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The Tellus Airborne Geophysical Survey of Northern Ireland: Final Processing Report

National Geoscience Framework Programme

Internal Report IR/06/136

JAC

Joint Airborne-geoscience Capability

Geological Survey of Finland/British Geological Survey

BRITISH GEOLOGICAL SURVEY

National Geoscience Framework Programme

INTERNAL REPORT IR/06/136

The Tellus Airborne Geophysical Survey of Northern Ireland: Final Processing Report

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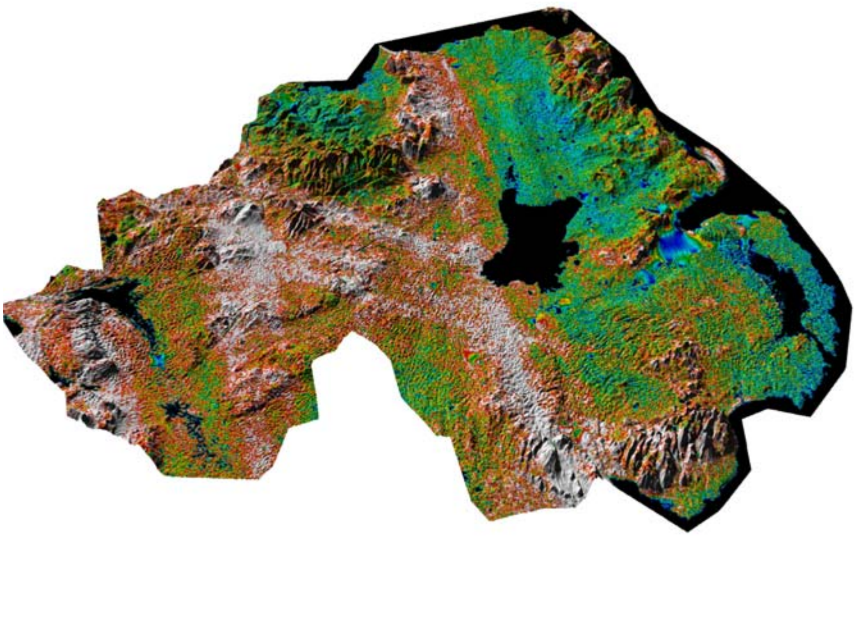
Keywords

Tellus, Airborne survey, geophysics, Northern Ireland

Front cover

Tellus Caesium-137 data for Northern Ireland, displayed on airborne DTM, as a perspective view.



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Foreword

This report describes the processing carried out on the data from the Tellus airborne geophysical survey of Northern Ireland. The survey was conducted in two Phases over the period 2005 to 2006. Phase 1 took place in 2005 and Phase 2 completed the survey during the first half of 2006. This report describes the processing undertaken during both Phases of the survey. This processing report accompanies the final data delivered to the client during the last quarter of 2006.

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Summary

This report provides descriptions of the processing of the Tellus airborne geophysical survey conducted during 2005 and 2006 in Northern Ireland. Two previous reports (Beamish et. al, 2006 a,b) described the logistics of the PHASE 1 survey conducted in 2005 and the PHASE 2 survey carried out in 2006. The BGS, as part of the Joint Airborne Geoscience Capability (JAC) established with the Geological Survey of Finland (GTK), carried out the survey under contract to the Department of Enterprise, Trade and Investment (DETI), Northern Ireland. The survey was conducted at high resolution (a flight line spacing of 200 m) and at low altitude (56 m) across the geopolitical landmass of Northern Ireland. Flight lines were extended into the sea and across the border into the Republic of Ireland.

The three main data sets acquired are magnetic, radiometric (gamma ray spectrometry) and active frequency domain electromagnetic. The summary details of the survey operation are listed in Table1:

Survey line spacing	200 m
Survey line direction	345 degrees
Tie line spacing (trial)	2000 m
Tie-line direction	75 degrees
Minimum survey altitude (rural)	56 m
Minimum survey altitude (other)	244 m
Typical survey speed	70 m/s
Magnetic sampling	0.1 sec
Electromagnetic sampling	0.25 sec
Radiometric sampling	1 sec
GPS positional sampling	1 sec
Magnetic/GPS base station sampling	1 sec

Table 1. Summary details of the Tellus survey.

The complete Block/line sequence of the Tellus survey is summarised in Table 2.

Complete Lines acquired in survey blocks				
BLOCK	**Line Start number**	**Line End number**	**Number of lines**	**Line-km**
Survey Lines (345 and 165 degrees, 200 m separations)				
A	0002	0354	353	11,496
B	0518	0854	337	9,561
C1	1001	1215	216	10,390
D1	2001	2215	216	8,622
E1	3031	3215	216	6,294
C2	1214	1435	222	9,962
D2	2214	2440	313	13,320
E2	3214	3527	314	10,813
TOTALS			2897	81,168
Tie Lines (255 and 75 degrees, 2 km separations)*				
A & B	5002	5031	30	1,245

Table 2. Summary details of the complete Tellus survey. Note * Tie-lines were only acquired during the PHASE 1 survey as part of an evaluation into tie-line levelling procedures.

The processing of the Tellus data took place in two stages. The two processing stages resulted in data sets referred to as Version 1 and Version 2. The client required delivery of the 2005 data sets prior to the completion of the survey in 2006. In addition, during the 2005 survey, the client imposed restrictions on flying the eastern area of the survey. This resulted in the specified 5 Block survey plan being modified to an eight Block configuration. The Version 1 data were processed and delivered on an individual Block basis (8 in total). The subsequent Version 2 data, resulted from the merging/reprocessing of the data across all of the eight survey Blocks. It is these data that form the final processed and delivered Tellus data sets.

1 Introduction

The airborne geophysical survey described here resulted from a scoping study undertaken by the CSA Group Ltd in 2003 (O'Neill, 2003). The study reported its findings to the Department of Enterprise Trade and Investment (DETI), Northern Ireland. The report indicated that the principal objective of the airborne geophysical survey is to acquire high-resolution magnetic, radiometric and electro-magnetic (EM) survey data, which can be used to generate interpretation products, for the benefit of public and private development in the resource and environmental sectors. The airborne survey should yield information on geological structure and lithology, surficial geology, overburden characteristics, shallow geological characteristics, hydrology, vegetation, topography and possibly air and water quality. The derived datasets can also be used to support government policy decisions in economic and sustainable development, social infrastructure, environment and human health.

Previous airborne geophysical surveys in Northern Ireland were predominantly flown in the 1970's, as shown in Table 3. Although these earlier surveys would have been considered high-tech at the time, they are now regarded as low-resolution surveys with respect to line spacing, flight altitude, geophysical equipment sensitivity, spatial resolution, and processing and interpretation technology.

Date	Technique	Line km	Area	Client	Contractor
1959-1960	Mag	17,500	Whole of NI	NI Govt.	Canadian Aero Service Ltd
1965	Input EM ?	400	Tyrone	Tara	Barringer Research Ltd
1971-1972	Mag	1,920	Tyrone / Fermanagh	Amax	Geoterrex
1978	Mag / TEM	2,000	Tyrone	Moydow	Geoterrex
1997	Mag / TEM	5,000	Sperrin Mts.	Billiton	Tesla

Table 3. Previous aerogeogeophysical surveys conducted in Northern Ireland.

Using an estimated total requirement of about 90,000 line-km for the whole survey (including tie-lines), a two season survey was considered the most sensible option. It should be noted that different survey plans give rise to different totals of flight line-km. Different survey directions give rise to different zonations with respect to both the political border and coastline.

The contract to the BGS, Natural Environmental Research Council, to perform the airborne survey was awarded towards the end of 2004. The project runs from 01 April 2004 to 31 March 2007. The Geological Survey of Northern Ireland (GSNI) performs the management of the Tellus project. The principal interfaces with the airborne survey are the Project Manager (Mike Young), the Assistant Project Manager (Marie Cowan) and the Project Geophysicist (Chris Van Dam). The Tellus project team together with the BGS-GTK JAC were responsible for the design, implementation and delivery of the airborne geophysical survey programme.

A specific element of the project brief was a major outreach programme. A firm of PR consultants (Weber-Shandwick) was employed to design and undertake this activity. Among their tasks was a programme of public information (advice, distribution of circulars, and maintenance of the information line and arrangements of strategic mentions in the local press) prior to and during the ground and airborne surveys. The Tellus project team provided the interface with the consultants. In practice, the remit of acquiring low level airborne data in parallel with close to real-time communications with the public, added difficulties and extra dimensions to the usual quality control and management of survey operations. Exceptions to the survey flight specification were generated at intervals throughout the survey as requested by the Tellus project team. Essentially this entailed fly-high or other deviations from the flight plan in order to avoid existing or potential public annoyance.

A full set of flying permits was acquired in order to conduct the survey. Permissions were obtained from the Department of Transport (permission to operate a foreign registered aircraft in the UK), the UK Civil Aviation Authority (CAA), (special events and unusual aerial activity) and Aerial Work permissions from the Irish Aviation Authority. The airspace coordination notice, issued by the CAA, included exemptions from the restrictions of flying in South Armagh and over security establishments. Permission was granted by the CAA to undertake surveying at a minimum height of 185 feet (minimum separation distance of 500 feet) in the absence of structures. Elsewhere, a minimum height of 800 feet (minimum separation distance of 1000 feet) was permitted. The conditions required a routine flying height of 56.4 m with increases to heights above 244 m, when structures such as conurbations were encountered.

2 Survey: Location and details

2.1 ORIGINAL SURVEY SCHEME

The Tellus high resolution airborne geophysical survey was designed using the boundary of the geopolitical landmass of Northern Ireland. Flight lines were extended about 2 km across the border, both across the land/sea interface and into the Republic of Ireland. Flight line spacing was set at an interval of 200 m. The flight line direction (345 degrees geographic) was set by GSNI on the basis of geological trends. The survey flight plan was designed by the JAC Manager, Maija Kurimo. The original survey area was divided into 5 survey blocks labelled A to E. These are shown, schematically, in Figure 1.

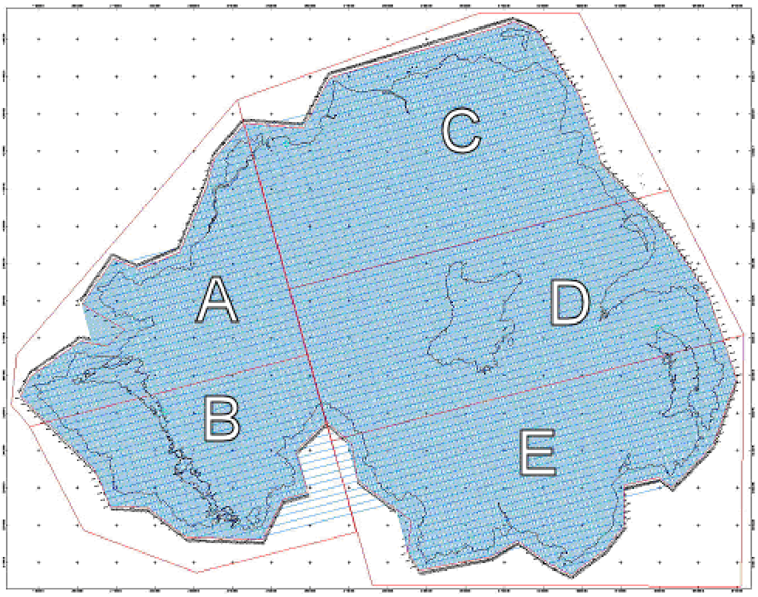


Figure 1. Original, ideal, 5 block survey flight plan for Tellus. The diagram is schematic due to the density of lines at the scale shown.

Flight line lengths of about 50 km were considered optimum in terms of this specific systematic mapping programme. In order to minimise ferry flights, the use of 3 base airports (Enniskillen, Londonderry and Newtonards) was established. The complex nature of the border resulted in some short flight line lengths, particularly in the west of the survey area.

The above scheme is referred to as the idealised or planned survey. This plan provided an estimate of 80,459 line-km (increasing to 81,704 line-km with the tie-lines for Blocks A&B). It is again worth noting that different survey plans give rise to different totals of flight line-km. Different survey directions give rise to different zonations and different numbers of lines (and line lengths) with respect to both the political border and coastline. The above idealised plan includes the overlaps and extensions discussed above. As an example, with a 200 m line spacing and the given outline plan of Northern Ireland (coast and border), planning schemes can give rise to totals of between 77,850 and 82,000 line-km for different survey flight directions.

Flight line overlaps between Blocks in the flight line direction (i.e. between Blocks A and B, Blocks C and D and across Blocks D and E) were specified to be 500 m. This figure was extended to a typical overlap length of 1 km during the survey.

A trial into the utility of acquiring tie-lines (orthogonal to flight lines) for use in the processing (levelling) of the magnetic survey data was conducted during PHASE 1 operations (Beamish et al., 2006a). An evaluation of magnetic levelling procedures carried out in early 2006 indicated that the use of virtual tie-lines provided acceptable results. The technique (Hautaniemi et al., 2005) does not require tie-lines to be flown. No tie-lines were acquired during the PHASE 2 survey.

2.2 FINAL SURVEY SCHEME

The coverage achieved during the PHASE 1 and PHASE 2 surveys is summarised in Figure 2. Blocks A and B were completed according to the original plan. Partial coverage was achieved in Blocks C, D and E during PHASE 1. In each case, the western-most areas were completed to avoid extending the survey activities into the eastern sector of the area (at the request of the client). The partial blocks completed during 2005 have been designated Blocks C1, D1 and E1. The final lines of the 3 blocks form a contiguous survey line formed by Lines 1215 (Block C1), 2215 (Block D1) and 3215 (Block E1). The 2006 survey acquired data across Blocks C2, D2 and E2. Two lines were repeated from the previous survey. These were Lines 1214 and 1215 (Block C2), Lines 2214 and 2215 (Block D2) and Lines 3214 and 3215 (Block E2).

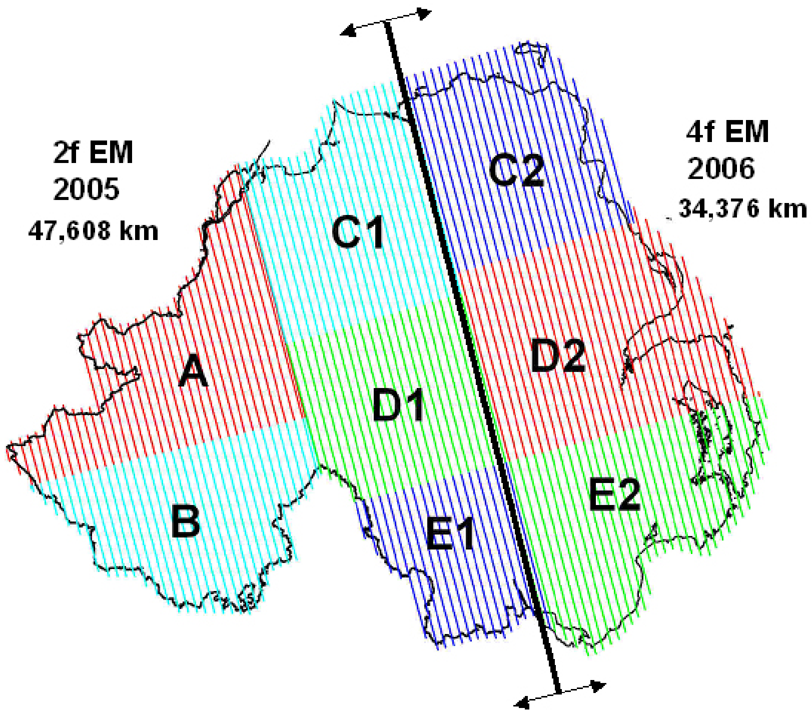


Figure 2. Block scheme defining final Tellus airborne survey. Phase 1 Blocks (2005) are A, B, C1, D1 and E1. Phase 2 Blocks (2006) are C2, D2 and E2. 2f and 4f refer to the 2 frequency and 4 frequency EM systems, respectively.

