)

An additional cut-to-coast data, ANG_RAD_CC.xyz set is also included in the final processed folder and includes:

X_BNG	Grid Easting (m) – British National Grid
Y_BNG	Grid Northing (m) – British National Grid
LINE	Line number
DIR	Flight direction (degrees clockwise)
DTM	Digital Terrain Model (m)
RALT	Radar altitude (m)
LALT	Laser altitude (m)
D_KAL	Potassium (%K)
D_THO	Thorium (ppm, eTh)
D_TOT	Total counts (Ur units)
D_URA	Uranium (ppm, eU)
KAL_CC_LP53	Potassium (%K) after 5x5 convolution filter – 3 iterations
THO_CC_LP53	Thorium (ppm, eTh) after 5x5 convolution filter – 3 iterations

TOT_CC_LP53 Total counts (Ur units) after 5x5 convolution filter – 3 iterations
URA_CC_LP53 Uranium (ppm, eU) after 5x5 convolution filter – 3 iterations

5 Positional processing and line trimming

Post-processing differential correction is done after a survey flight, allowing greater positional accuracy. The purpose is to find the exact coordinates for each of the measuring sensors in the local coordinate system. Real-time differentially corrected coordinates are not as accurate as the post-flight differentially corrected ones since the post-processing differential correction program (Javad Pinnacle™) processes the data forwards and backwards in its algorithms, which is not possible in real time. The inputs are the flight and base station satellite recordings. The quality of the satellite coordinates is verified by observing the number of satellites and by using a quality (PDOP, Position Dilution of Precision) parameter. The JAC program GPS2KOG uses the differentially corrected GPS WGS84-coordinates to transform to a local grid (planar) coordinate system. The local geographical grid system used for the processing of the Anglesey survey was British National Grid.

A digital terrain model is calculated from the survey data as the height from the reference ellipsoid (WGS-84). The data used are GPS height and the height above the ground/terrain as measured by the radar altimeter. With single frequency GPS+GLONASS receivers in differential mode we can measure the reference height to an accuracy of less than 1.5 metres. The accuracy of the radar altimeter is typically better than 0.5 metres. It should be noted that the radar measures a distance to the nearest reflecting object. Buildings, trees and major constructions typically provide such reflections, so that the elevation measurement is better described as a *Terrain* rather than an *Elevation* model. A typical resultant accuracy of 2 metres is anticipated for the DTM measurements. Ground control sites would be needed to convert these geocentric heights to height above sea level.

Radar Altitude (RALT), GPS altitude above geoid (Z) and the resulting DTM are provided with all the processed geophysical data sets. When the nominal survey altitude above ground is less than ~146 m, we anticipate the type of accuracies quoted above. With increasing altitude (due to CAA regulations or in certain mountain areas), the RALT and hence DTM measurement becomes less accurate.

All delivered data are untrimmed. Some of the images are clipped to coast to better utilise the range of the colour palette.

6 Maps of the survey area

All the images presented in this section are derived from the final levelled data sets.

6.1 OVERVIEW

In overview, the magnetic data respond to both at-surface and concealed magnetic rocks at all depths (wavelength dependent). The magnetic data shown here are Total Magnetic Intensity (TMI, in nT). The radiometric data respond to about 30 cm of the radiometric content of the surface material. The actual content might relate to either the soil material (e.g. mineralogy but also moisture content) and/or the parent geological material. The basic EM data comprise coupling ratios that may be difficult to interpret in a simple fashion, due to both a dependence on sensor elevation and the fact that both in-phase and quadrature components are required to understand the response. The coupling ratios are converted to estimates of apparent resistivity and apparent depth as described previously. Apparent resistivity (AR) may also be converted to apparent conductivity (AC) using the formula $AC = 1000.0/AR$, where AR is in Ohm.m and AC is in mS/m. The half-space parameters form more convenient interpretation products but, as they derive from a uniform Earth assumption, they have limitations when geology/resistivity varies rapidly.

The depth of investigation of the JAC EM data may (typically) vary between 60 and 100 m. This is a simplification in that:

- i) sensitivity to resistivity variations is a maximum at the surface and decreases with depth
- ii) the statement only refers to the vertical distribution of resistivity

In broad terms, data at the lowest frequencies (900 Hz and 3 kHz) may reveal deeper structure while data at the highest frequency (25 kHz) relates to the shallow subsurface. When a resistivity anomaly occurs at or near the surface, data at all frequencies may respond with the amplitude of the response decreasing with decreasing frequency.

6.2 SIGNAL/NOISE FEATURES IN THE DATA

When data are acquired across populated areas, several issues are worth noting.

The first is that regulatory/safety high-fly conditions result in zones of reduced or loss of geophysical signal. The spatial pattern of high-fly is imposed on the resulting images, and this 'spatial convolution' may be complex. Typically the magnetic data retains a signal but at a reduced amplitude while RAD and EM may show 'out-of-ground' effects. An image highlighting the regions where the radar altitude records a height over 100 m is included in section 6.3.

The geophysical data may respond to both geology and/or cultural features across any given survey area. Detailed interpretation of the geophysical responses ultimately requires an understanding on the non-geological responses e.g. topographic and other maps must be used in conjunction with the geophysical data.

Magnetic data typically responds to buildings/structures with high metal content. The distortions are usually easily observed when examining detailed line-based data while in gridded images, the distortions appear as highly localised 'bulls-eyes' (closed contours). Therefore magnetic data require careful consideration of cultural features when interpreting.

The radiometric signal above made-ground and structures should reduce to zero (theoretically) however the footprint of the response (height dependent) is typically so large that the response is averaged (smeared) across both geological and non-geological zones.

The EM data (being an active source measurement) is perhaps, most prone to man-made interference. Noise distortion is entirely survey area specific. For this reason, reference should be made to images of the power-line monitor (PLM). In addition, linear/quasi linear features observed in the EM images may also relate to roads, or to road-side routing of services (e.g. electricity, gas, water).

6.3 IMAGES

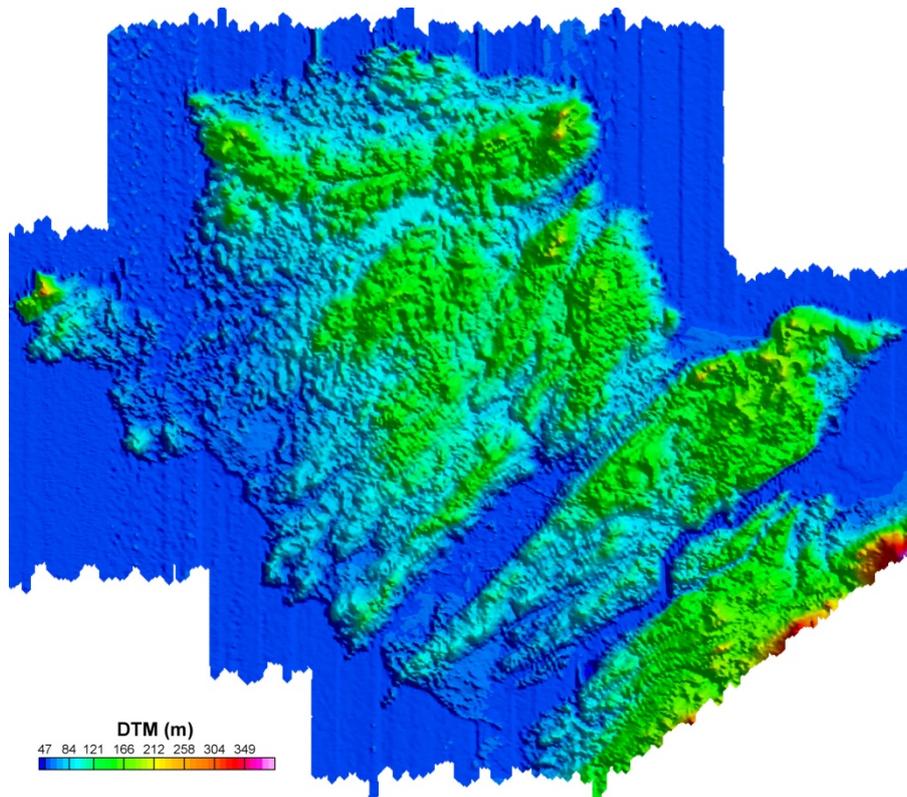


Figure 6. Digital terrain model.

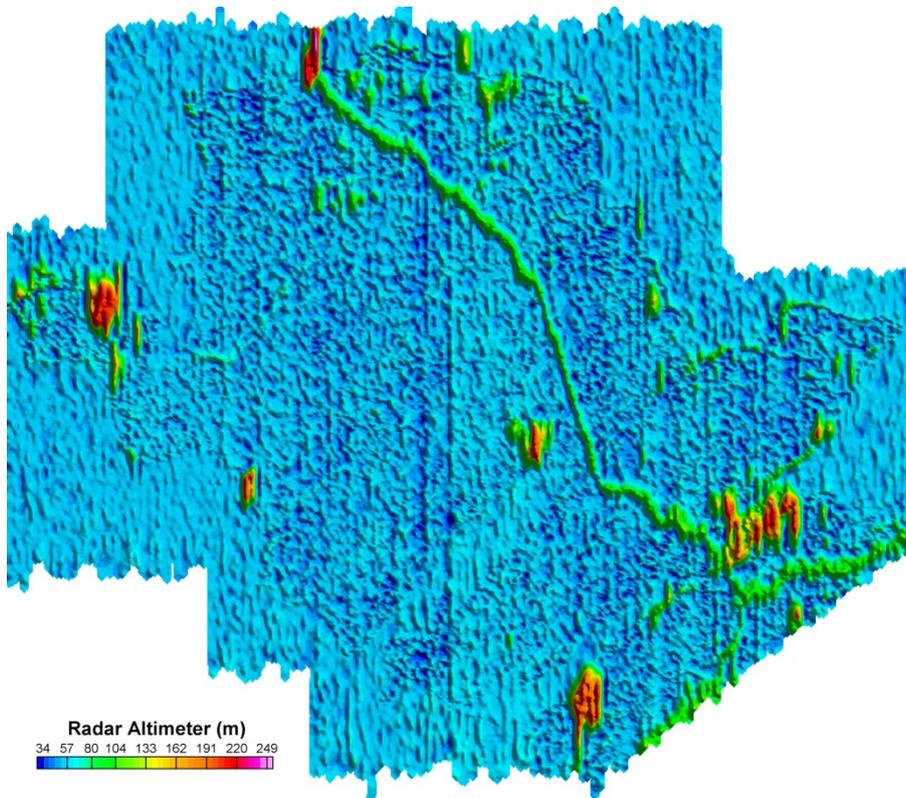


Figure 7. Altitude (RALT).