A major reconfiguration/upgrade of the JAC EM system took place during the winter of 2005-2006. The 2 frequency AEM95 system was upgraded to the 4 frequency AEM05 system (Kurimo et al., 2006) and this was used during the PHASE 2 survey. The 2005 EM survey data provided 3.125 and 14.368 kHz data while the 2006 EM data provided 0.912, 3.005, 11.962 and 24.510 kHz data. The upgrade was judged sufficiently worthwhile to negate the potential issue caused by the use of two different but ‘equivalent’ frequencies of (3.125 and 3.005 kHz), (14.368 and 11.962 kHz) across two parts of the whole survey. The coils are contained in new wing-tip pods shown in Figure 3. As part of the upgrade, the existing right wing magnetometer (used in 2005) was placed in a nose stinger (Figure 3). The new configuration provides both along-line and cross-line magnetic gradient information. The system replaced left and right wing-tip magnetic sensors used during the PHASE 1 survey.

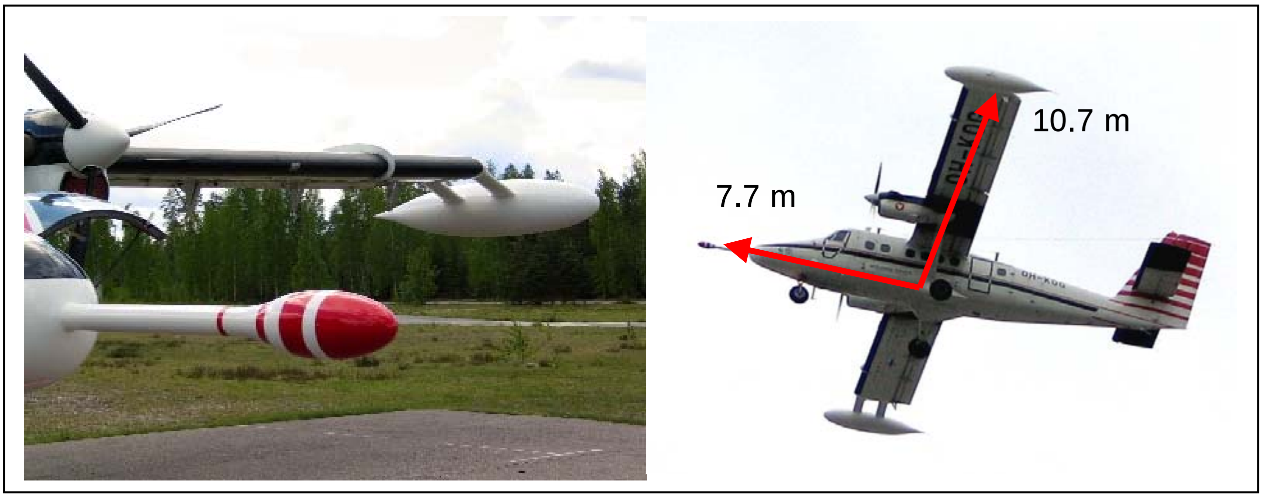


Figure 3. Configuration of magnetic sensors of the AEM05 JAC system used during PHASE 2.

3 Data delivery

3.1 OVERVIEW

The survey specification document (original dated 26 June 2005) indicated that the deliverables resulting from the JAC airborne survey should be restricted to reports covering progress, operations and processing together with processed geophysical data (in line located and grid formats), a survey logistics report and copies of flight logs. The actual digital (located) data was defined in two parts (I and II) as:

Located Data I :

- Line Number
- Flight Number
- Date (yymmdd)
- Time
- Easting Irish National Grid (metres)
- Northing Irish National Grid (metres)
- Longitude UTM
- Latitude UTM
- EM coupling ratios (0.9 kHz, both in-phase/quadrature)
- EM coupling ratios (3 kHz, both in-phase/quadrature)
- EM coupling ratios (12 kHz, both in-phase/quadrature)
- EM coupling ratios (25 kHz, both in-phase/quadrature)
- Apparent conductivity (0.9 kHz)
- Apparent conductivity (3 kHz)
- Apparent conductivity (12 kHz)
- Apparent conductivity (25 kHz)
- Apparent depth (0.9 kHz)
- Apparent depth (3 kHz)
- Apparent depth (12 kHz)
- Apparent depth (25 kHz)
- Total Magnetic Intensity Value (uncorrected nT)
- Total Magnetic Intensity Value (corrected and levelled nT), in the form of an IGRF residual (that is, with a mean close to zero).
- Total Magnetic Intensity Value (corrected and levelled nT), in the form of an IGRF residual with a suitable datum added (to avoid negative values).
- Horizontal magnetic gradient calculated from corrected observed data
- Residual of upward continued (by 50 m) corrected observed magnetic data

- Magnetic Diurnal Value (nT)
- Radar Altimeter Reading (metres)
- Barometric Altimeter (metres)
- GPS Altitude (height above geoid) (metres)
- Total Count (corrected and levelled cps)
- Air absorbed dose (nGy/hr)
- Potassium (corrected and levelled concentration %)
- Uranium (corrected and levelled concentration (ppm)
- Thorium (corrected and levelled concentration (ppm)
- ^{137}Cs (Bq/m^{2}) (added after post processing)

- **Located Data II (256 channel radiometric data):**
- Line Number
- Flight Number
- Date (yymmdd)
- Time
- Easting Irish National Grid (metres)
- Northing Irish National Grid (metres)
- Longitude UTM
- Latitude UTM
- 256 Channel Radiometric Data

3.2 DELIVERY OF 256 CHANNEL RADIOMETRIC DATA

The second located data set relates to the full 256-channel spectra (upward and downward-looking) obtained from the radiometric measurements. Delivery of these data was deferred until completion of the whole survey. The spectral data were obtained from the raw flight data files (.kog). The spectra are raw and unprocessed. The positional data (differentially-corrected Easting and Northing) were obtained from the final delivered radiometric data using a cross-database lookup technique (based on fiducial). The data file Radiometric_Raw_Data.XYZ (i.e. Geosoft ASCII .xyz) was delivered on 30 October 2006. The definition of the delivered data is as follows:

```
Definition of channels in delivered .xyz files:

        X:      Grid Easting (m)
        Y:      Grid Northing (m)
        LAT:    WGS84 latitude in decimal degrees
        LONG:   WGS84 longitude in decimal degrees
        FID:    numerical sum of Julian day and seconds past previous midnight
        Date:   Date (YYYYMMDD)
        Day:    Day number (Julian)
        Time:   Time (HHMMSS.SS)
        DIR:    Flight direction (degrees clockwise)
        RALT:   Radar altitude (m)
        BALT:   Barometric altitude (m)
        TOUT:   External temperature (degrees C)
        Idn256: Raw 256-channel radiometric data for downward looking crystal
        Iup256: Raw 256-channel radiometric data for upward looking crystal
```

The channels RALT, BALT and TOUT are required by spectral processing software. These data also formed the basis of the spectral processing undertaken to provide the estimates of ^{137}Cs (Bq/m^2) described later. The remainder of this report describes processing procedures applied to Located data I.

3.3 DELIVERY IN PRACTICE

The Located Data I list indicates that the EM Fraser half-space parameters should be provided as apparent conductivity and apparent depth. In practice, the standard Fraser procedure and convention involves calculation and delivery of apparent resistivity in ohm.m. This convention has been adopted. Apparent conductivity (Ac in mS/m) can be obtained from apparent resistivity (Ar in ohm.m) using the expression : Ac=1000.0/Ar.

The first 2005 season of the Tellus survey resulted in the acquisition of 2 complete blocks (A and B) and 3 incomplete blocks (C, D and E) of data. It was decided to redefine the incomplete blocks as 'complete' blocks C1, D1 and E1 in order to allow data delivery of the 2005 data to proceed prior to the start of Season 2 acquisition. The most appropriate delivery procedure was to process the five 2005 blocks as separate self-contained units of data.

A complete set of blocks (eight in total), defining the complete survey of Northern Ireland, only became available following completion of the 2006 survey.

The delivery procedure adopted was to process the five self-contained blocks for 2005 during the period November 2005 to March 2006. These data deliveries were termed 'Version 1' data in order to distinguish them from later deliveries that could only be achieved when all data acquisition was complete (i.e. it would not have been sensible to attempt to process then merge individual data from individual blocks until the composite data set had been acquired and assessed.)

Having provided Version 1 data for the 5 blocks obtained in 2005, it was also then necessary to provide Version 1 data for the remaining 3 blocks obtained in 2006. PHASE 2 acquisition was completed by the beginning of June 2006. Post survey processing of these data then proceeded during June and July. Due to the early start date of surveying in 2006 (transfer flights from Helsinki began on 25 March), the frozen conditions in Finland resulted in an inability to perform two of the initial pre-survey calibrations: 1) Radiometric stripping ratios and 2) EM calibration over the sea in the Gulf of Finland (Beamish et al., 2006a,b). These two calibrations could only be performed in July when OH-KOG returned to base at Pori airfield. Final recalibration of the 2006 radiometric and EM data could only be achieved from the beginning of August, onwards.

Version 1 ASCII (.xyz) delivered data sets were each accompanied by a data content/column/description text file (typically a README_channels.txt file). There are different files for each of the 3 data sets. A typical magnetic data README file (for Block B) is:

```
Definition of channels in .xyz files delivered:

MAG files (e.g. blockB_magL_v1.xyz, blockB_magR_v1.xyz) means magnetic data of left wingtip magnetometer (magL) and right
wingtip magnetometer (magR) from Block B

        X:      Grid Easting (m)
        Y:      Grid Northing (m)
        LAT:    WGS84 latitude in decimal degrees
        LONG:   WGS84 longitude in decimal degrees
        FID:    numerical sum of Julian day and seconds past previous midnight
        Flight: Flight number
        DATE:   Date (YYYYMMDD)
        Day:    Day number (Julian)
        Time:   Time (HHMMSS.SS)
        DIR:    Flight direction (degrees clockwise)
        RALT:   Radar altitude (m)
        GPS_H:  GPS altitude (m) above geoid (WGS84)
        DTM:    Digital Terrain Model (m)

        ORIGL (or ORIGR):               Uncorrected magnetic total intensity (nT)
        BASE:                           Residual of the original and base station corrected data (nT)
        MAG_LEFT (or MAG_RIGHT):        Total magnetic intensity (nT)
        MAGL_IGRF (or MAGR_IGRF):       IGRF model total magnetic intensity (nT)
        MAGL_RES (or MAGR_RES):         Residual of base station corrected and IGRF model data (nT)
        MAGL_RES_BASELINE (or MAGR_RES_BASELINE): Baseline normalised residual of base station corrected and IGRF model
data (nT)


Note:   IGRF model used is 10th generation. Survey date applied is 2005/07/01. Baseline e.g. MAGL_RES_BASELINE applied for
blockB is 1310 nT.

        blockB_magL_v1.xyz: 18 data points have been dummied

        blockBB_magL_v1.xyz: 9 data points have been dummied

        blockBB_magR_v1.xyz: 6 data points have been dummied


Merged databases with left and right wingtip data together are included (blockB_magLR_v1.gdb). Both the left and right mag
files have been imported to the database so that for each line number there are two versions, for example for line 518
there are versions 518.0 and 518.1, the former is the left magnetometer data and the latter the right magnetometer data.
```

The corresponding radiometric README file for Block B is:

```
Definition of channels in delivered .xyz files:

RAD file (e.g. blockB_rad_v1.xyz) means Radiometric data (rad) from Block B

        X:      Grid Easting (m)
        Y:      Grid Northing (m)
        LAT:    WGS84 latitude in decimal degrees
        LONG:   WGS84 longitude in decimal degrees
        FID:    numerical sum of Julian day and seconds past previous midnight
        Flight: Flight number
        Day:    Day number (Julian)
        Time:   Time (HHMMSS.SS)
        DIR:    Flight direction (degrees clockwise)
        RALT:   Radar altitude (m)
        BALT:   Barometric altitude (m)
        TOUT:   External temperature (degrees C)
        GPS_H:  GPS altitude (m) above geoid (WGS84)
        DTM:    Digital Terrain Model (m)

        D_TOT_CPS:      Total Counts (Ur units) meaning sum of all counts from 400 to 3000 keV
        D_TOT_NGY:      Total counts (nGy/h = nanoGray per hour) expressed as air absorbed dose rate
        D_KAL:          Potassium (%K)
        D_URA:          Uranium (ppm, eU)
        D_THO:          Thorium (ppm, eTh)
```

The corresponding EM README file for Block B is:

```
EMAP file (e.g. blockB_emap_v1.xyz) means Electromagnetic data (em) and Apparent Resistivity data (ap) from Block B

        X:      Grid Easting (m)
        Y:      Grid Northing (m)
        LAT:    WGS84 latitude in decimal degrees
        LONG:   WGS84 longitude in decimal degrees
        FID:    numerical sum of Julian day and seconds past previous midnight
        Flight: Flight number
        Day:    Day number (Julian)
        Time:   Time (HHMMSS.SS)
        DIR:    Flight direction (degrees clockwise)
        RALT:   Radar altitude (m)
        GPS_H:  GPS altitude (m) above geoid (WGS84)
        DTM:    Digital Terrain Model (m)
        PLM:    Power-line monitor (no units)

        RE3:    EM real (in-phase) component, low frequency 3125 Hz, ppm
        IM3:    EM imaginary (quadrature) component, low frequency 3125 Hz, ppm
        RE14:   EM real (in-phase) component, high frequency 14368 Hz, ppm
        IM14:   EM imaginary (quadrature) component, high frequency 14368 Hz, ppm
        F3ApRes:        EM apparent resistivity, low frequency 3125 Hz, ohm.m
        F3Depth:        EM apparent depth, low frequency 3125 Hz, m
        F14ApRes:       EM apparent resistivity, high frequency 14368 Hz, ohm.m
        F14Depth:       EM apparent depth, high frequency 14368 Hz, m

Note: in _v1.xyz EMAP data sets, the EM coupling ratios (RE3, IM3, RE14 and IM14) have been microlevelled (see GTK special
publication and recent microlevelling paper from Geophysics 2006).
Ideally they should have been labelled RE3mlev, IM3mlev, RE14mlev, IM14mlev.
```

In practice, the two latter file descriptions were amalgamated into one single README file with the name README_channels_RAD_EM.txt.

3.4 FEATURES OF THE VERSION 1 DATA

Flight-line data are acquired according to an idealised flight plan for the survey (Beamish et al, 2006a,b). Essentially the spatial extent of each of the 8 blocks is defined by a polygon that outlines the ideal survey. In practice data are acquired, along a flight-line, that extends beyond the ideal coordinates. The increase in line-length is a safety margin to ensure that the specified (ideal) line length is acquired. The actual increase depends on flying parameters in terms of topography and turn-to-next-line requirements. The end of flight line is a marker condition in data acquisition (e.g. finish of survey specification flying and commencing turn manoeuvres).

An example of on-line flight lengths (shown as gridded data) in relation to the ideal polygon is shown in Figure 4. The example uses the DTM data for BlockB.

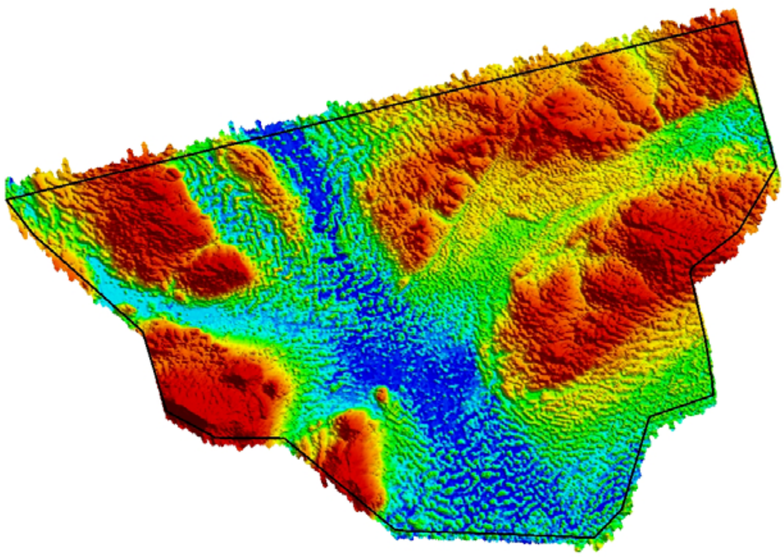


Figure 4. Example of untrimmed delivered data (Block B, DTM), shown as a grid and ideal polygon for the Block (heavy black line).

Flight line lengths typically extend between 0.5 and 1.5 km beyond the ideal coordinates. In the north the extensions provide useful overlap for across Block levelling assessments (i.e. across Blocks A and B). In the south, the extensions are within the Republic of Ireland.

The essential features of all 8 delivered Version 1 data sets are:

- Version 1 data have all been delivered as untrimmed (to ideal coordinates), to allow the maximum data set to be defined in the first instance.
- The Version 1 data have not been assessed for across Block levelling continuity. They are self-contained units of individual Block data.

3.5 FEATURES OF THE VERSION 2 DATA

The term Version 2 indicates that the processed data form a combined data set (.xyz) across the whole survey area (8 blocks). This is in contrast to Version 1 data (.xyz) which formed individual blocks. Note that Version 1 data included all online data (e.g. ragged edges to North and South borders of each block). These ragged edges were additional line-km to the ideal survey blocks (they provided block overlaps used for assessment of 'level' issues across blocks).

Version 2 data have been combined across all 8 eight blocks using data processed within 8 individual, non-overlapping blocks. This procedure allowed an assessment of the level differences/issues arising from the 2-year acquisition and the reconfiguration in the magnetic and electromagnetic sensors. The Version 2 data have been trimmed to the ideal survey outline described in Section 2. The processing stages, used to arrive at the Version 2 data, are described in Section 5.

4 Version 1 data processing

The processing procedures applied to the Version 1 data for each of the 8 Blocks are described in the following sections.

4.1 RADIOMETRIC PROCESSING

This section describes the processing procedures applied to the Version 1 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). The set of procedures used in the calibration and processing of the Version 1 radiometric data are fully described in the logistic reports for the two phases of the project (Beamish et al., 2006 a,b). The two reports, one for each season/phase provide the calibration data (cosmic coefficients, stripping ratios, height attenuation coefficients and concentration coefficients) applied to the radiometric data from each season.

In practice, although in-field processing of the radiometric data was undertaken, all the survey data acquired were reprocessed in the office to provide validated (uniformly correct calibration factors for each season) data sets. The main radiometric software package used in these procedures is RADCOR (Beamish et al., 2006 a,b).

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 Tellus radiometric data are shown in Table 4:

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 4. The recommended (IAEA) energy rates of the spectral windows.

A review of the main procedures is provided below.

4.1.1 Dead time correction

The spectrometer needs a short time to process each pulse and so might have 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.

4.1.2 Filtering before correction

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. To calculate radon background from the upward-looking detector data, heavily filtered uranium upward, uranium downward and thorium downward data are used.

4.1.3 Aircraft and cosmic background

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 it 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 referred to by Beamish et al. (2006 a,b).

4.1.4 Radon background

Radon gas makes it difficult to measure uranium concentrations accurately. It is not always evenly distributed in the air and thus eliminating it from background radiation is not simple. Determination of the constants necessary for the correction of the background due to radon using upward detectors requires several steps. 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.

4.1.5 Effective height and 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 must be corrected to a nominal height to remove the effect of varying survey altitude and thus make them comparable. The background corrected total count and stripped count rates vary exponentially with aircraft altitude.

4.1.6 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. The dimensions of our transportable calibration pads are 1m x 1m x 30cm 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.

4.1.7 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 214Bi and 208Tl 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.

4.1.8 Levelling of Radiometric data

In radiometric surveys external conditions, which affect the measurements, can vary daily and with season. The moisture of soil and presence of Radon gas can cause residual errors between adjacent lines and also along a line. This problem is usually seen as the raised “level” of a complete line. There are a number of processing procedures designed to level data, some of which are specific to radiometrics and others that can be applied to any geophysical data. Levelling errors are usually only seen in Uranium and Total Count.

In the case of the Version 1 data, a judgement was made in relation to the degree of residual offsets in the Uranium and Total Count data sets across each Block. Essentially the decision is based on the requirement that a high quality grid/map should be achieved for the data sets. If required, the procedure used was to apply along and across line median filtering (“Floating median difference method”) to remove long wavelength level errors from the radiometric data. Sometimes short wavelength Radon residual errors caused by a short rain shower must also be removed. The JAC RALEV microlevelling program uses spatial parameters (along and across line), in a similar manner to that used in EM microlevelling.

RALEV uses an along line radius (typically 1000 m) and an across-line radius that controls the number of lines involved in estimating the result at a particular point. Using a value of 500 m, 5 lines are used in the procedure (for a flight line spacing of 200 m).

The application of microlevelling to the delivered Uranium and Total Count channels varied between PHASE 1 and PHASE 2 data. With reference to Table 6, and the PHASE 1 Block deliveries of Blocks A, B, C1 and E1, no microlevelling was applied. Only in the case of Block D1 was microlevelling applied to the Uranium and Total channels, as this was judged appropriate.

In the case of PHASE 2 delivered Version 1 data (Blocks C2, D2 and E2) both unlevelled and microlevelled data were supplied. An example of the radiometric channel delivery scheme (a README.TXT file) for the Version 1 PHASE 2 data is shown below. It should be noted that different procedures for radiometric leveling were investigated and applied in the final Version 2 delivered data.

```
Definition of channels in delivered .xyz files:

RAD file (e.g. BlockC2_Rad_v1.xyz) means Radiometric data (rad) from Block C2 (C2 equals to 2006 survey)

          X:      Grid Easting (m)
          Y:      Grid Northing (m)
          LAT:    WGS84 latitude in decimal degrees
          LONG:   WGS84 longitude in decimal degrees
          FID:    numerical sum of Julian day and seconds past previous midnight
          Flight: Flight number
          Day:    Day number (Julian)
          Date:   Date (YYYYMMDD)
          Time:   Time (HHMMSS.SS)
          DIR:    Flight direction (degrees clockwise)
          RALT:   Radar altitude (m)
          BALT:   Barometric altitude (m)
          TOUT:   External temperature (degrees C)
          GPS_H:  GPS altitude (m) above geoid (WGS84)
          DTM:    Digital Terrain Model (m)

          D_TOT_CPS:      Total Counts (Ur units) meaning sum of all counts from 400 to 3000 keV
          D_TOT_CPS_Lev:  Microlevelled equivilent of D_TOT_CPS
          D_TOT_NGY:      Total counts (nGy/h = nanoGray per hour) expressed as air absorbed dose rate
          D_TOT_NGY_Lev:  Microlevelled equivilent of D_TOT_NGY
          D_KAL:          Potassium (%K)
          D_KAL_Lev:      Microlevelled equivilent of D_KAL
          D_URA:          Uranium (ppm, eU)
          D_URA_Lev:      Microlevelled equivilent of D_URA
          D_THO:          Thorium (ppm, eTh)
          D_THO_Lev:      Microlevelled equivilent of D_THO

Note:   in BlockC2_Rad_v1.xyz D_TOT_CPS_Lev, D_TOT_NGY_Lev and D_URA_Lev data should be used (see GTK
special publication and recent microlevelling paper from Geophysics 2006).
```

4.2 ELECROMAGNETIC PROCESSING

This section describes the processing procedures applied to the Version 1 electromagnetic data.

4.2.1 Prelevelling

Although this procedure is conducted in the field, it is refined further at the post-processing stage. A zero-level is adjusted to an artificial level at the beginning of each survey flight to ensure a large enough scale to register both positive and negative anomalies. The registered values then are independent of the real zero-level. This calibration is performed at a high altitude (e.g. 300 metres above ground) to provide an out-of-ground response. The zero-level calibration procedure is repeated at the end of each flight. The level of the EM data can be corrected linearly using these calibration results. This preliminary automatic 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 in an hour if there is no temperature gradient. If the flight lines are long, the air temperature can sometimes vary significantly during a flight line, and this may introduce a non-linear drift to the zero-level. A temperature variation of one degree centigrade changes the coil separation so that the zero-level may change by about 70 ppm. 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, which may have a non-linear relationship with the variation in wing length due to temperature change, and hence the coil separation. There are also other reasons for this drift, such as temperature variations in the coils and in other analogue components, which are never ideal.

The non-linear drift is estimated for each flight and for each EM component. 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 during that flight for each component. 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. Figure 5 shows an example of the procedure applied to the imaginary 14 kHz component data.

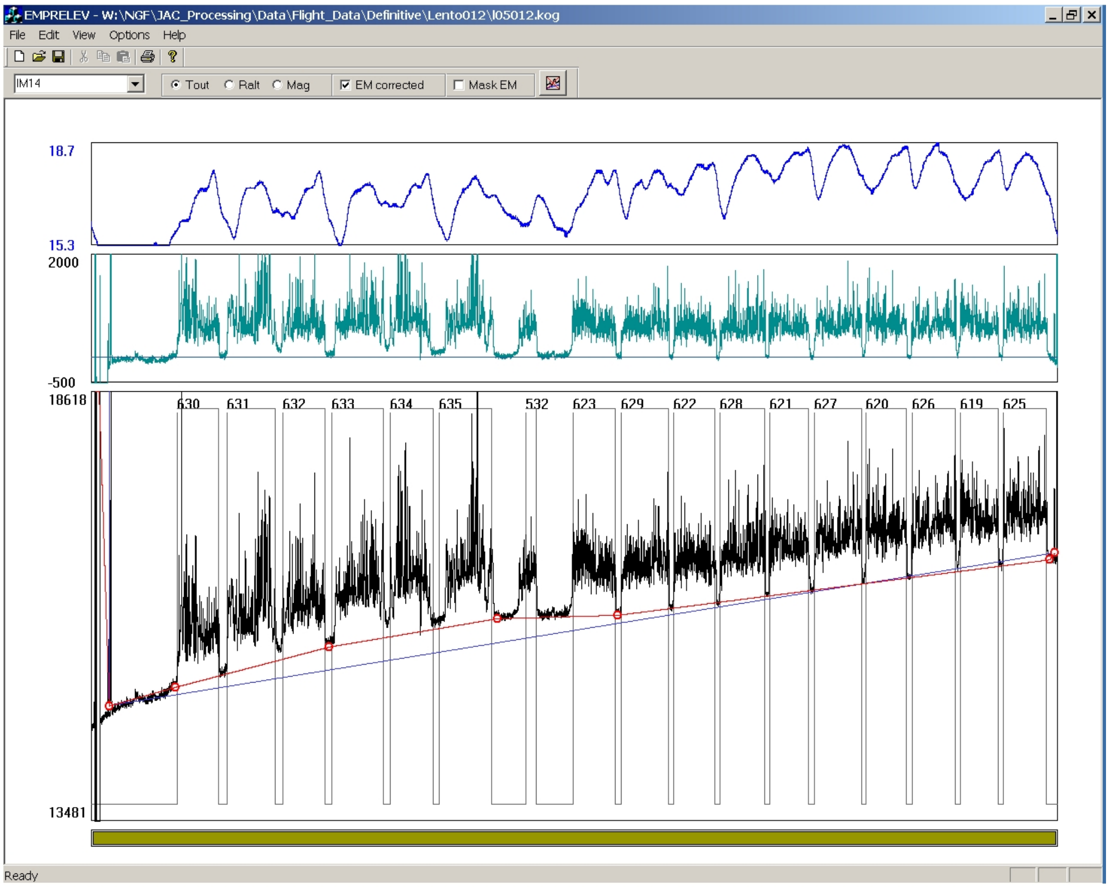


Figure 5. Example of Emprelev applied to 14 kHz imaginary component profile of one complete flight (17 flight lines) presented together with the drift estimation points (small red circles) and linear drift estimation line (blue), which connects the calibration points and the first and last red circles. It can be seen that the non-linear drift estimation gives a far better result than the automatic linear estimation.

4.2.2 Levelling

The prelevelling is followed by a further line-by-line checking and adjustment (if required) of the zero levels of each line of data and of each component. A JAC graphical Windows program, Level32 is used for this purpose. An example of this program is presented in Figure 6.

A variable number of profiles of an EM component can be presented simultaneously in a window. Lines are sorted in the data file, and 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 case of a fast drift three or more points might be used.

Using the above procedures, the EM data from individual lines, may have been detrended (linear and non-linear) and a residual offset may have been applied. These procedures are line-based and do not perturb the EM data anomalies that have an expected wavelength much less than the line length. The data provided are the most appropriate data for use in quantitative procedures (e.g. modeling/inversion) that require minimum filtering/distortion of individual anomalies.

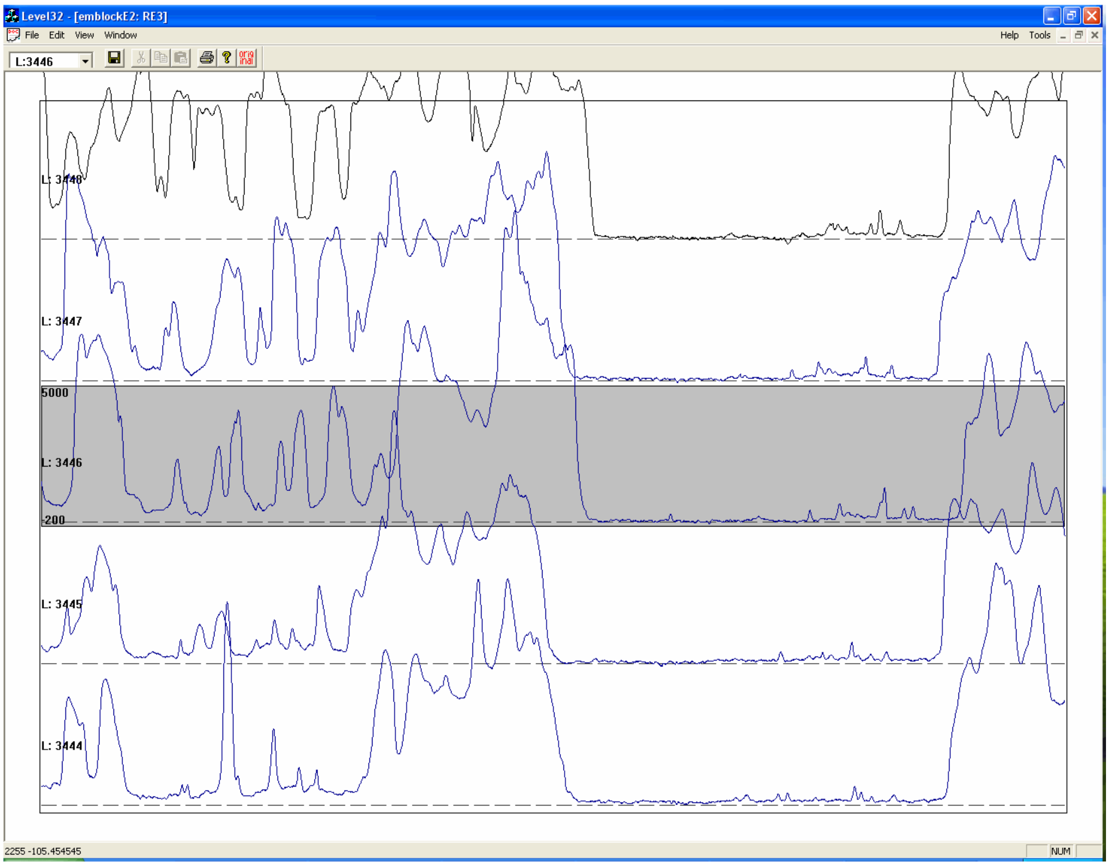


Figure 6. Example of LEVEL32 applied to 3 kHz real component across 5 sequential flight lines (3 are usually used). DC level adjustments are interactively made to each line (current line for adjustment is shown in grey).