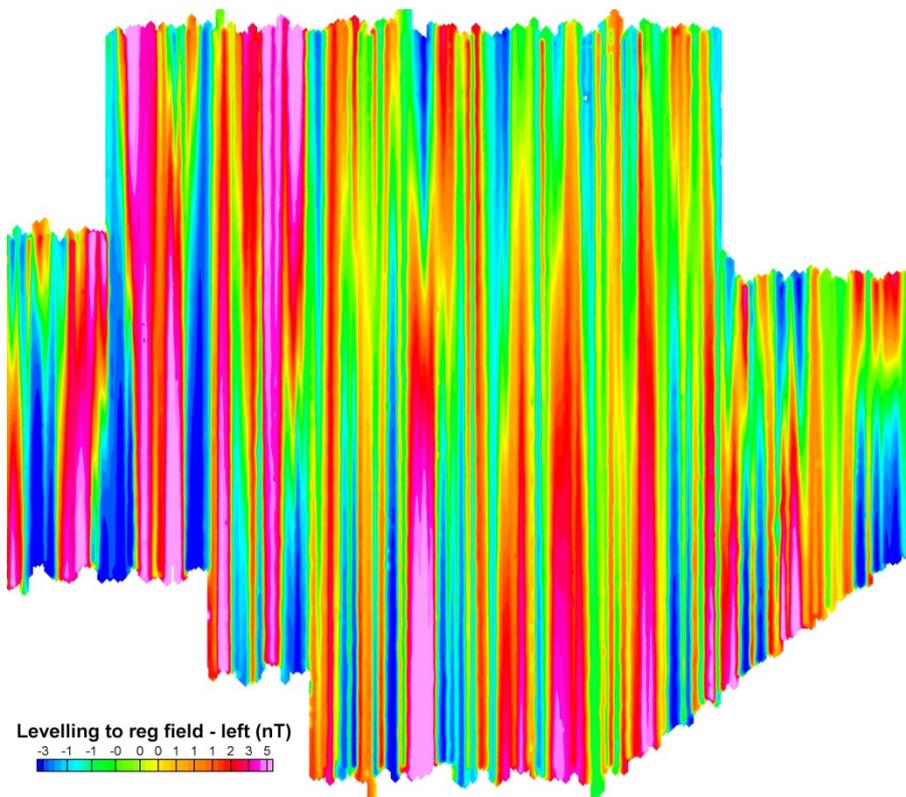


Figure 8. Levelling corrections applied after minimisation to regional field (left wing tip).

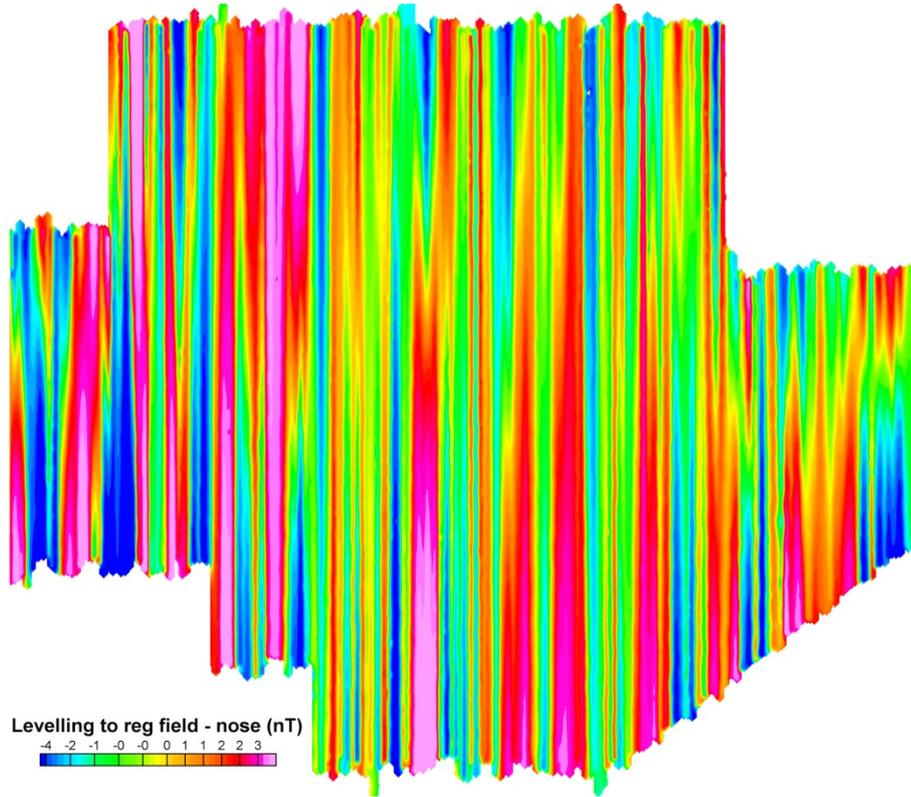


Figure 9. Levelling corrections applied after minimisation to regional field (nose tip).

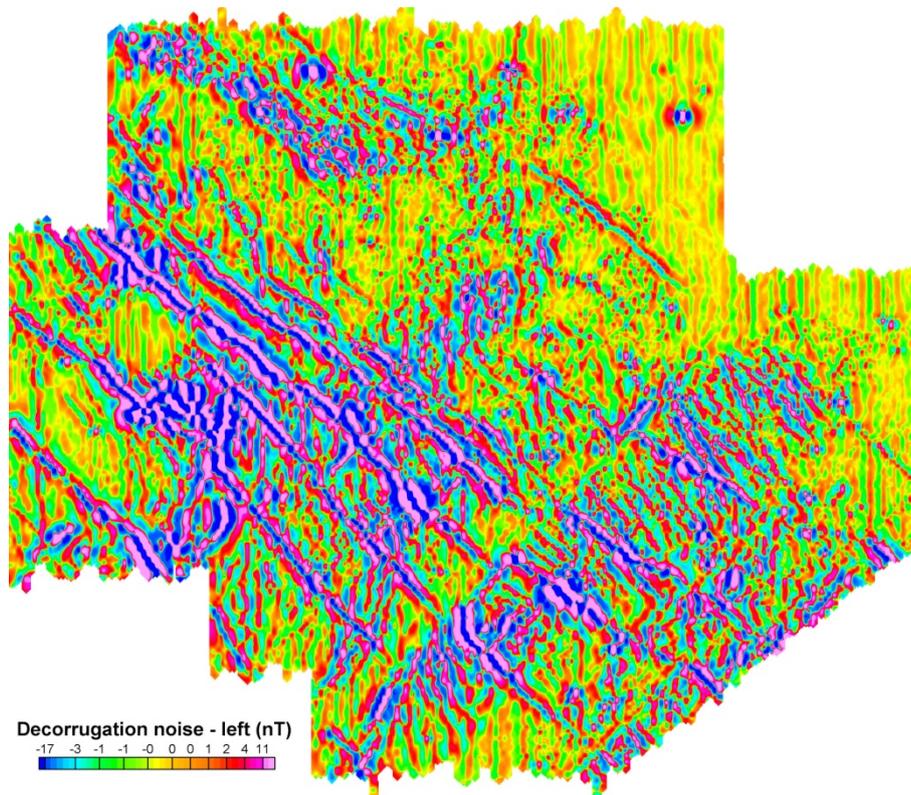


Figure 10. Levelling corrections applied by decorrugation procedure (left wing tip).

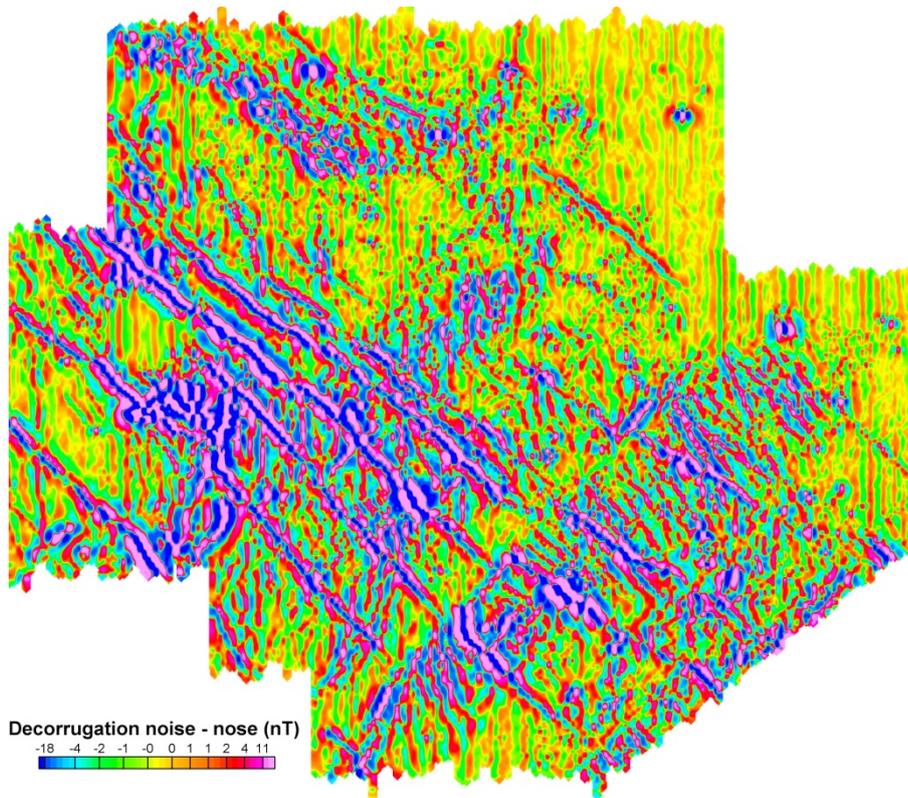


Figure 11. Levelling corrections applied decorrugation procedure (nose tip).