4.2.3 Microlevelling

When the above data are gridded, small residual line-to-line leveling errors may become apparent. These may be 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 and images. Most microlevelling procedures apply filters and spatial averages to individual and multiple lines. All such procedures have limitations and are capable of distorting data. The application of such procedures depends (usually) on a set of control parameters (e.g. those associated with filters and spatial wavelengths). For each data set, a level of judgement is required to balance/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 Mauring and Kihle (2006).

The microlevelling program EMLEV uses an along line radius (typically 1000 m) and an across-line radius that controls the number of lines involved in estimating the result at a particular point. Using a value of 500 m, 5 lines are used in the procedure (for a flight line spacing of 200 m).

4.2.4 Estimation of apparent resistivity and apparent 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. No misfit error is provided (Beamish, 2002). The transformation programs used are based on a GTK version of TRANSAEM. The program employs minimum limits on the real and imaginary coupling ratios to identify the noise level in the coupling ratios. The figures typically used are 20 ppm for both real and quadrature components. These thresholds have been extended to 80 ppm for the 912 Hz PHASE 2 data.

The behaviour of the AEM-05 coupling ratios for a range of half-space resistivities is shown in Figure 7.

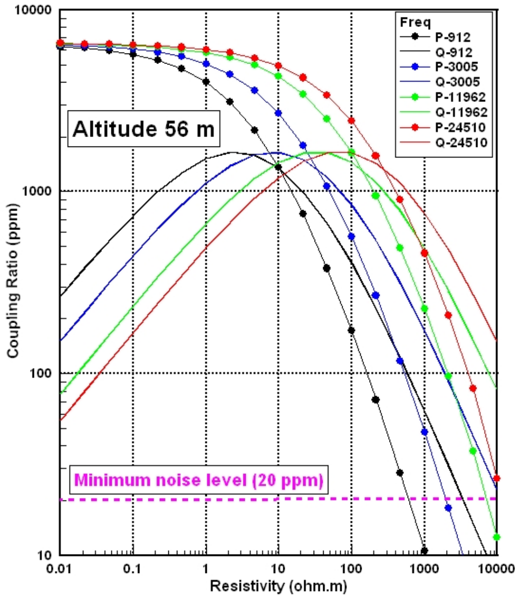


Figure 7. 4 frequency AEM-05 coupling ratios (in-phase=P, quadrature=Q) across a range of half-space resistivities, at an elevation of 56 m.

A system noise level of 20 ppm is indicated. The actual survey noise levels in the EM channels may be higher. It can be seen that, particularly in resistive terrains, the lower frequency in-phase (P) components may approach and descend into the noise level. This behaviour limits our ability to obtain valid estimates of apparent resistivity and depth. 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.

Under certain conditions, apparent resistivity and depth data require microlevelling as previously described for the EM in-phase and quadrature components. A special version of the "Floating median difference method" (FMD) for apparent resistivity has been developed for that purpose. The microlevelling program APLEV uses an along line radius (typically 1000 m) and an across-line radius that controls the number of lines involved in estimating the result at a particular point. Using a value of 500 m, 5 lines are used in the procedure (for a flight line spacing of 200 m).

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

4.2.5 Notes on Phase 2 (2006) EM data

The EM data obtained across Blocks C2, D2 and E2 during PHASE 2 were acquired in a complex spatial/time pattern due to various (daily) flying restrictions imposed on the survey. Such complex spatial patterns are not ideal in terms of the resulting EM data qualities. The following notes are provided in relation to the Version 1 delivery of EM data for Blocks C2, D2 and E2.

4.2.5.1 HIGH-FLY ZONES

The EM system is most effective when survey altitude is as low as possible. As altitude is increased coupling with the ground is reduced, degrading results. At high altitudes there is no coupling and results will be unreliable. Season 2 EM data are greatly reduced in quality by the survey altitude restrictions imposed. The high fly restrictions imposed by the Civil Aviation Authority result in high fly over urban areas and power lines. High fly is also inevitable in high relief areas where it is not possible to maintain a nominal 56m above ground level. The problem was greatly compounded in Season 2 of survey flying by the high number of high flies requested over farms, stables and concerned members of the public. It is not advisable to interpret the EM data without taking into account the survey altitude. Figure 8 shows all areas of the Season 2 survey where altitude was greater than 75m. Figure 9 shows a detailed view of high-fly zones within Block D2.

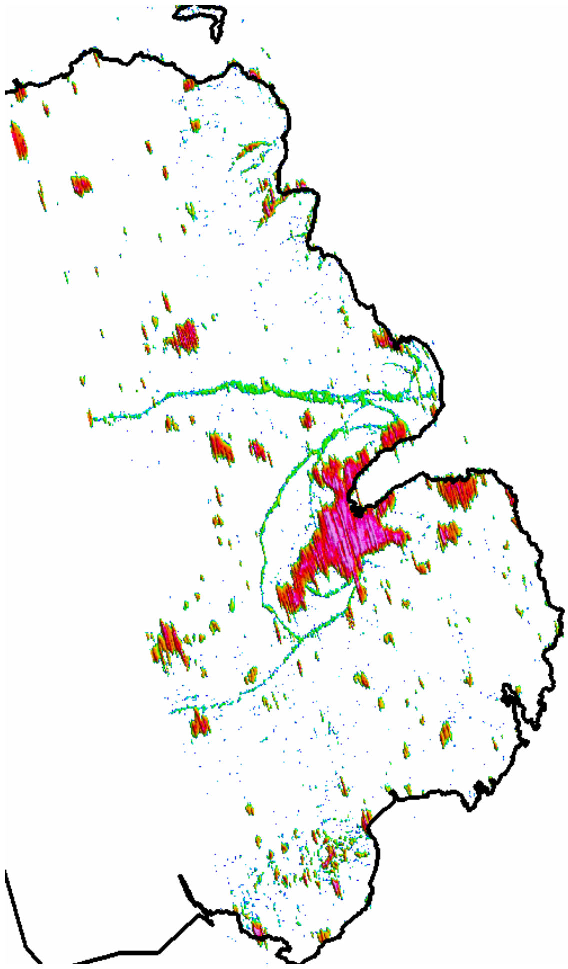


Figure 8. High-fly in Season 2 data where data quality will have been degraded.

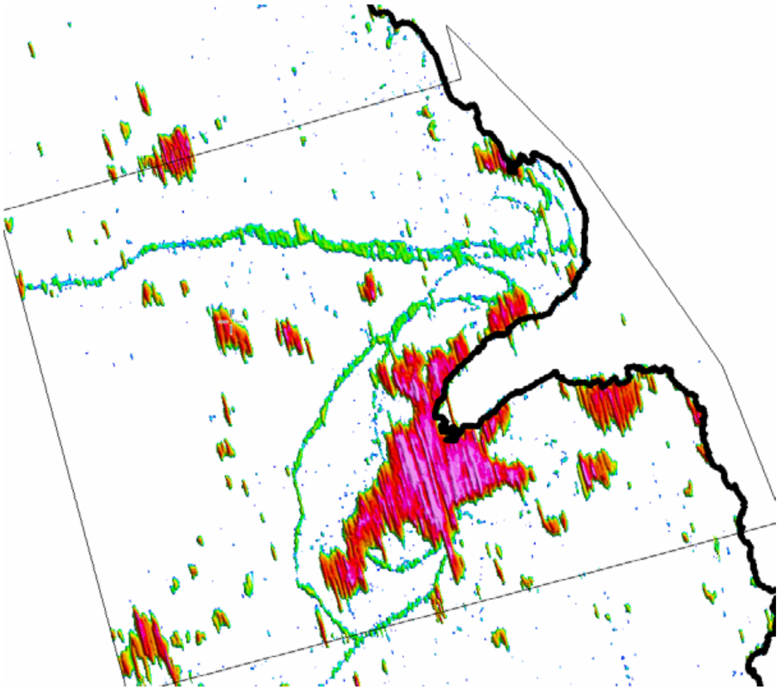


Figure 9. High-fly in Block D2 where data quality will have been degraded.

4.2.5.2 ANTHROPOGENIC INFLUENCE

As well as the survey altitude there are other anthropogenic influences on the data that require careful consideration. Considerable EM noise is experienced close to the power lines, especially in the vicinity of Kilroot Power station.

Early survey lines in Block D2 are also affected by aircraft VHF. The flight crew liaise with air traffic control (ATC) on a daily basis and briefed ATC not to make VHF radio calls during survey lines. All VHF communication normally occurs off line, although the occasional call does occur on-line. The reception of a call is not a geophysical problem, but the flight crew are duty bound to respond, and this transmitted response will typically affect EM and magnetic sensors. Early in the survey ATC made many VHF calls whilst the aircraft was entering the approaches to Aldergrove. This is most obvious over Lough Neagh as a spike in the EM data. In time, the aircrew managed to brief ATC better and VHF was no longer a problem. Identification of the EM spikes is not straightforward and these were only identified and removed in the Version 2 data.

4.2.5.3 TEMPORAL VARIATION OF BODIES OF WATER

One significant change that has been observed in the new four-frequency system is a different response over salt water. This is observed over Belfast Lough, as shown by the central cross-hair in Figure 10.

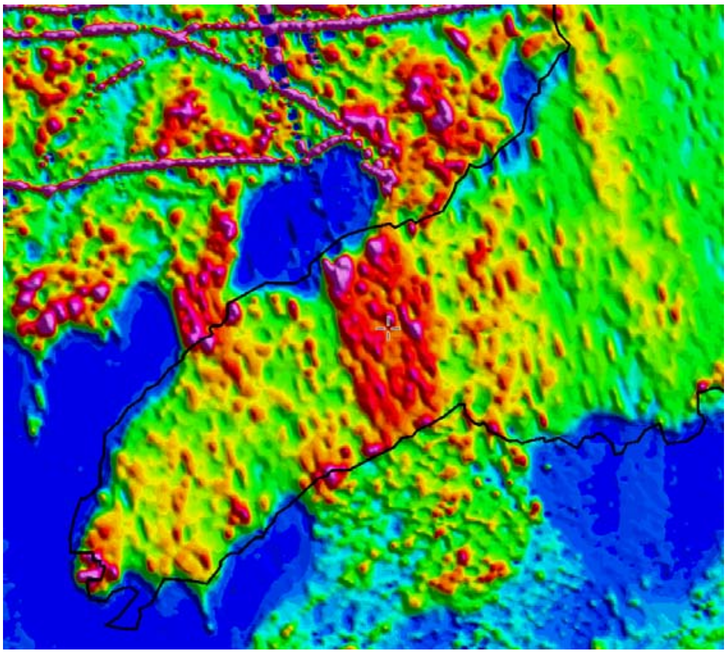


Figure 10. Temporal variation of EM response over seawater (Im3).

When this particular feature was first noticed considerable effort was taken to identify the origin of the result; initial thoughts were data-processing errors. The data response within this zone is markedly different from the responses either side. When the seawater response is shown as green in Figure 10, the IM3 component has remained constant with small variations, whereas where the raised level shown in red occurs, the response is a lot more variable. Initial thoughts were that this was a levelling error, but in making the red-portion more in line with the green areas the result is an obvious out of level result over land. This is clearly not a zero level issue as the dark blue region seen on land to the north is a clear data zero created by a high fly over Carrickfergus. Examination of the survey altitude showed no obvious cause for this feature. Bathymetry data and marine charts for Belfast Lough show a channel running WSW – ENE, but no feature is seen in this orientation. The only data correlation seen in the data is that all of these raised level data where flown on the same day and that the feature is seen in all frequencies. Therefore the conclusion is that this is a real anomaly created by the temporal variation of temperature/salinity in Belfast Lough or may be due to variations in water depths at different states of the tide. Similar features are seen throughout the coastal zone and also within Lough Neagh and Strangford Lough.

Bodies of water are non-geological and change with time. This does not mean that the EM data contain no information over water, but it does mean that considerable care is needed in such zones and the data require additional information to be considered such as bathymetry and tidal state. With this in mind there are many considerations that can be taken to cosmetically improve the appearance of images obtained from such data. Figure 11 shows the apparent resistivity for the 3kHz EM. The first image is the entire PHASE 2 dataset, showing variations in EM response over the sea, giving an appearance of poorly levelled data. The second image is the same data with the sea masked. The third image shows high-fly zones over 100m also masked. This clearly shows that the on-land geological response from the system is well levelled. The masking of high fly zones is important as areas indicated as being low, such as in IM components, are in fact not low geological values, they are out of ground effects; which should be viewed as null data as opposed to low data.

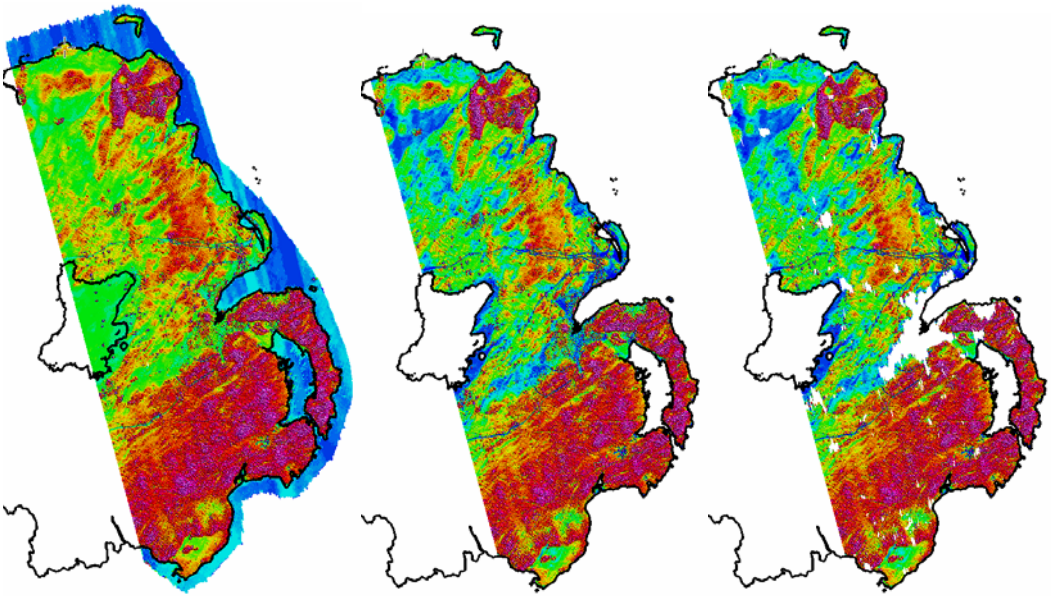


Figure 11. Illustration of masking in order to increase the cosmetic appearance of EM resistivity data. From left to right: all data, masked water bodies, masked water and high fly zones.

4.2.5.4 Apparent Resistivity issues

In Block D2 there is an apparent stripe in the inverted apparent resistivity results for the 3kHz data. This is most apparent when viewing the area shown in Figure 12. Close examination of the EM data shows no apparent "out of level" result for either real or imaginary datasets. The area under the cross-hair (upper centre) is related to geology, but there is nothing obviously wrong with the data to the south of the high fly area (top left). Therefore the origin of this apparent stripe in apparent resistivity is unknown.