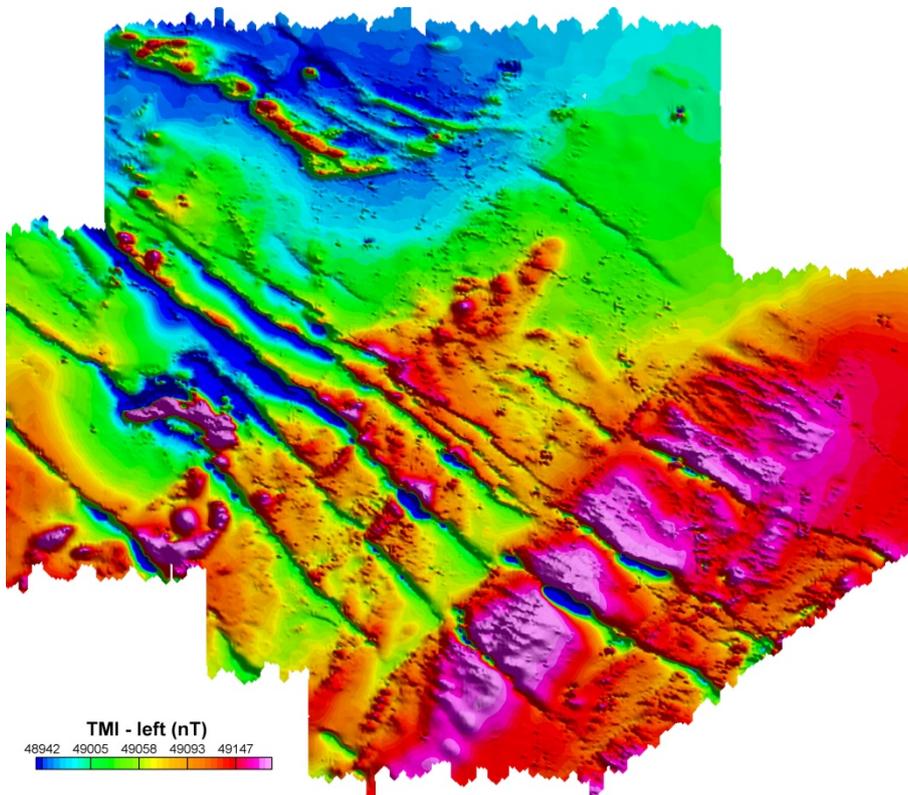


Figure 12. Total magnetic intensity (left wing tip).

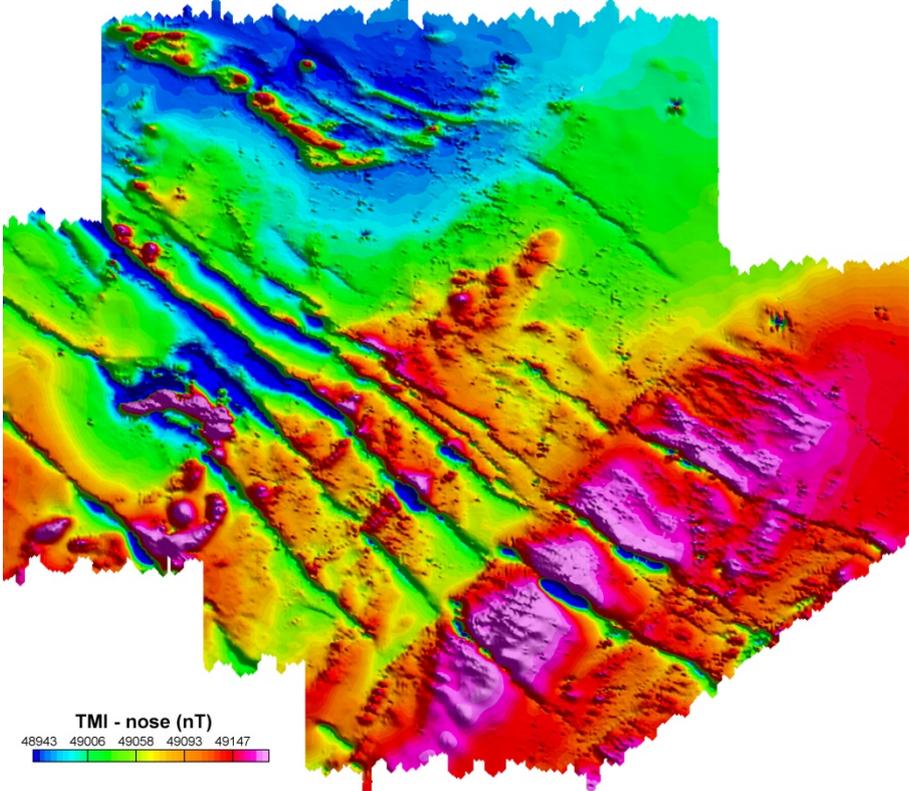


Figure 13. Total magnetic intensity (nose tip).

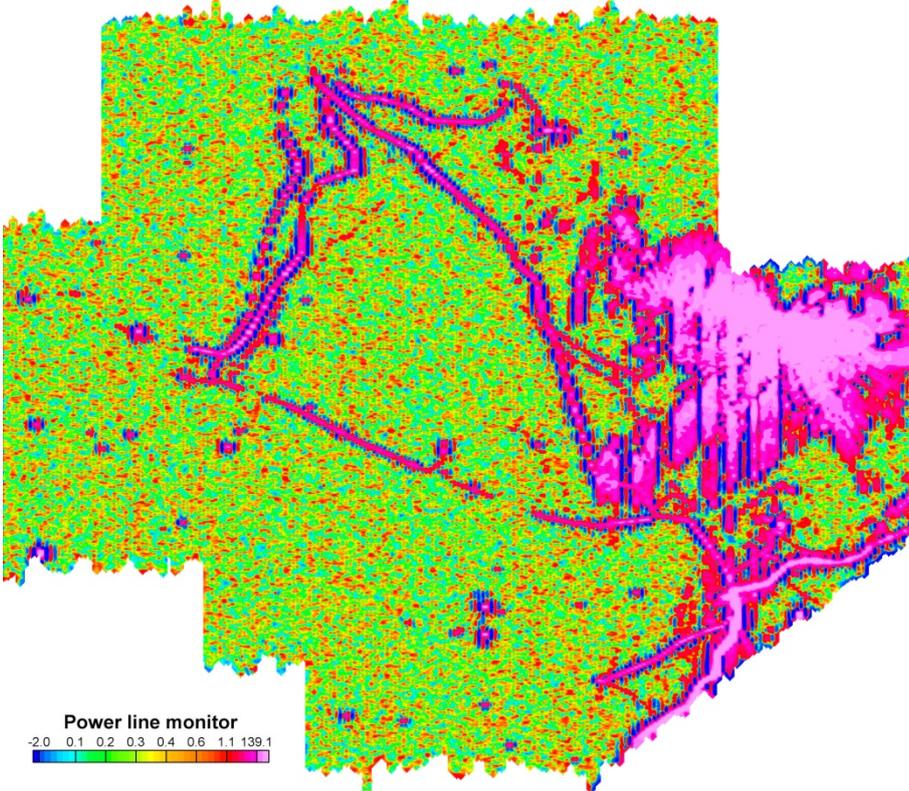


Figure 14. Power line monitor

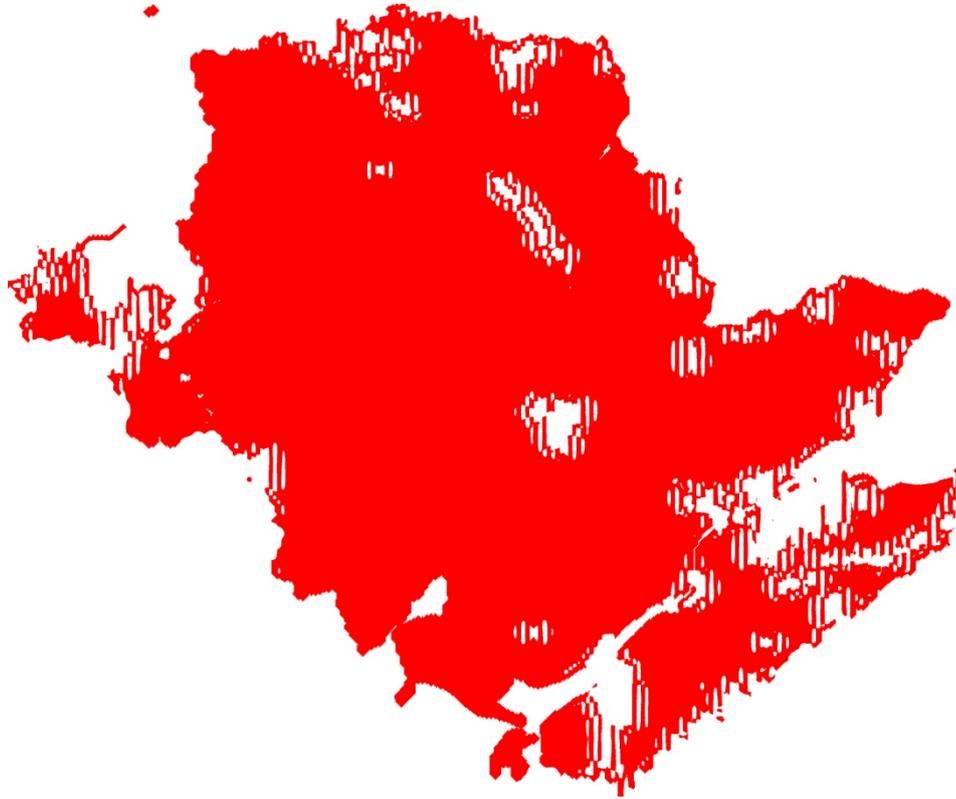


Figure 15. Radar altitude (DALT) less than 100 m (red).