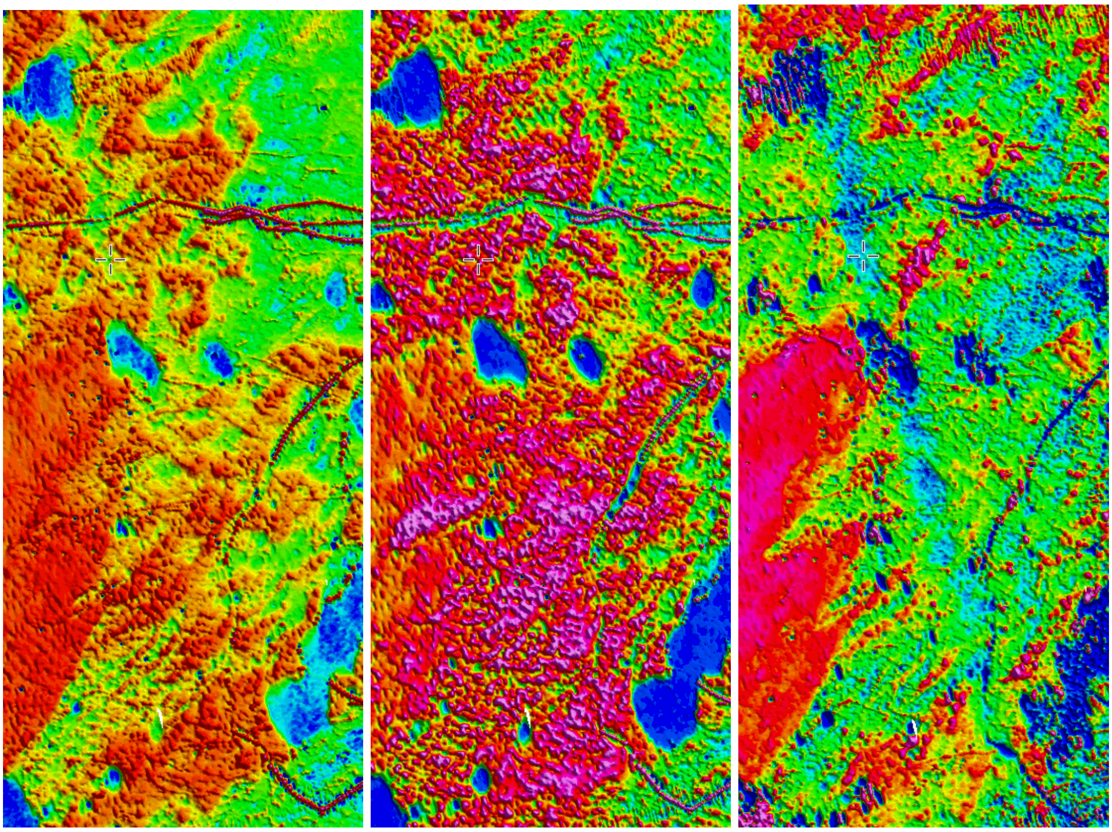


Figure 12. Detail from Block D2. Apparent stripe in resistivity; from left to right; RE03, IM03, F3ApRes.

4.3 MAGNETIC PROCESSING

This section describes the processing procedures applied to the Version 1 magnetic data. The standards used in airborne magnetic processing are well established and documented (e.g. Luyendyk 1997). The set of procedures used in the calibration and processing of the Version 1 magnetic data are fully described in the logistic reports for the two phases of the project (Beamish *et al.*, 2006 a,b). The two reports, one for each season/phase provide the calibration data (magnetic compensation, figure-of-merit, heading correction, magnetic noise, and lag correction) applied to the magnetic data from each season.

In practice, although in-field processing of the magnetic data was undertaken, all the survey data acquired were 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 (Beamish *et al.*, 2006 a,b).

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

4.3.1 Aircraft correction

The aircraft is a magnetised obstacle moving in the Earth's magnetic field. The magnetic impact depends on flight direction (heading) and the movement of the aircraft (pitch, roll, yaw). The properties 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 in Beamish *et al.* (2006 a,b). Data from the aircraft logging system include raw magnetic data and compensated magnetic data. This could allow magnetic compensation to be re-calculated post flight, although in practice this was not necessary.

4.3.2 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. Beamish *et al.* (2006 a,b) describes the four base stations used during the two season Tellus survey; during Season 1, three base stations were used (Enniskillen Airport A and B, and Derry Airport). During season 2, a single base station was maintained at Newtonards airfield.

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. The suitable allowed 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 exceeds these limits are rejected in the field and reflown, but all data are re-checked for micro-pulsation activity.

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 basestation in Mag32. In practice it was not necessary to adjust the default values.

The magnetic data are also adjusted to a common level for the four basestations. These levels are determined by comparing magnetic observatory data and local basestation data for a period of magnetic calm. The following basestation magnetic values were calculated:

Enniskillen Airport A: 49200.0 nT

Enniskillen Airport B: 49183.8 nT

Derry Airport: 49325.6 nT

Newtonards Airport: 49242.1 nT

These values correct the magnetic field to a common base level.

4.3.3 Lag correction

A lag test is performed to verify the recording delay (see Beamish *et al.*, 2006a,b). Due to the real time RMS compensation, its prefiltering, 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 0.3 seconds is applied to the data by MAGCOR. This is confirmed as appropriate by the continuation of linear magnetic features that cross-cut the flight line direction obliquely.

4.3.4 Heading correction

The aircraft is a magnetised metallic obstacle moving in the Earth's magnetic field. This results in different magnetic values recorded in the two flight line directions (165/345°). Beamish *et al.* (2006 a,b) describe the correction parameters achieved during the calibration flights. The heading correction applied by MAGCOR is a simple DC shift of line data based simply on the direction of travel.

Heading correction error is one of the most common sources of levelling error after data processing. Heading corrections are not always stable with time or may vary when objects are taken from or placed within the aircraft. Heading correction is also calculated from only three flight lines. A heading correction refinement can occur later in the processing stream prior to levelling by examining the statistics of entire survey blocks. The calculation of the mean for the two different flight directions can show the error in heading correction. This extra stage of heading correction was not applied to all survey blocks and merely makes the virtual tie-line levelling stage shorter.

4.3.5 Aircraft influence

The aircraft has a number of mission-critical system on board that create a magnetic source that 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 1 – 2 seconds during its operation. The hydraulic pump is mission critical and has been shielded as much as possible. It tends to operate after long periods of significant rudder and ailerons use, such as in mountainous regions. When the pump is operated, the duration is recorded and the magnetic data is then removed automatically.

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 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 was particularly problematic during surveying of survey block D2 near to Belfast International Airport. These data are not automatically removed from the dataset and required manual checking of flight lines where VHF had been flagged.

The nature of the hydraulic pump, VHF and windscreen wipers is not predicable and cannot be easily corrected for. Therefore data removal is the only option.

4.3.6 Data QC

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

4.3.7 Levelling magnetic data

Some levelling of magnetic data is still needed after all the corrections described above. One source of residual error is the incomplete diurnal correction. Magnetic base stations are almost always located some distance from the measuring aircraft; but the transient field varies in time and also space. The error is small, usually less than 1 nT, but it can be very clearly 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. The tie line correction is 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 at these points.

JAC uses the Virtual Tieline Levelling approach in order to level magnetic data. This uses the MAGLEV program. Left and Right/Nose channel data are read into the program, along with virtual tielines. These are lines that are digitised from within Geosoft Oasis montaj on maps of magnetic data. Lines are selected that crosscut flight lines in areas of low magnetic gradient. Data are then displayed in MAGLEV, as shown in Figure 13. Commonly it is easy to spot singular lines that are out of level and these can be adjusted into level interactively. A DC shift for each adjusted line is applied to the entire line. It is common to digitise two lines that cross all suspect lines so as to reduce the likelihood of adjusting a flight line based on a localised gradient as opposed to the regional gradient. When levelling errors are derived from heading corrections, it is common to observe that one of the magnetometers, e.g. the left one, is well adjusted and that the other (right) is not. This then usually dictates that the right one would be adjusted to the level of the left one, or visa versa.

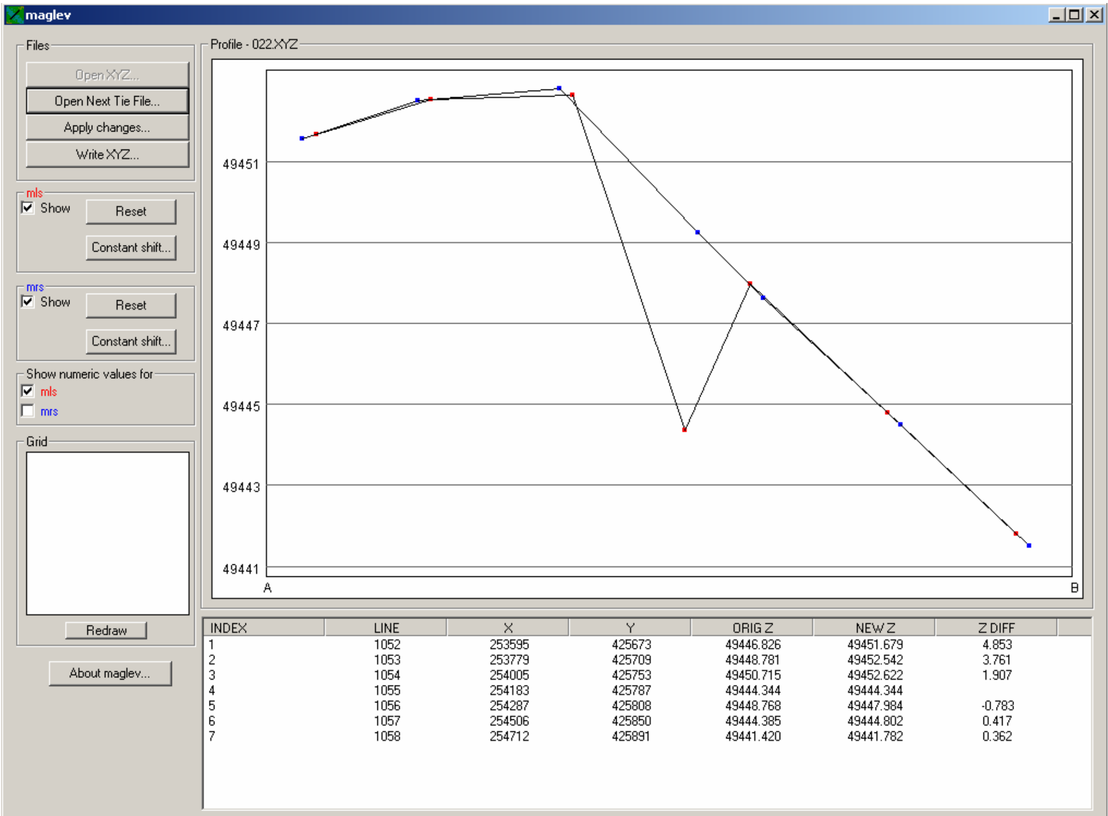


Figure 13 The MagLev program as used for virtual tie line levelling. This view shows that the left magnetometer values (in red) are being adjusted to match the right ones (in blue). One flight line is still to be adjusted.

4.3.8 Short-period drift of the magnetometers

Area B magnetic data showed a characteristic that had not been previously encountered. It was apparent that one of the magnetometers had a drifting level, which was seen to have a non-linear nature along individual flight lines. This problem only came to light when data were levelled using the virtual tie-line approach. It is common to select two virtual tie-lines that cross problematic lines; this reduces the problems of adjusting a line based on their 'local' gradient as opposed to the required 'regional' one. The non-linear drift is seen once the line cannot be levelled, or by the appearance that virtual tie-line levelling makes data worse.

Investigation of this problem showed that the right magnetometer was stable, with drift occurring in the left one. Later in the survey there had been observed problems with the left magnetometer and it was replaced. The drift characteristic was a long wavelength simple function. This feature was remedied by using the virtual tie-line approach to level the right magnetometer. These data were gridded and sampled into the left data channel [*mr_grid*]. The left [*mgcl*] and right channel [*mr_grid*] should be similar, but with differences in the high frequency localised magnetic field. The magnetometer drift can be estimated from the difference between *mgcl* and *mr_grid*. A tight B-spline function was fitted to a filtered drift estimate, which has data masked where the gradient along line is above a given threshold. This method determines a simple function, which when subtracted from the left magnetometer data gives a good result.

4.3.9 Secular variation and IGRF

The processing stream of the magnetic data has been designed so that secular variation can be changed in the future if required. It is common to correct for this affect prior to levelling. If for any reason a different model is required for the estimate of the magnetic field, this then requires re-levelling.

The reference field chosen for the Tellus survey was the International Geomagnetic Reference Field (IGRF). The IGRF is updated every 5 years, with the latest version (10th generation) published in 2005. The IGRF model is then extrapolated to the survey date. At a later date after the IGRF has been updated (i.e. 2010), the Definitive Geomagnetic Reference Field (DGRF) could be calculated; this would give a better estimate of the Earth's magnetic field. Appendix 1 lists the IGRF as applied to the Tellus data.

The IGRF was calculated using Geosoft Oasis montaj, using GPS height as the elevation channel. The IGRF model includes a time varying component and a date is required. A certain amount of the time varying component is corrected by the magnetic basestation. Therefore, the date used in the IGRF survey is the date of the setting up of the basestation and not the date of the flight.

The estimate of the IGRF is supplied with the final data, which could allow a different reference field to be applied in the future. The IGRF is subtracted from the Total magnetic field to give the Magnetic anomaly.

Magnetic data are also supplied baseline corrected. These are simply the IGRF corrected magnetic anomaly data with a DC shift, resulting in only positive data values.

4.4 POSITIONAL PROCESSING

Positional, including height, processing information has been described in the logistic reports for the project. The studies in the logistics report indicate that the differentially corrected coordinates (X, Y) obtained during the survey are of sub-meter accuracy.

Positioning is done after a survey flight, which allows for more time and even more effort to achieve accurate results. The purpose is to find the exact coordinates for each of the measuring sensors in the actual, local coordinate system for each measurement. Real-time differentially corrected coordinates are not as accurate as the post-flight differentially corrected ones. The postprocessing differential correction program used (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 Tellus data is the IRISH GRID 1975 used as a national reference system by both The Republic of Ireland and Northern Ireland.

Details of the system can be found on the Ordnance Survey of Northern Ireland Web site. Table 5 provides a main summary.

IRISH GRID (1975) National Datum	
Projection	Transverse Mercator (Gauss Conformal)
True Origin	Lat. 53° 30´North, 8° 00´ West of Greenwich
False Origin	200,000 m W, 250,000 m S, of true origin
Scale factor on central meridian	1.000035
Reference Ellipsoid	Airy (modified)
Semi-major axis (a)	6 377 340.189 m
Eccentricity (e^2)	0. 0006 670 540

Table 5. Summary parameters for the IRISH GRID (1975) that define the local grid coordinates (Easting and Northing) used in the Tellus aerogeophysical project.

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 (GPS_Z) and the resulting DTM are provided with all the processed geophysical data sets in both Version 1 and Version 2 deliveries. 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 and in certain mountain areas), the RALT and hence DTM measurement becomes less accurate.

During the survey of Block C1, on-board GPS altitude became less accurate. The resulting DTM is also less accurate. The major GPS-Z errors occur along 2 lines only:

L1123:3 Time	08:03:57.0 to 08:04:15.7
	08:04:57.1 to 08:06:05.9
	08:09:26.1 to 08:09:47.9
L3167:5 Time	15:53:49.0 to 15:53:38.0

Data have been interpolated in the database. It should also be noted that:

- DTM data have not been microlevelled as the procedures for microlevelling potential field data are not applicable to DTM data, where GPS-Z is inherently inaccurate.