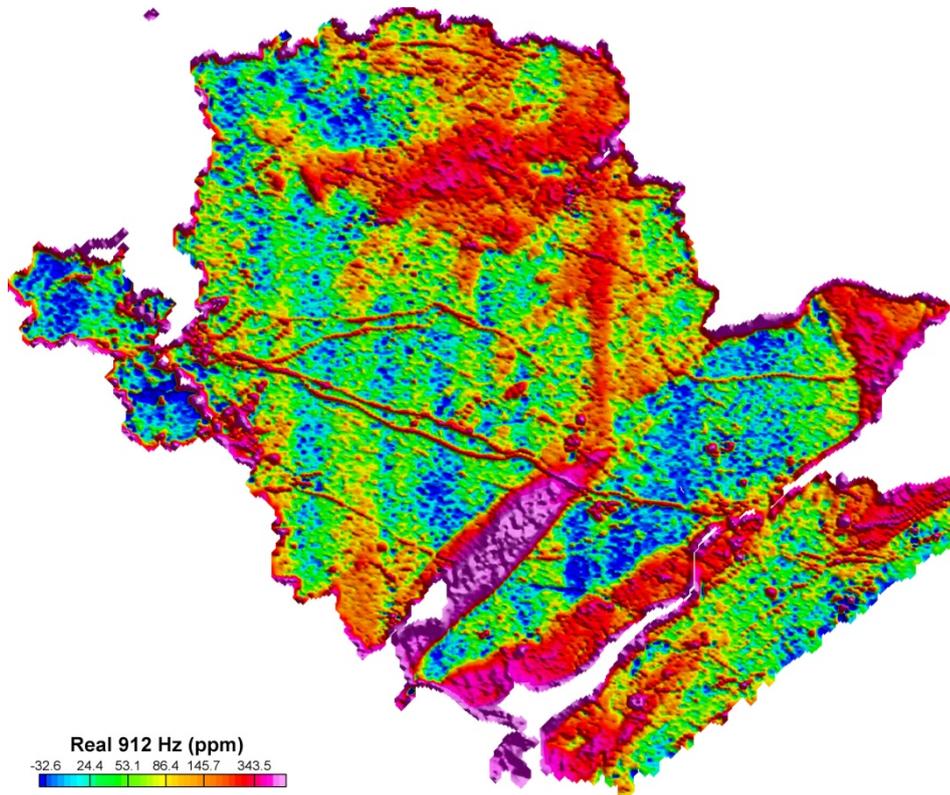


Figure 16. EM: Real component, 0.912 kHz.

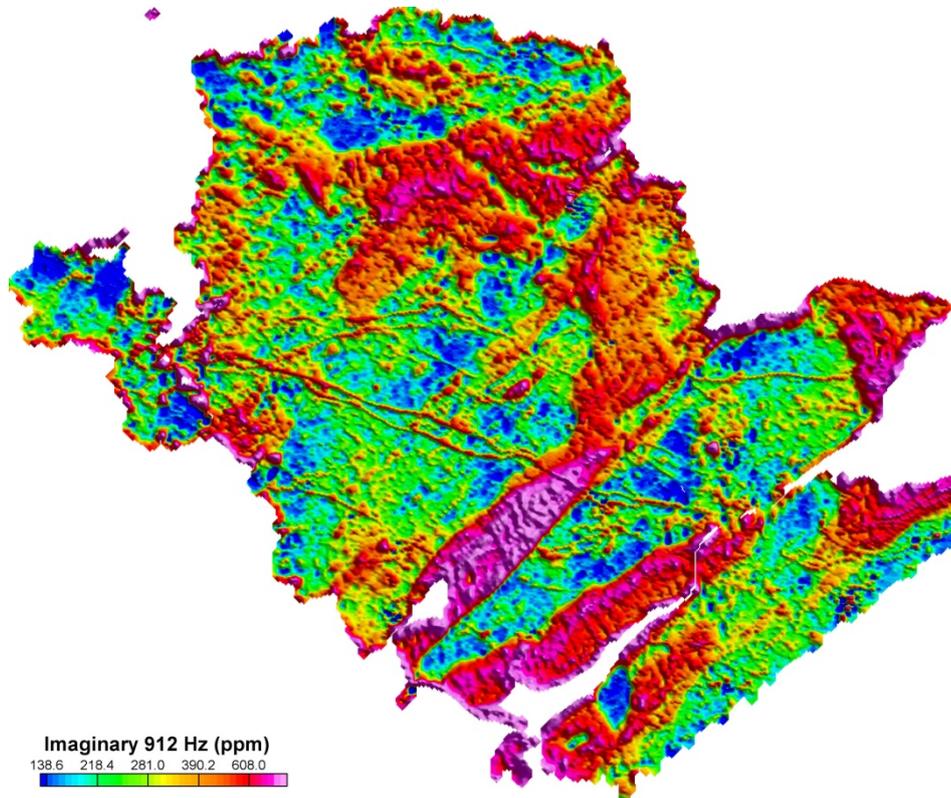


Figure 17. EM: Imaginary component, 0.912 kHz.

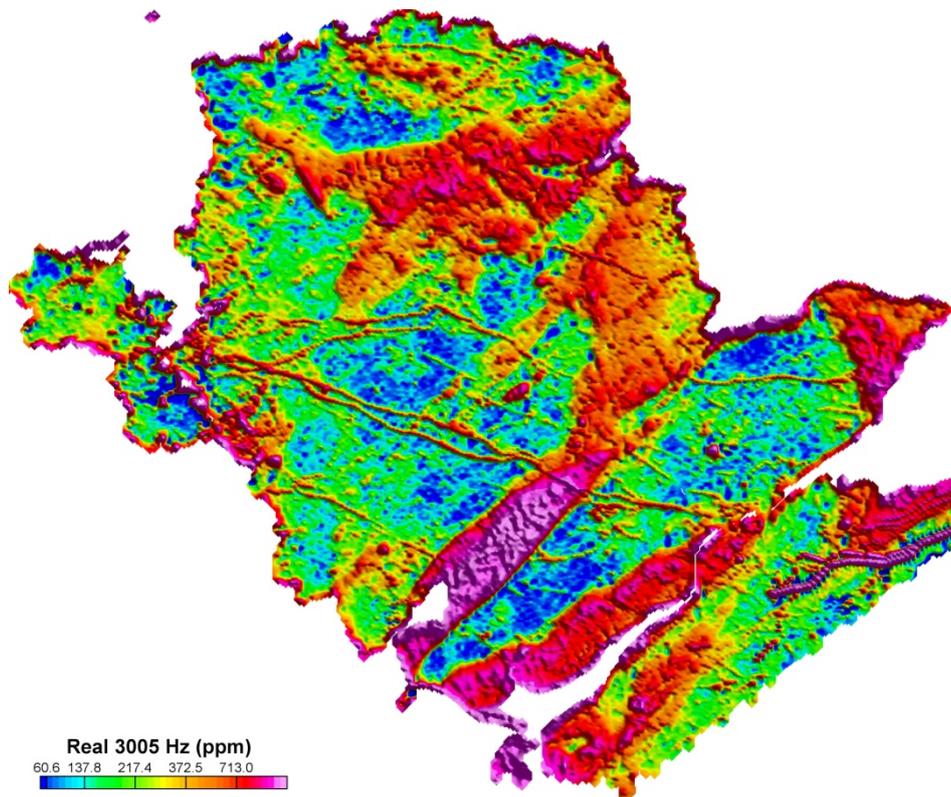


Figure 18. EM: Real component, 3 kHz.