- Bodies of water, especially the sea, are temporal. As such, the height of the DTM on parallel lines from different flights can be considerably different depending on the state of the tide or the charge of Loughs.

4.5 SUMMARY OF VERSION 1 DATA FILES

The files delivered as Version 1 ASCII (.xyz) data are listed in Table 6.

BLK	MAG file / date	RAD file / date	EMAP file / date
A	BlockA_magL_v1.XYZ BlockA_magR_v1.XYZ 09/03/2006	BlockA_rad_v1.XYZ 08/02/2006	BlockA_emap_v1.XYZ 30/01/2006
B	BlockB_magL_v1.XYZ BlockB_magR_v1.XYZ 14/03/2006	BlockB_rad_v1.XYZ 16/02/2006	BlockB_emap_v1.XYZ 16/02/2006
C1	BlockC1_magL_v1.XYZ BlockC1_magR_v1.XYZ 05/04/2006	BlockC_rad_v1.XYZ 16/03/2006	BlockC_emap_v1.XYZ 16/03/2006
D1	BlockD1_magL_v1.XYZ BlockD1_magR_v1.XYZ 16/03/2006	BlockD1_rad_v1.XYZ 01/03/2006	BlockD1_emap_v1.XYZ 01/03/2006
E1	BlockE1_magL_v1.XYZ BlockE1_magR_v1.XYZ 16/03/2006	BlockE1_rad_v1.XYZ 09/02/2006	BlockE1_emap_v1.XYZ 21/02/2006
C2	AreaC2_magL_v1.XYZ AreaC2_magN_v1.XYZ 31/07/2006	AreaC2_Rad_v1.XYZ 18/08/2006	BlockC2_emap_v1.XYZ 15/09/2006
D2	AreaD2_magL_v1.XYZ AreaD2_magN_v1.XYZ 07/08/2006	AreaD2_Rad_v1.XYZ 18/08/2006	BlockD2_emap_v1.XYZ 15/09/2006
E2	AreaE2_magL_v1.XYZ AreaE2_magN_v1.XYZ 04/08/2006	AreaC2_Rad_v1.XYZ 18/08/2006	BlockE2_emap_v1.XYZ 15/09/2006

Table 6 Version 1 delivered data files

4.6 OTHER .XYZ VERSION 1 DATA

1) Initial magnetic data delivery. Two files for Block A were delivered. These files were mlaaalev.xyz and mraaalev.xyz (ml=left-wing magnetometer, mr=right-wing magnetometer) and have a date stamp of 31/01/2006. The accompanying notes read:

```
NOTES ON GTK LEVELED BLOCK A MAGNETIC DATA
--------------------------------------------

1. There are two XYZ files, mraaalev.xyz and mlaaalev.xyz.
These contain the leveled right and left magnetic
measurement results for block A, respectively.

2. There is also a Geosoft database file a_mag_both_gtk.gdb.
Both the left and right mag files have been imported to
the database so that for each line number there are two versions,
for example for line 2 there are versions 2.0 and 2.1, the
former of which is the left magnetometer data and the latter
the right magnetometer data.

3. The levels of the two magnetometers are consistent and
they are meant to be used together for gridding. It is
our recommendation that gridding is done using the
database as it ensures that both the magnetometers are used
in gridding process. Of course the magnetometers can also
be used independently but that will lower the level of detail
of the grid.

4. There is also an image mag_leveled.png that is an
image export of the 50-meter cell size grid made using
both magnetometers' data (gridded using standard Oasis Montaj
minimum curvature).

5. The levelling was done based on GTK procedures and
refined by some very low wavelength polynomials along the lines
as a further microlevelling procedure.
```

2) A set of 5 ascii (.xyz) files containing magnetic mean and magnetic gradient information for the PHASE 1 data blocks A, B, C1, D1 and E1 were delivered on 29/06/2006. The data files have the filename AreaX_MagGrad.XYZ, where X denotes one of the 5 blocks (A, B, C, D and E). The actual blocks are those of PHASE 1 i.e. A, B, C1, D1 and E1. The data contents of each file are:

```
XX:            Grid Easting (m) taken as the mid-point between left and right magnetometer sensors
YY:            Grid Northing (m) taken as the mid-point between left and right magnetometer sensors

MAG_MEAN       Mean residual of base station corrected and IGRF model data (nT)
GRAD_PERP      Cross-plane magnetic gradient adjusted to be east to west (nT/m)
GRAD_LINE      Along-line magnetic gradient adjusted to be south to north (nT/m)
LEVERR_Damp    Damped microlevelling error (nT)
LEVERR_Spline  B-spline of microlevelling error to remove remaining geological signal
MAG_ML1        Microlevelled (using damped LEVERR) mean residual of base station corrected & IGRF model data (nT)
MAG_ML2        Microlevelled mean residual of base station corrected and IGRF model data (nT)
```

These data precede an evaluation of the PHASE 2 reconfigured dual magnetometer to left-wing tip and nose. They are not definitive in terms of consistency across the full survey area.

3) Initial levelled magnetic data for Block A and Block B were provided for the levelling comparison tests. A tie-line data magnetic data set was generated for combined Blocks A and B. The data (mls_TIE_AB.xyz and mlr_TIE_AB.xyz) were delivered with the following notes:

```
Contents of CD:
Pre-levelled MAG data for BLOCK B:
ml_ORIG_B_DB.xyz (MAG LEFT)
mr_ORIG_B_DB.xyz (MAG RIGHT)
tie line MAG data for combined Blocks A and B:
mls_TIE_AB.xyz
mrs_TIE_AB.xyz
----------------------------------------
Suffix L (or l) refers to left wing-tip channel. Suffix R (or r) refers to right wing-tip channel.
Both sets of files are in same format.
The original MAG channels are ORIG (ORIGL and ORIGR). These are uncorrected for base station station
variations (diurnal).
The base station MAG is in channel BASE.
The MAG corrected for base station variations (diurnal) is MGC (MGCL and MGCL) and is formed by the
subtraction MGC = (ORIG -BASE).
All data in nT.
-------------------------------------------
Other channels:
        X:      Grid Easting (m)
        Y:      Grid Northing (m)
        Flight: Flight number
        Day:    Day number (Julian)
        Time:   Time (HHMMSS.SS)
        DIR:    Flight direction (degrees clockwise)
        RALT:   Radar altitude (m)
        GPS_H:  GPS altitude (m) above geoid (WGS84)
        DTM:    Digital Terrain Model (m)
```

5 Version 2 data processing

The processing procedures applied to the Version 2 data for the complete survey area are described in the following sections.

5.1 RADIOMETRIC PROCESSING

The Version 2 radiometric data comprise a combined data set (.xyz) across the whole survey area (8 Blocks). This is in contrast to Version 1 data (.xyz) which formed individual blocks. Note that Version 1 data included all online data (e.g. ragged edges to North and South borders of each block). These ragged edges were additional line-km to the ideal survey blocks (they provided block overlaps used for the assessment of 'level' issues across blocks).

Version 2 data have been combined across all 8 eight blocks using data processed within 8 individual, non-overlapping blocks. The overlapping/common lines (1214, 1215; 2214,2215; 3214,3125) allowed us to assess the level differences/issues arising from the 2-year acquisition of the radiometric data.

The two main procedures applied to the production of the Version 2 data are:

1) Seasonal adjustments. The PHASE 2 (2006) data were adjusted to the levels of the PHASE 1 (2005) data. The procedures were applied to all the radiometric data sets, although in the case of Uranium, the adjustment was marginal.
2) Radon/levelling adjustments. Following a study of 5 possible processing options, the Greens (1987) levelling procedure was applied to the Uranium and Total Count data sets. The Thorium and Potassium data sets are unlevelled.

Following a description of the seasonal adjustments applied, a study of the options for levelling the Tellus data is presented. A description of the application of Green (1987) levelling applied to the data is then given. Finally a note regarding the intrinsic noise levels of the data is provided.

5.1.1 Seasonal adjustments

An assessment of the statistical behaviour of the 2005 (PHASE 1) and 2006 (PHASE 2) data sets was undertaken. The study used Version 1 data across floating blocks and the overlapping lines discussed previously. In general the PHASE 2 data set shows a lower level than the PHASE 1 data set.

The simplest way to correct for the seasonal change is a simple DC level shift, i.e., adding a single number to all PHASE 2 data to bring them in line with the PHASE 1 level. In this case the adjusted values, d_{adj}, for PHASE 2 are related to the original values, d, through the relationship: $d_{adj} = d + c$, where c is the DC level shift. The appropriate level shift for each element, as well as for Total Count, was chosen by comparing data from the overlapping lines (1214, 1215, 2214, 2215, 3214 and 3215). This procedure works well for uranium but fails for all other elements and Total Count because there is a much higher seasonal change in the high-Count high-ground area in the south (blocks E1/E2) compared to that in the low-Count areas further north (blocks C1/C2 and D1/D2). This can be seen quite clearly in Figure 15 for Total Count.

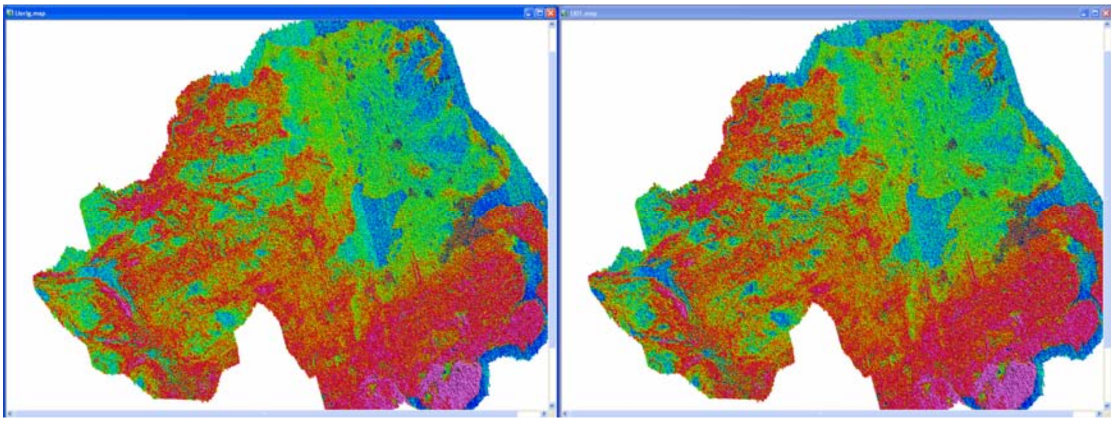


Figure 14. Uranium data before (left) and after (right) DC level shift.

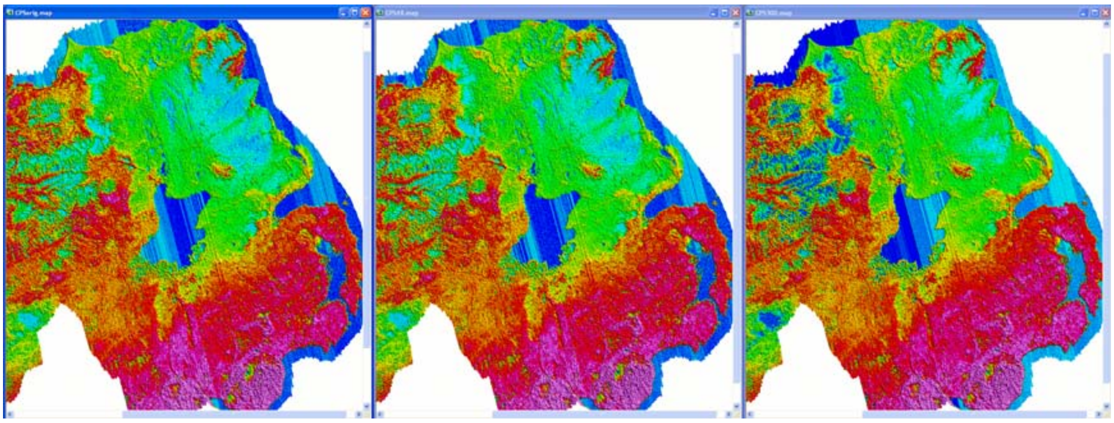


Figure 15. Total Count data: before seasonal adjustment (left), after a 48-Count DC shift (middle) and after a 300-Count DC shift (right). A low DC shift works well in the north but not in the south. The opposite is true for a high DC shift.

In order to obtain a satisfactory seasonal adjustment for all areas, a linear shift was employed. In this case the adjusted values, d_{adj}, for PHASE 2 are related to the original values, d, through the relationship: $d_{adj} = a * d + b$. The coefficients a and b are determined by multiple linear regression. The coefficient a is a gain factor and b is a DC level shift. An example of the results for Total Count is shown in Figure 16. The following table summarises the coefficients used in the seasonal adjustment:

	Linear shift
TOT_CPS	a = 1.09, b = 76.64
TOT_NGY	a = 1.12, b = 0
K	a = 1.22, b = 0
Th	a = 1.24, b = 0
U	a = 0, b = 0.1 (DC level shift)

Table 7 Coefficients applied in Version 2 radiometric seasonal adjustments.

The seasonal adjustments required that the Line 1215 from 2006 be used for Block C1. Due to the nature of the changes to the Block structure (2005 to 2006) a 4.5 km data gap remains at the south end of Line 1215.

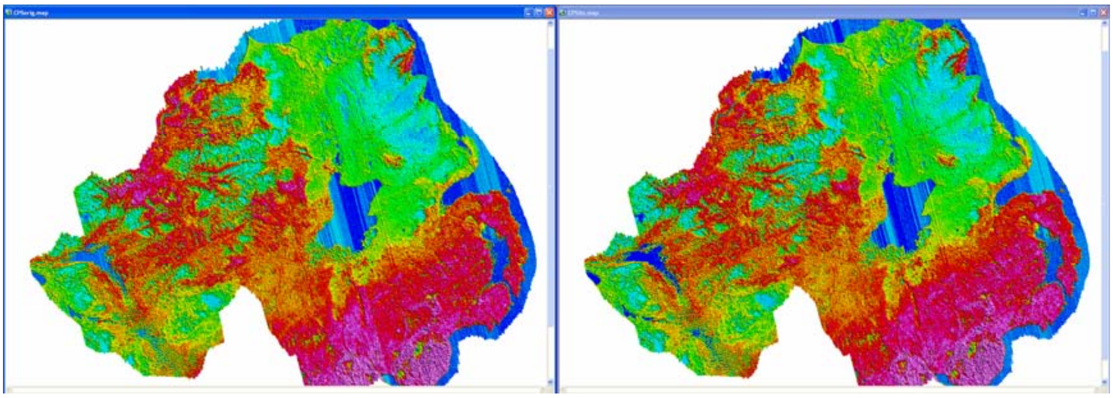


Figure 16. Total Count data before (left) and after (right) linear shift.

5.1.2 Radon/Levelling options for Radiometric data.

Radiometric data are commonly affected by atmospheric radon, which is not fully removed by the processing procedure. This problem is usually seen as a raised "level" of a complete line. Version 1 data sets were adjusted for variations in radon content using the JAC microlevelling procedure for radiometric data (Hautaniemi et. 2005; Minty et al., 1997). Details are provided in Section 4.1.

There are a number of processing procedures designed to level data, some of which are specific to radiometrics and others that are general for geophysical data. Levelling errors are usually only observed in Uranium and Total Count.