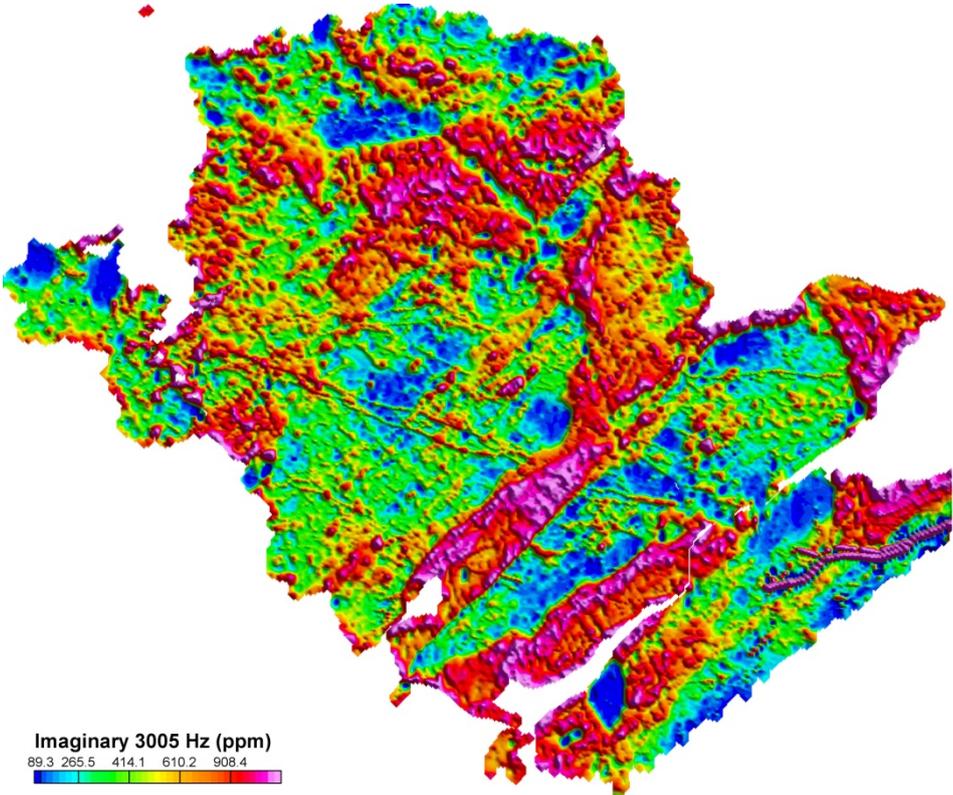


Figure 19. EM: Imaginary component, 3 kHz.

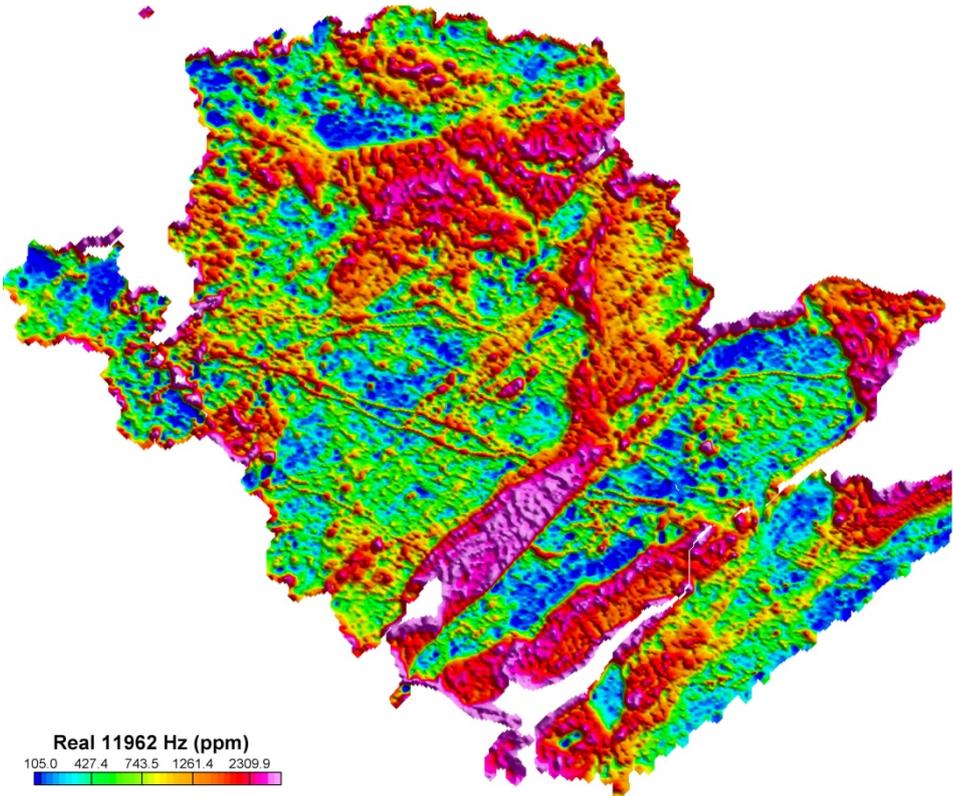


Figure 20. EM: Real component, 12 kHz.

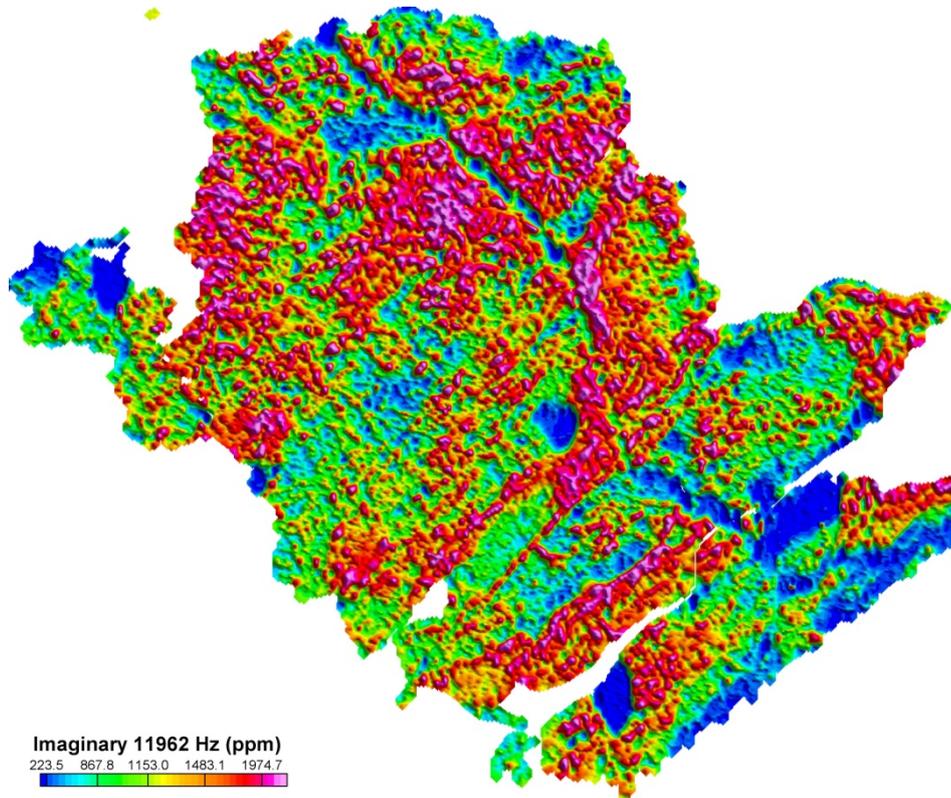


Figure 21. EM: Imaginary component, 12 kHz.

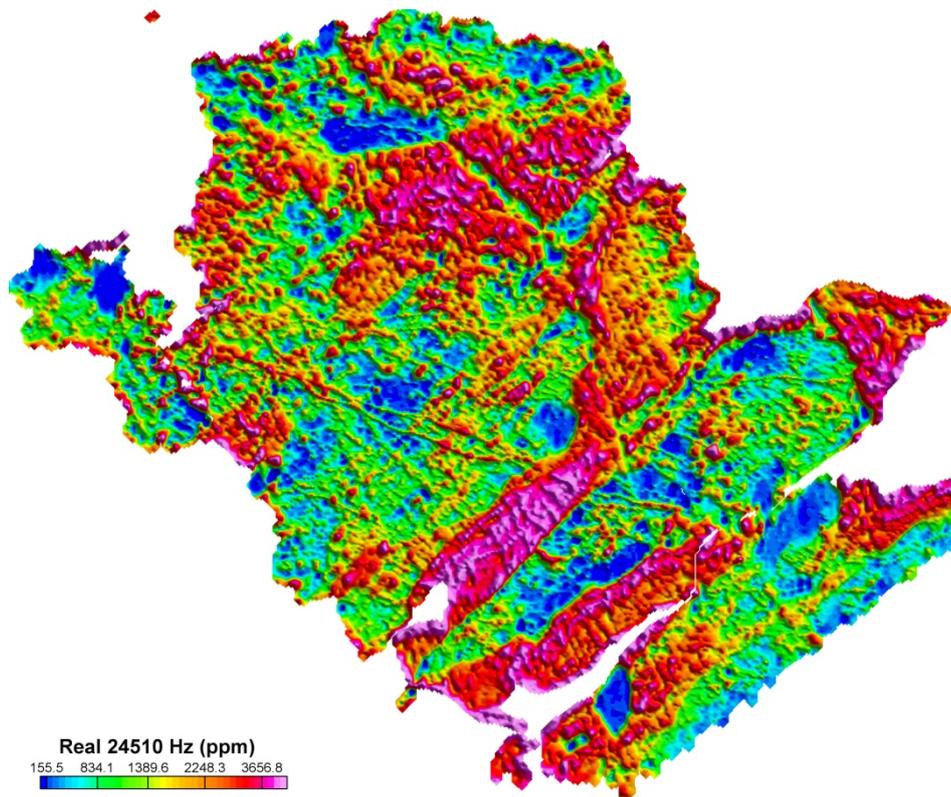


Figure 22. EM: Real component, 24.5 kHz.

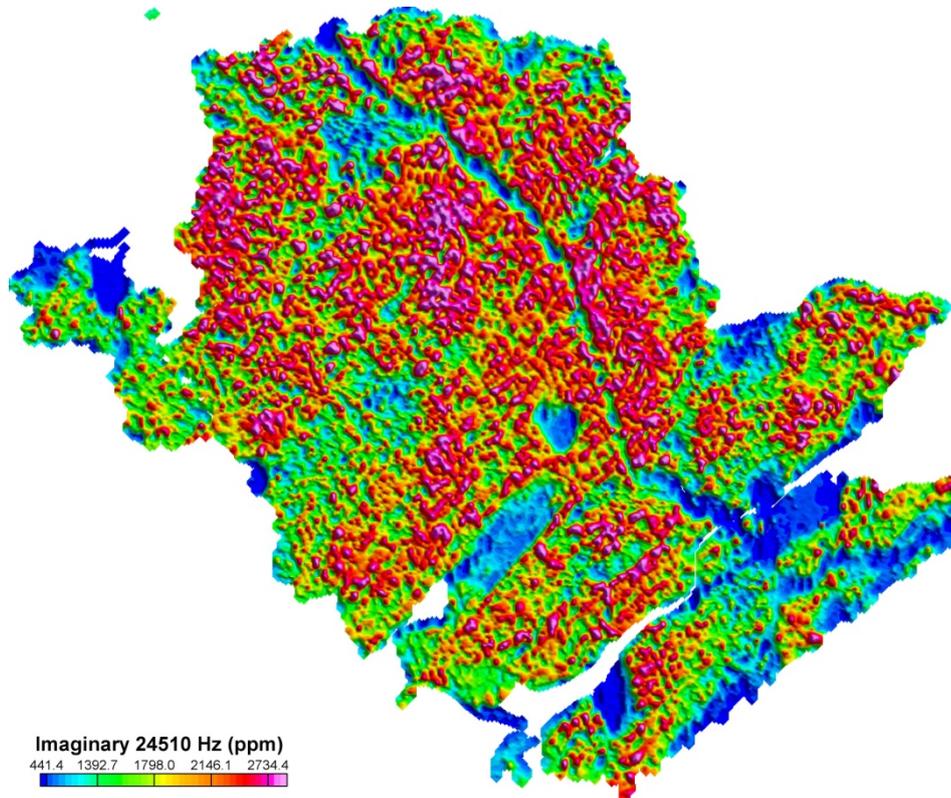


Figure 23. EM: Imaginary component, 24.5 kHz.

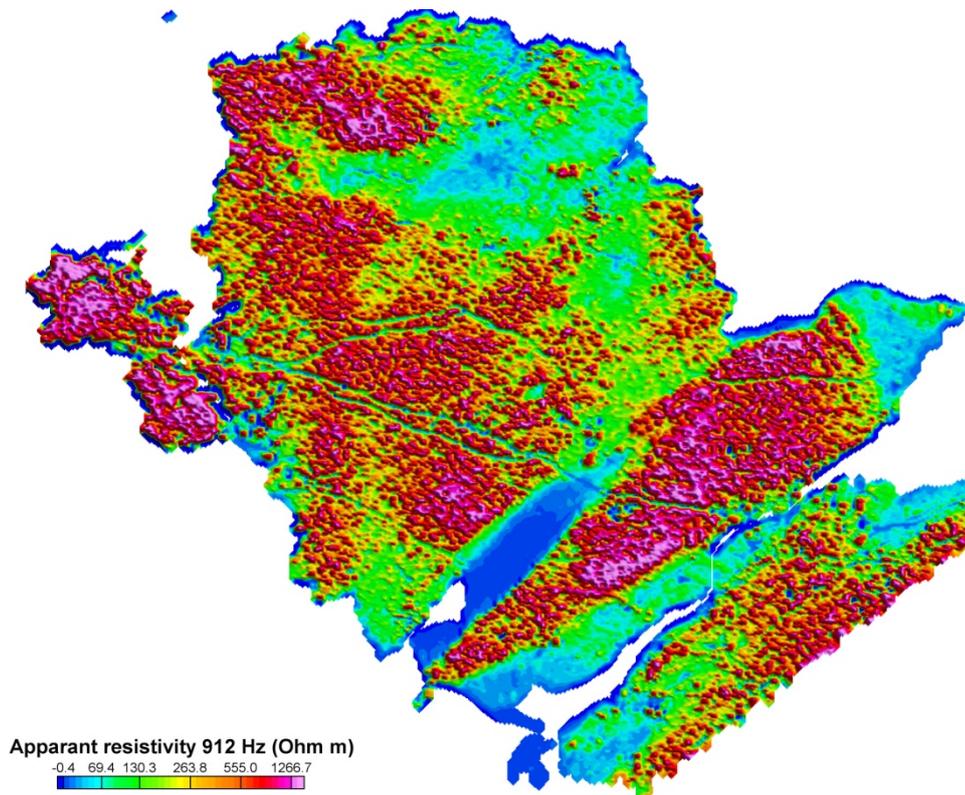


Figure 24. EM: Apparent resistivity, 0.912 kHz.

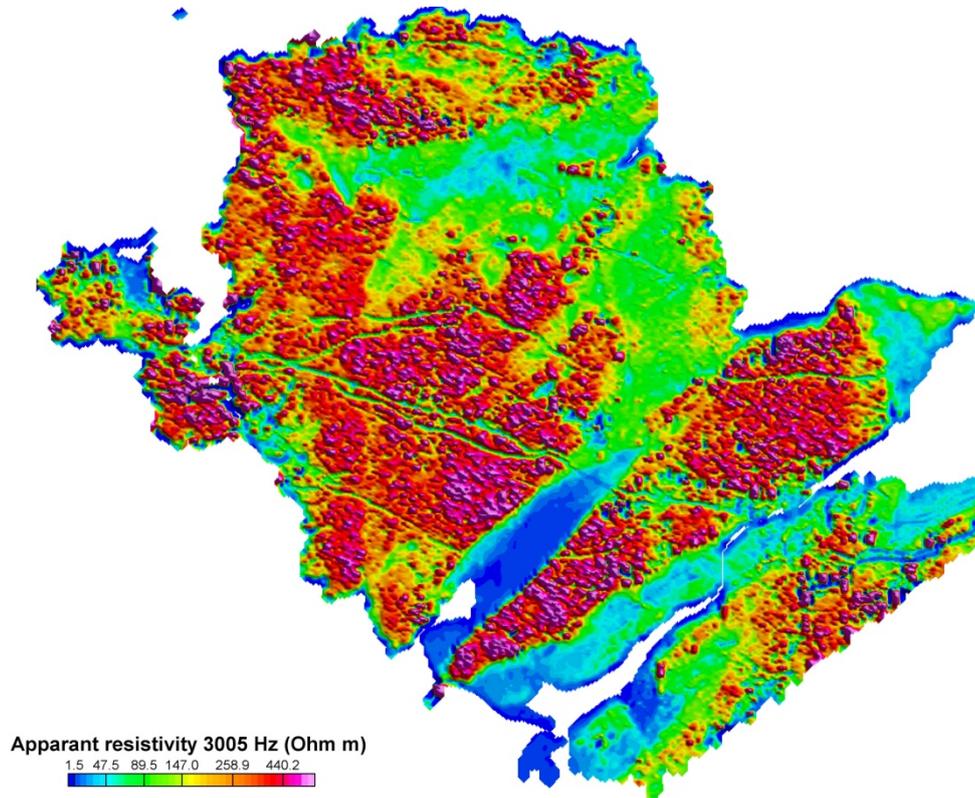


Figure 25. EM: Apparent resistivity, 3 kHz.

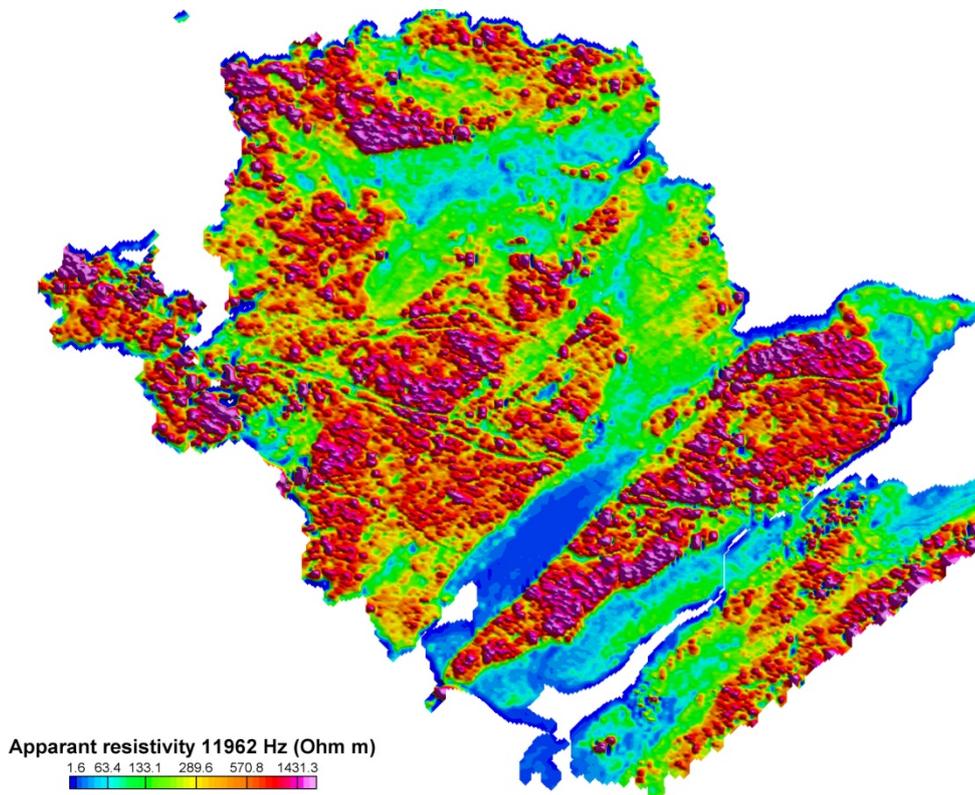


Figure 26. EM: Apparent resistivity, 12 kHz.