For this study a section of Block D2 affected by levelling errors was selected and subjected to a number of levelling techniques. The starting data (2 areas within Block D2) are shown below (Figure 17) for Total Count:

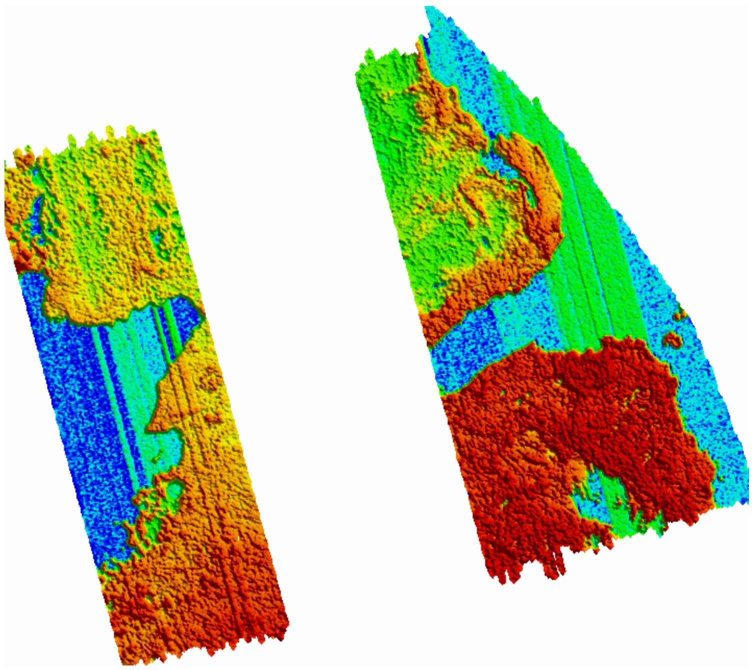


Figure 17. Original block D2 affected by radon/levelling errors.

JAC MICROLEVELLING

When data contaminated by atmospheric radon is observed the entire block is microlevelled using the JAC procedure. This spatial domain median filtering approach is very effective at bringing singular lines into level with their neighbours. The result of JAC levelling is shown below:

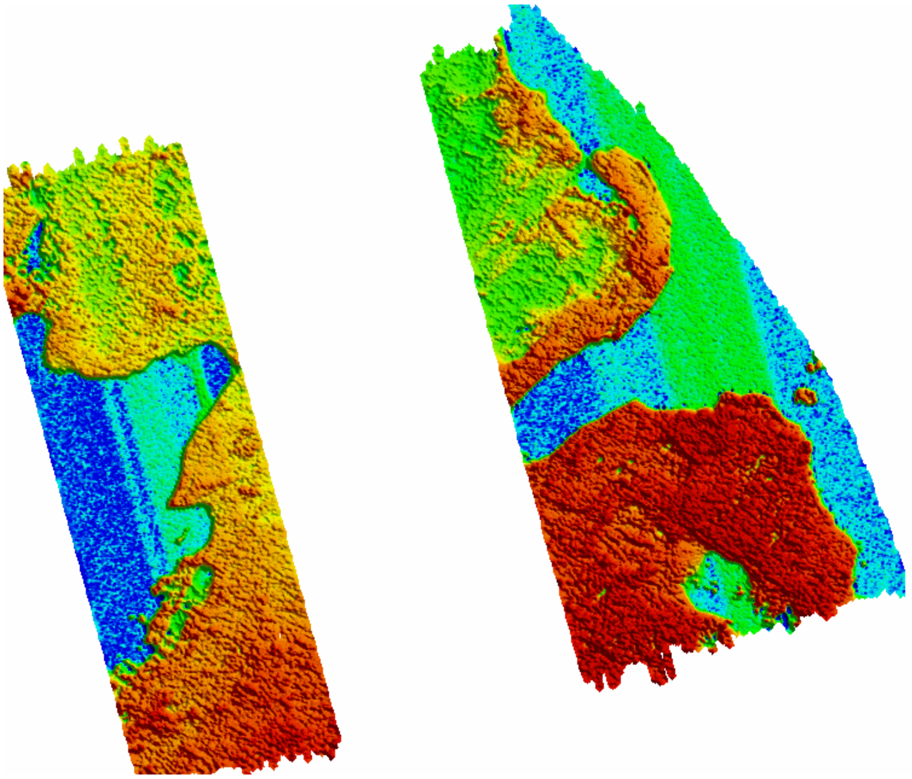


Figure 18. Block D2 data after JAC microlevelling procedure.

PROS & CONS

+ Effectively brings on-shore geological features into level

+ Creates a pleasing result for display of regional data

– Is not designed to cope with offsets in data that are broader than the search radius of the filter, usually line spacing; therefore does not reduce sequences of lines that are out of level.

– Effectively removes “real” responses that appear on singular lines, or ones that cut flight lines at low angles.

– Creates artificial low spikes if data are stepped along line, such as seen in Total Count during the transition from land (high values) to water (effectively zero values).

5.1.2.1 MODIFIED JAC PROCEDURE

The JAC procedure is very effective at identifying levelling errors smaller than the search radii along line and perpendicular to the line, as is common with the error associated with EM. The error related to radiometrics tends to be much longer than the along line radius and can be considered more as a DC or tilt error of the entire line. A test was undertaken to look at the difference between the non-levelled and levelled result. This tends to show a general long frequency trend, superimposed upon which is a high frequency component. By fitting DC shifts, tilt or any other function to this difference data it was possible to identify the general complete line error. The result of the modified approach is shown below:

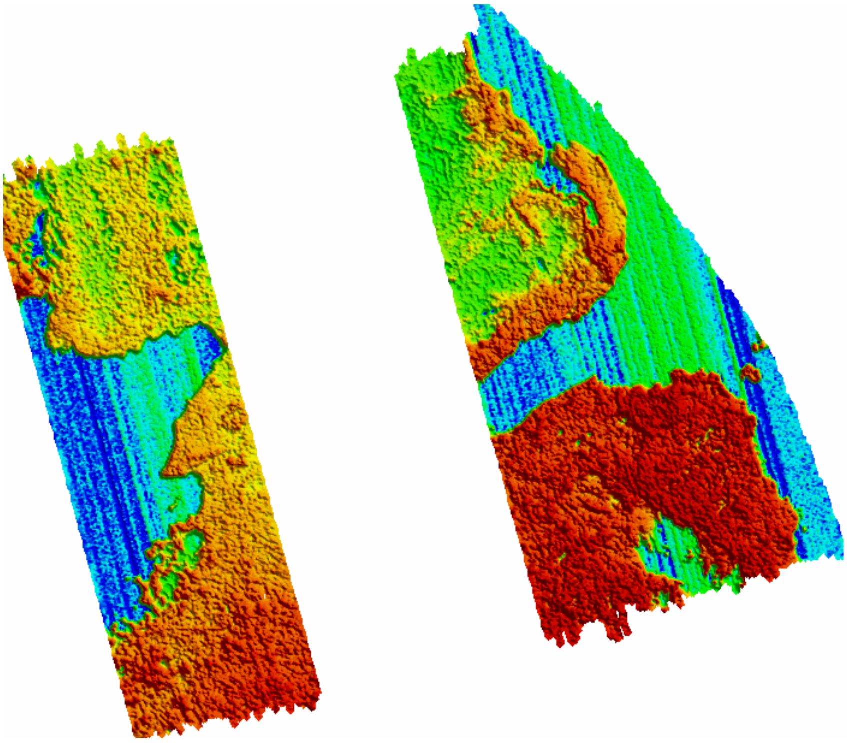


Figure 19. Block D2 data after modified JAC procedure.

PROS & CONS

+ No longer alters on-shore geological response much, retaining single line features.
− Makes no difference off-shore as JAC processing has not been able to alter stepped data.
− Still see some on-shore residual levelling errors suggesting that the affect of radon is not uniform along the entire line.
− Struggles on some lines offshore, especially near to the islands off shore.

5.1.2.2 WATER BODY LEVELLING

A common approach to microlevelling is to use information gathered over large bodies of water. Here the data can be assumed to be zero, or at least close to zero, depending on water depth and other considerations. In order to achieve this levelling approach, all the on-shore data were masked leaving just data for Lough Neagh and the Irish Sea. Average Total Count values were estimated and these were adjusted to achieve an average of zero at these points. The results are shown below:

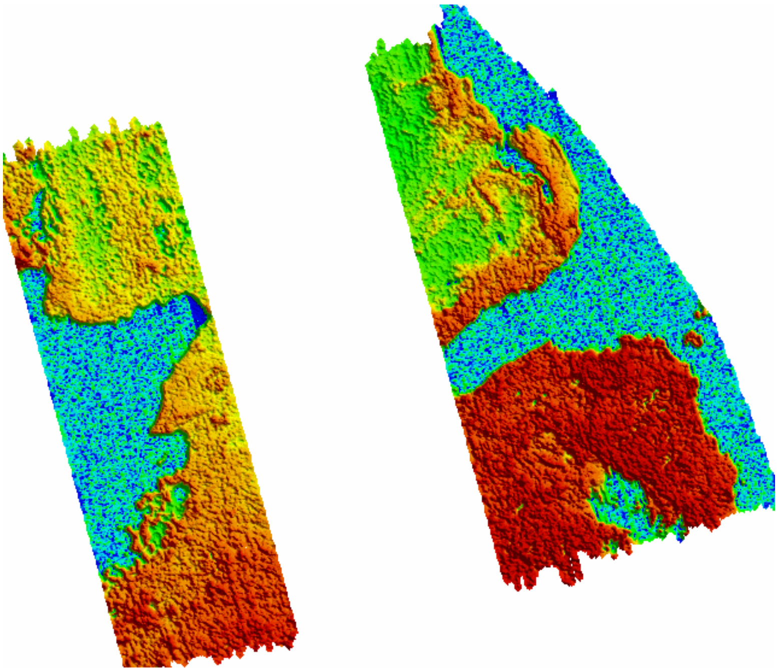


Figure 20. Block D2 data after water levelling procedure.

PROS & CONS

+ The results over water look more "consistent", giving a better aesthetical result.
+ Simple DC shift of data.
– Results on land are still out of level in places, possibly suggesting that radon contamination is not a simple DC function. Adjustment has resulted in some "in level" data now being out of level.
– Not every flight line has a large body of water; not every flight included data that were over water.
– Makes assumption that response over water is always the same and can result in over-compensation.
– Care has to be taken to make sure that no "on-shore" data is included in adjustment.

5.1.2.3 GREENS (1987) LEVELLING

The method of Green (1987) uses data for U, Th and K in order to identify the error in U based on their relationship with Th and K by regression. This results in an estimate for mean uranium per flight line based on the Th and K data and this is removed from every uranium data point along line. This is the method employed in the Intrepid radiometric processing procedure.

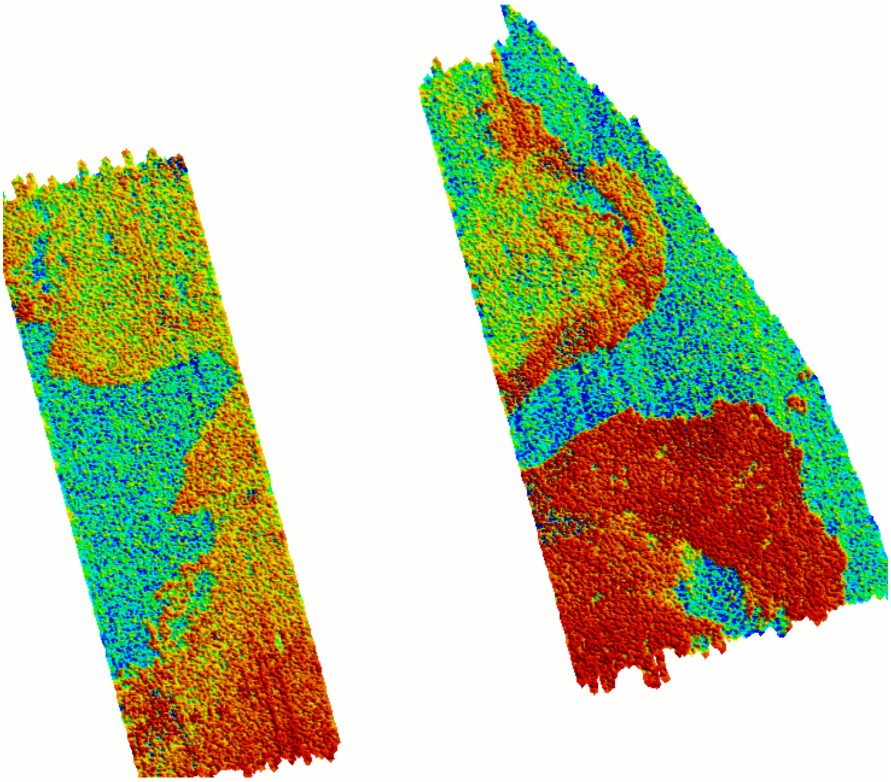


Figure 21. Block D2 data after Green's levelling procedure.

PROS & CONS

+ Improves data in an understandable way
+ Changes data only along and not across lines
− Not quite a perfect result in south of area where error is not linear along line.
− Water not yet “perfect”

5.1.2.4 BI-DIRECTIONAL MICROLEVELLING

The same bi-directional microlevelling was applied to Uranium and Total Count data to see if this approach was valid for radiometric data. The process aims to extract a "regional" result for the data, allowing line-based errors to be identified. The process works on bi-directional gridding, resulting in a grid for levelling error. This data is sampled into a database allowing control over what function is used to fit the error and as such what correction is applied to the data. For this study only DC shifts were seen as being appropriate for the data. The results are shown below for both Uranium and Total Count:

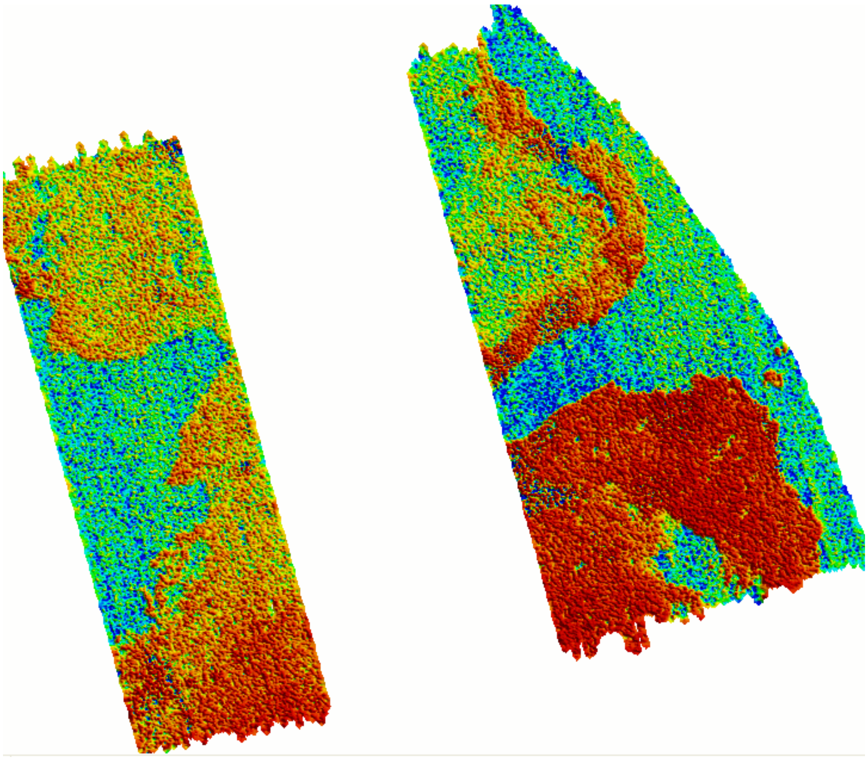


Figure 22. Uranium block D2 data after bi-directional microlevelling procedure.