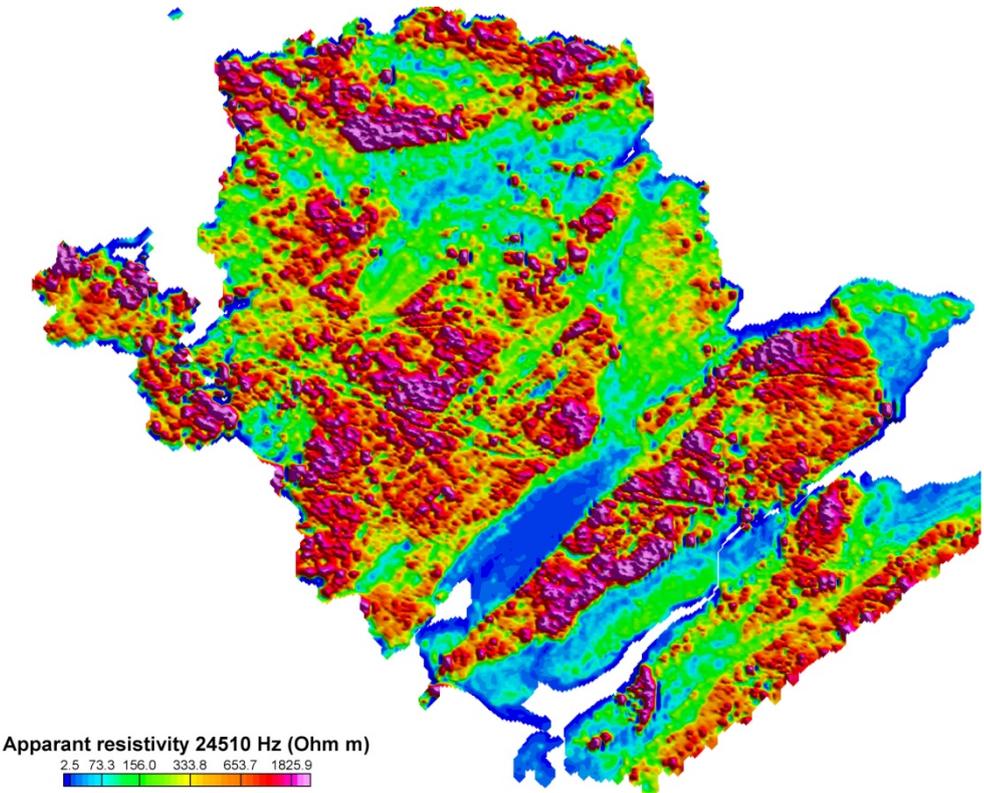


Figure 27. EM: Apparent resistivity, 24.5 kHz.

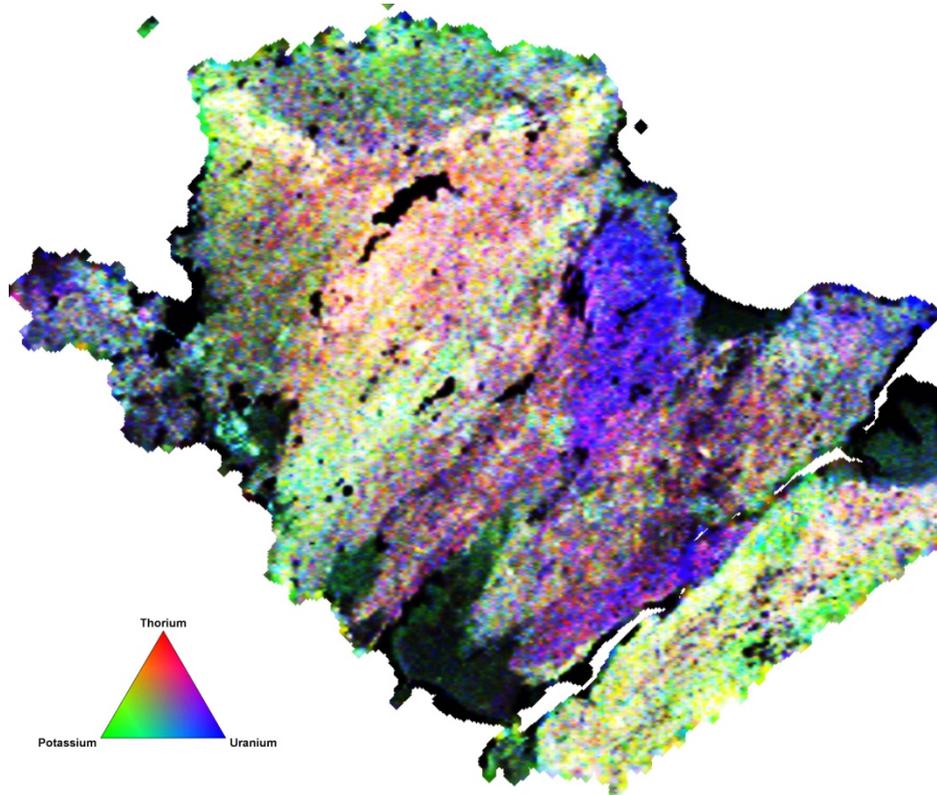


Figure 28. Radiometric ternary image.

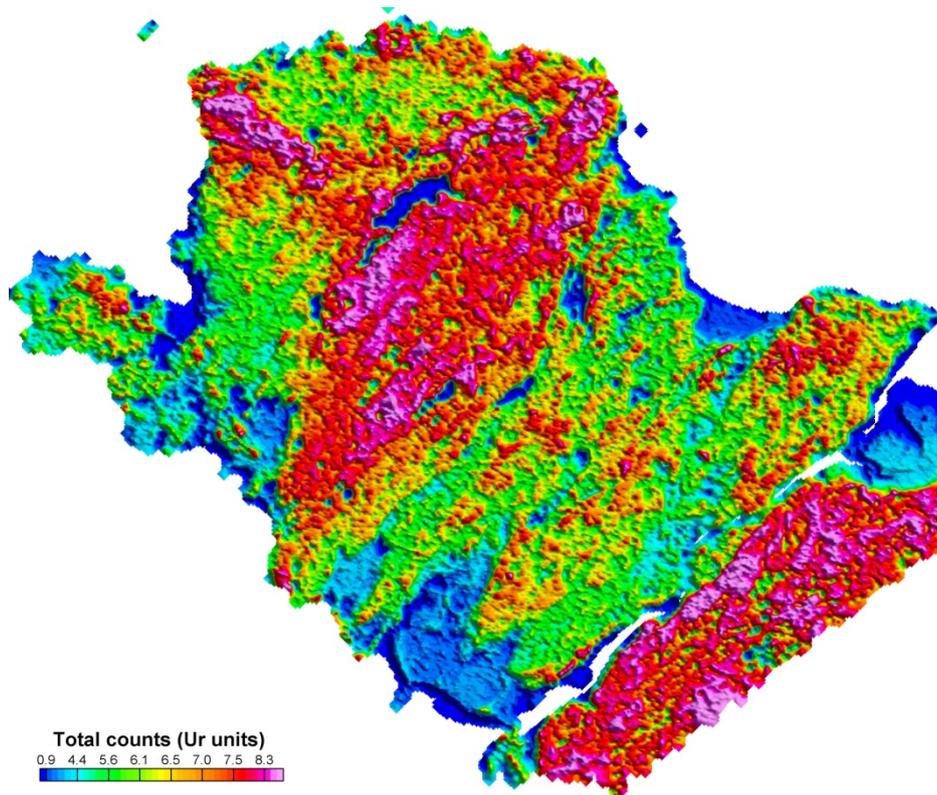


Figure 29. Total radiation (shaded relief).

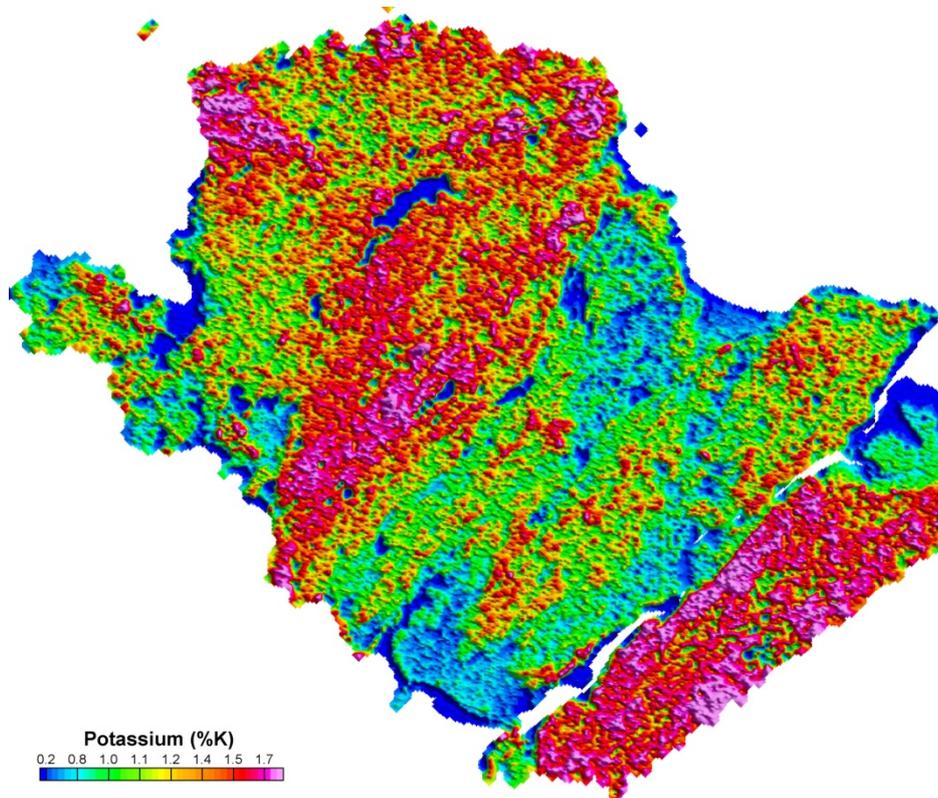


Figure 30. Potassium concentration (shaded relief).

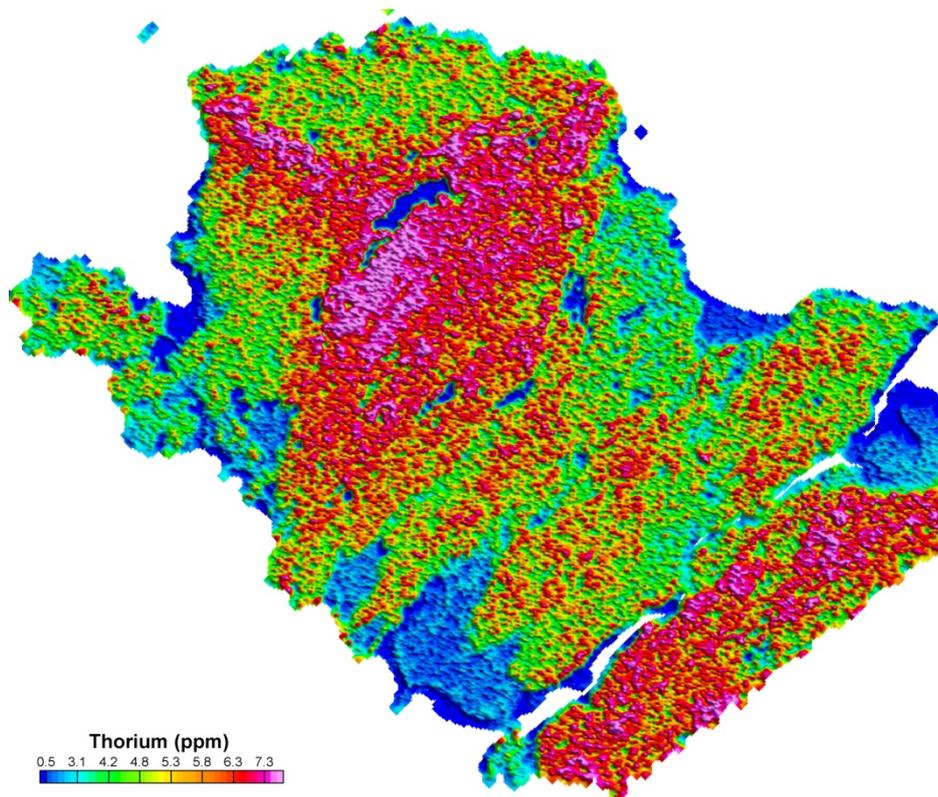


Figure 31. Thorium concentration (shaded relief).

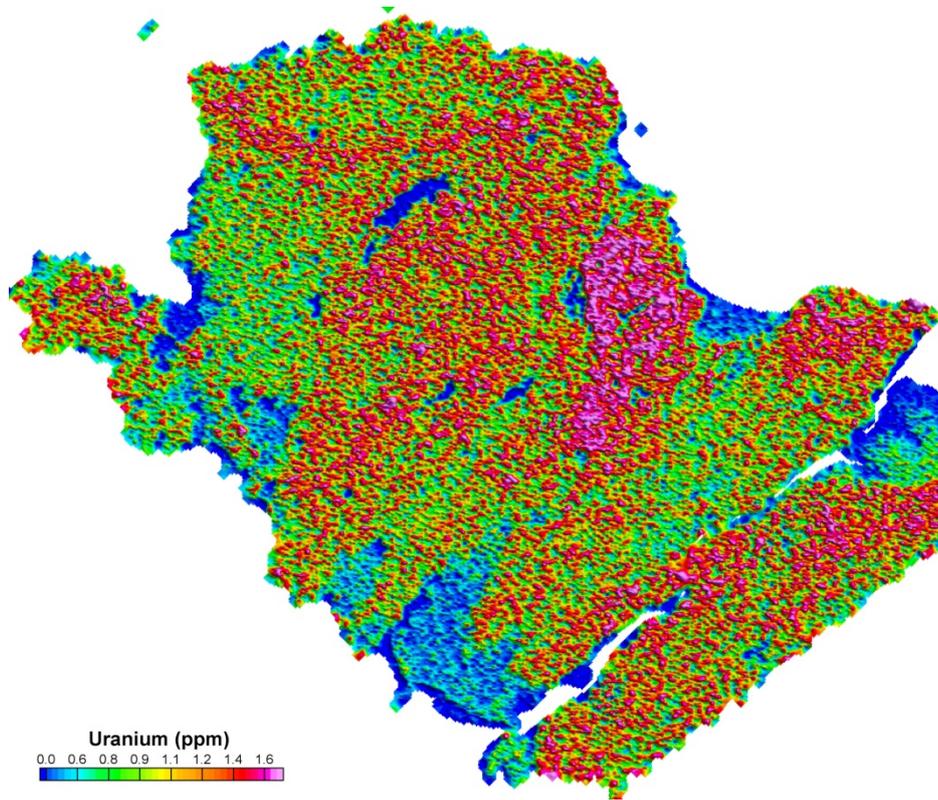


Figure 32. Uranium concentration (shaded-relief).

7 References

- Beamish, D., 2002, The canopy effect in airborne EM. *Geophysics*, 67, 1720-1728.
- Beamish, D. And White, J.C., 2009. The HiRES airborne geophysical survey of Anglesey: Logistics Report. *British Geological Survey Internal Report*, IR/09/061, 24pp.
- Fraser, D.C., 1978, Resistivity mapping with an airborne multicoil electromagnetic system, *Geophysics*, 43, 144-172.
- Geosoft Technical Note on Microlevelling using FFT Decorrugation
<http://www.geosoft.com/resources/technotes/pdfs/microleveling%20tech%20note.pdf>
- Grasty, R.L. and Hovgaard, J., 1996, The calibration of upward detectors in gamma ray surveys, Extended abstract, SEG annual meeting, Denver, 1442-1425.
- Grasty, R.L. and Minty, B.R.S., 1995, A guide to the technical specifications for airborne gamma ray surveys, Australian Geological Survey Organisation Record, 1995/20.
- Green, A.A., 1987, Levelling airborne gamma-radiation data using between-channel correlation information, *Geophysics*, 52, 1557-1562.
- Huang, H., 2008, Airborne geophysical data levelling based on line-to-line correlations, *Geophysics*, 73, F83-F89.
- Hautaniemi, H., Kurimo, M., Multala, J., Leväniemi, H. and Vironmäki, J., 2005, The 'three in one' aerogeophysical concept of GTK in 2004. In: Airo, M-L. (ed.) *Aerogeophysics in Finland 1972-2004: Methods, System Characteristics and Applications*, Geological Survey of Finland, Special Paper 39, 21-74.
- IAEA, 1991, Airborne gamma ray spectrometer surveying, International Atomic Energy Agency, Technical Report Series, No. 323.
- Liukkonen, J., 1996, Levelling methods for aerogeophysical data: 10 August 2005.
<http://www.gsf.fi/liukkonen/public/publications.html>
- Luyendyk, A.P.J., 1997, Processing of airborne magnetic data. *AGSO Journal of Australian Geology and Geophysics*, 17, 31-38.
- Mauring, E. and Kihle, O., 2006, Leveling aerogeophysical data using a moving differential median filter. *Geophysics*, 71, 5-11.
- Poikonen, A., Sulkanen, K., Oksama, M., & Suppala, I., 1998, Novel dual frequency fixed wing airborne EM system of Geological Survey of Finland (GTK). *Exploration Geophysics*, 29, 46-51.
- Suppala, I., Oksama, M. and Hongisto, H. 2005. GTK airborne EM system: characteristics and interpretation guidelines. In: Airo, M-L. (ed.) *Aerogeophysics in Finland 1972-2004: Methods, System Characteristics and Applications*, Geological Survey of Finland, Special paper 39, 103-118.

Appendix 1

THE MINIMISATION OF ERROR BETWEEN THE LINE DATA AND THE REGIONAL FIELD

Assuming that for each line the regional field can be expressed as \mathbf{d}^0 , and the unlevelled line data as \mathbf{d}^1 , both sampled equally at \mathbf{x} , where

$$\mathbf{d}^0 = (d_1^0, d_2^0, \dots, d_N^0)^T$$

$$\mathbf{d}^1 = (d_1^1, d_2^1, \dots, d_N^1)^T$$

$$\mathbf{x} = (x_1, x_2, \dots, x_N)$$

The error between equivalent nodes on \mathbf{d}^0 and \mathbf{d}^1 is determined to calculate $\Delta\mathbf{d}$ then a least squares minimisation is undertaken to calculate the optimal d.c. shift and tilt, expressed as $f(\mathbf{x})$, to apply to line \mathbf{d}^1 .

$$f(\mathbf{x}) = a_0 + a_1x$$

$$|\Delta\mathbf{d} - f(\mathbf{x})|^2 = \min$$

The minimisation technique is a fairly simplistic simulated annealing method that steps to a minimum solution unless specific criteria are met and random steps are introduced. Application of these corrections to \mathbf{d}^1 enables the method to output a levelled data set that maintains the line specific features without removal of any high frequency content.