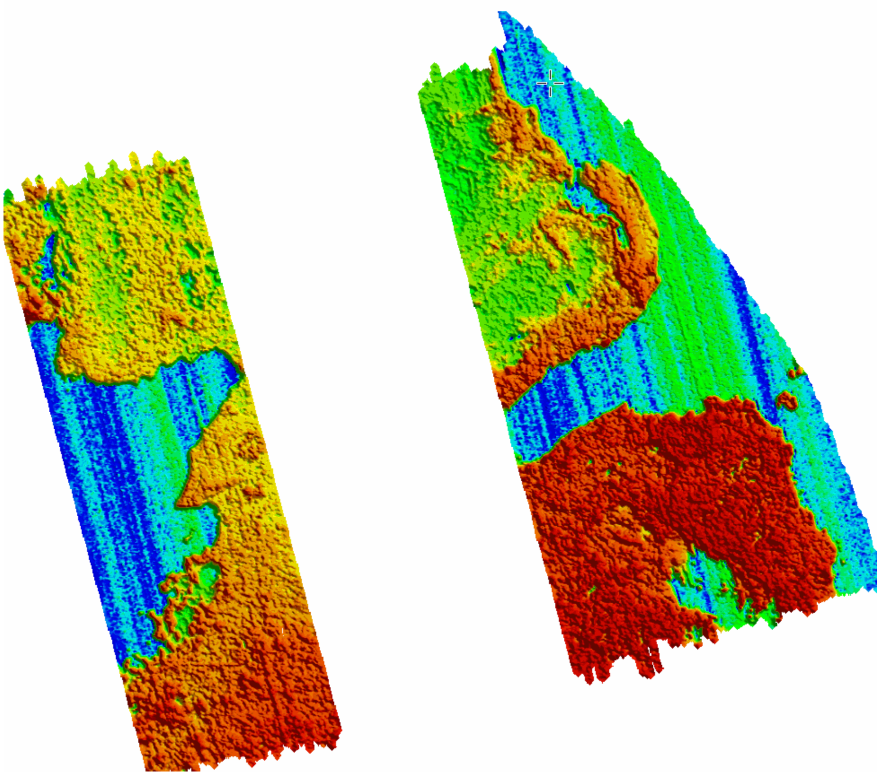


Figure 23. Total Count block D2 data after bi-directional levelling procedure.

PROS & CONS

+ Simple process that has some positive results onshore.
+ Good uranium result
– For strong "out of level" Total Count results there is still a residual levelling error.
– The calculated "regional" dataset cannot accommodate a step; therefore the stepped nature offshore in Total Count cannot be corrected.

The outcome of the studies was that the Greens levelling method was judged most effective for the Tellus data and it was applied to the levelling of both Uranium and Total Count data sets, as discussed below.

5.1.3 Greens radon/levelling adjustments

Following the 2005/2006 seasonal adjustments to each of the data sets, levelling of the resulting data was undertaken using the Green's (1987) levelling procedure. The procedure was only applied to the U, TOT (cps) and TOT (nGy/hr) data sets.

The uranium data set suffers from background changes usually associated with the decay of atmospheric radon. The magnitude of this atmospheric background is dependent upon the weather and the time of day. The same changes are evident in the Total Count channels but they do not affect to the same extent the thorium and potassium channels. Consequently, images of these channels usually show little banding of the type seen in the uranium and Total Count images. The Green's levelling procedure will tend to isolate background fluctuations by looking at the residuals from a regression of the uranium and Total Count channels on the other two channels. More specifically, a multiple linear regression of flight-line means for the uranium and Total Count channels is performed on the flight-line means for thorium and potassium: $\overline{Y} = a * \overline{K} + b * \overline{Th} + c$, where Y stands for uranium or Total Counts. The coefficients were obtained using the statistics across the whole (8 block) survey. The residuals obtained from this regression are used to correct the uranium and Total Count channels for each line. The following table summarises the regression coefficients obtained for uranium and Total Counts:

	a	*b*	*c*
U	-0.34	0.29	0.06
TOT_NGY	15.92	5.05	2.60
TOT_CPS	562.49	225.02	157.10

Table 8 Coefficients applied in Version 2 radiometric levelling.

Figure 24 shows an example of the effect of Green's levelling on a part of the Total Count image that exhibited a high degree of banding.

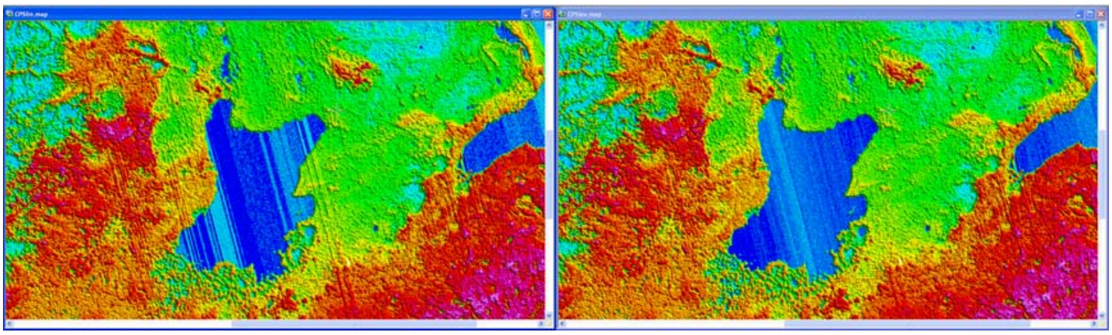


Figure 24. Total Count data before (left) and after (right) Green's levelling.

5.1.4 Studies of radiometric noise levels.

All the radiometric data sets have an intrinsic statistical noise level. These were examined by contouring the radiometric data sets below a low amplitude cut-off. An example is shown below using Thorium (Figure 25) and Potassium (Figure 26) in standard ppm units. The data range of the entire data set is from –1.19 to 38.96 ppm (thorium) and from –0.23 to 4.87 ppm (Potassium). All values below zero (Figure 25) and below 0.02 (Figure 26) are contoured in black.

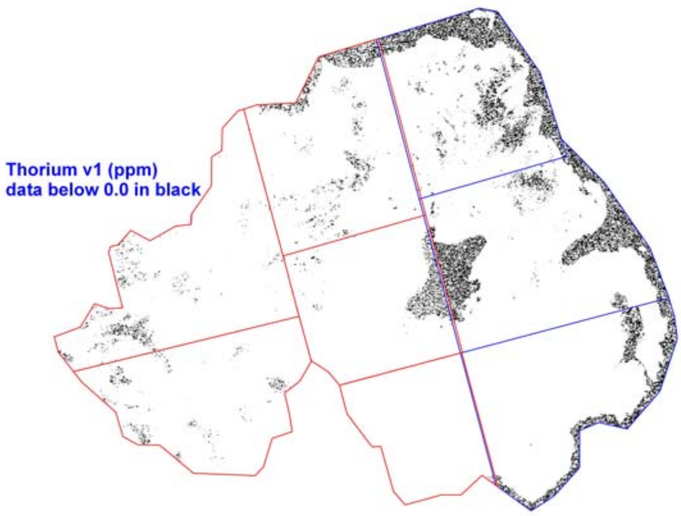


Figure 25. Thorium data below 0.0

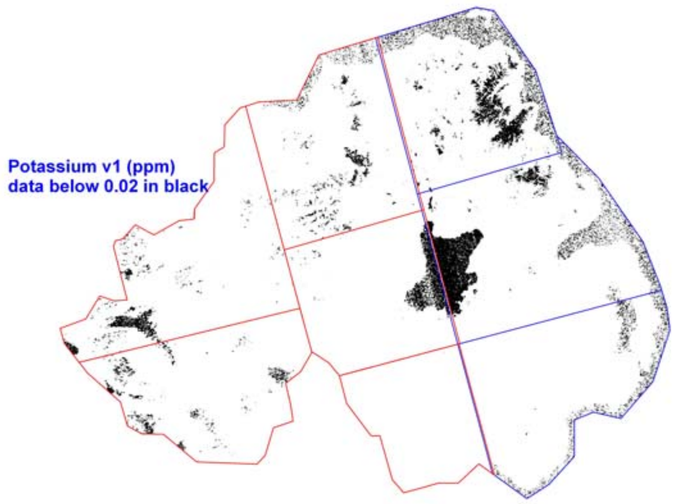


Figure 26. Potassium data below 0.02

At the chosen threshold (all values less than or equal to zero or 0.02), the contours are largely confined to zones of water (a material with an expected null radiometric response). The only other persistent zone on land occurs in association with high ground in the NE. By adjusting the chosen threshold, a broad assessment of the intrinsic statistical noise level for each of the radiometric data sets can be made. It is recommended that the intrinsic noise level of each radiometric data set be acknowledged when images of the data are produced.

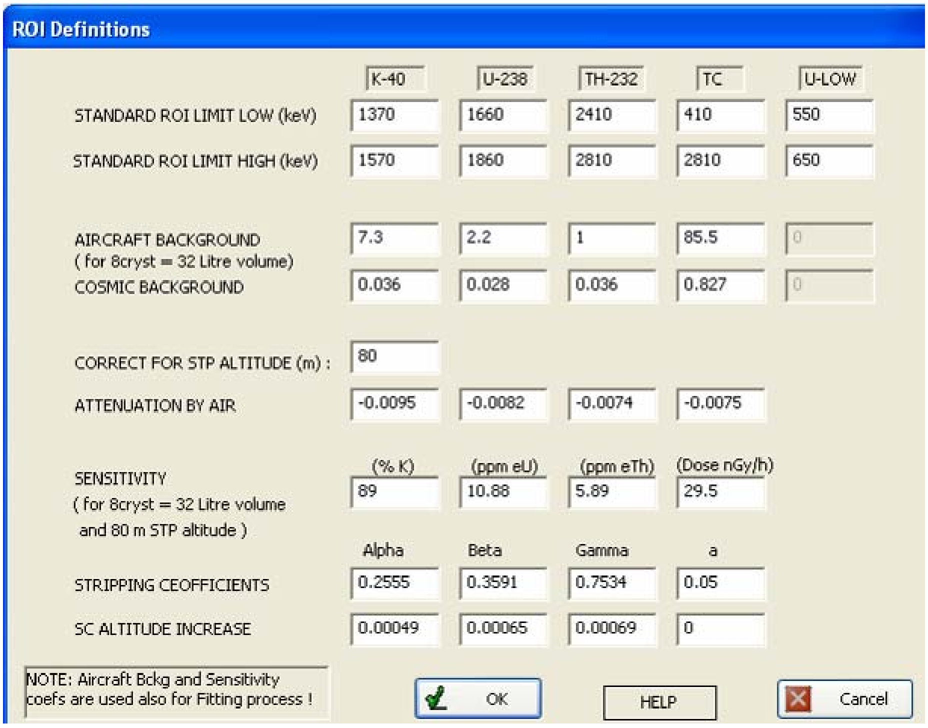
5.2 CAESIUM-137 PROCESSING

The processing of the full spectrum radiometric data was deferred until completion of the whole survey. This allowed an assessment of seasonal effects between PHASE 1 (2005) data and PHASE 2 (2006) data. The spectral processing to estimate ^{137}Cs was carried out in the Praga3 processing module within Geosoft.

5.2.1 Data preparation and PRAGA3 processing

Tellus KOG and LIN files were processed using a KOG2PRA script to create ASCII spectral files (.PRA files). The definitive lists of LIN files used in the original delivery of the radiometric data were used to ensure that only flights used in the final data delivery were included. In cases where lines existed twice in the resulting database (original flight and re-flight as often re-flights were flown for another parameter and the radiometric data was acceptable for both flights) the line was kept that had been used for the EM or the MAG to ensure consistency between datasets. The KOG2PRA script recognises repeats of line number, so that split lines had all sections included.

The ASCII files were imported into large Geosoft databases and PRAGA3 projects were set up using parameters derived from the Finnish calibration range (Figure 27). Some PRAGA3 default parameters were maintained, for example for attenuation by air where this was deemed appropriate by Cathy Scheib and Pavel Jurza (Author of PRAGA3). The stripping ratios for the 2005 data were: Alpha = 0.2375, Beta = 0.3765 and Gamma = 0.7259.



ROI Definitions

	K-40	U-238	TH-232	TC	U-LOW
STANDARD ROI LIMIT LOW (keV)	1370	1660	2410	410	550
STANDARD ROI LIMIT HIGH (keV)	1570	1860	2810	2810	650
AIRCRAFT BACKGROUND (for 8cryst = 32 Litre volume)	7.3	2.2	1	85.5	0
COSMIC BACKGROUND	0.036	0.028	0.036	0.827	0
CORRECT FOR STP ALTITUDE (m) :	80				
ATTENUATION BY AIR	-0.0095	-0.0082	-0.0074	-0.0075	
	(% K)	(ppm eU)	(ppm eTh)	(Dose nGy/h)	
SENSITIVITY (for 8cryst = 32 Litre volume and 80 m STP altitude)	89	10.88	5.89	29.5	
	Alpha	Beta	Gamma	a	
STRIPPING CEOFFICIENTS	0.2555	0.3591	0.7534	0.05	
SC ALTITUDE INCREASE	0.00049	0.00065	0.00069	0	

NOTE: Aircraft Bckg and Sensitivity coefs are used also for Fitting process !

OK HELP Cancel

Figure 27. Regions of Interest and calibration parameters used for the 2006 data in PRAGA3

^{137}Cs data was calculated in PRAGA3 in one database for PHASE 1(Season 1), and one for PHASE 2 (Season 2). This approach was better than working on a block-by-block basis as PRAGA3 energy calibration is more accurate when more data is used at once. It was not possible to use both seasons together due to the different stripping ratios between the two survey years and the decay correction required due to the time lag between the phases of the survey. The energy calibration factors used were a = -0.00008153, b = 1.004, c = -1.5. A background spectral file (.BAC) created from over-water flights and high altitude flights was worked into the model to account for the ^{137}Cs source on board (a stabilization source in the upward looking detector). Least squares fitting was used to calculate ^{137}Cs in Bqm^{-2}. Data is delivered in KBqm^{-2} as this is the unit most commonly used for this type of data. 2005 data were decay corrected to the time of the 2006 survey to ensure a comparable level of ^{137}Cs was provided for both surveys. This was done using the standard radioactive decay equation: $A_t = A_o e^{-\lambda t}$ where λ = ln2/half-life ^{137}Cs, where A_t is activity at time t, and A_o is the original measured activity. Therefore λ = 0.6931/30.17 (= 0.022974, half-life of ^{137}Cs is 30.17 years). As the two surveys were approximately 0.75 of a year apart, season 1 corrected ^{137}Cs was calculated as follows:

$$\text{Season 1 corrected } ^{137}\text{Cs} = \text{Season 1 measured } ^{137}\text{Cs} * e^{-(0.22974*0.75)}$$

Data from both seasons were gridded together to ensure there was no obvious difference between the two years of survey. There was no ‘join’ between the two years visible in Loch Neagh or in the sea reflecting that the background correction was correct and was the same across the two years of the survey. Lines 1214 &1215, 2214 &2215 and 3214 &3215, which were flown in each year of the survey, were checked for consistency between years. Although the results were very encouraging, a slight shift (based on the average difference of the lines between years) was applied to lower the Season 1 data (0.262 KBqm^{-2}). This slight shift between years was obviously a function of varying ground conditions (moisture content, atmospheric conditions) as there was no offset visible over water.

As exponential height attenuation corrections only hold true up to a flying height of approximately 160m, the ^{137}Cs data in high-fly areas (>160m) have been masked out as high altitude was producing erroneously low ^{137}Cs values. Much of the area over water has been masked too.

The striking banding patterns (Figure 28), some of which run approximately in the flight line direction were investigated to verify their validity or otherwise. The tie lines flown for Blocks A and B were processed for ^{137}Cs in PRAGA3. Tie-lines were flown at 255 and 75 degrees with a line spacing of 2000 m. As the tie-lines are perpendicular to the general flight line direction, the fact that the same features are visible (albeit with a decrease in resolution of x10) confirms that although the banding does go largely in the flight line direction, they are real features (Figure 29).

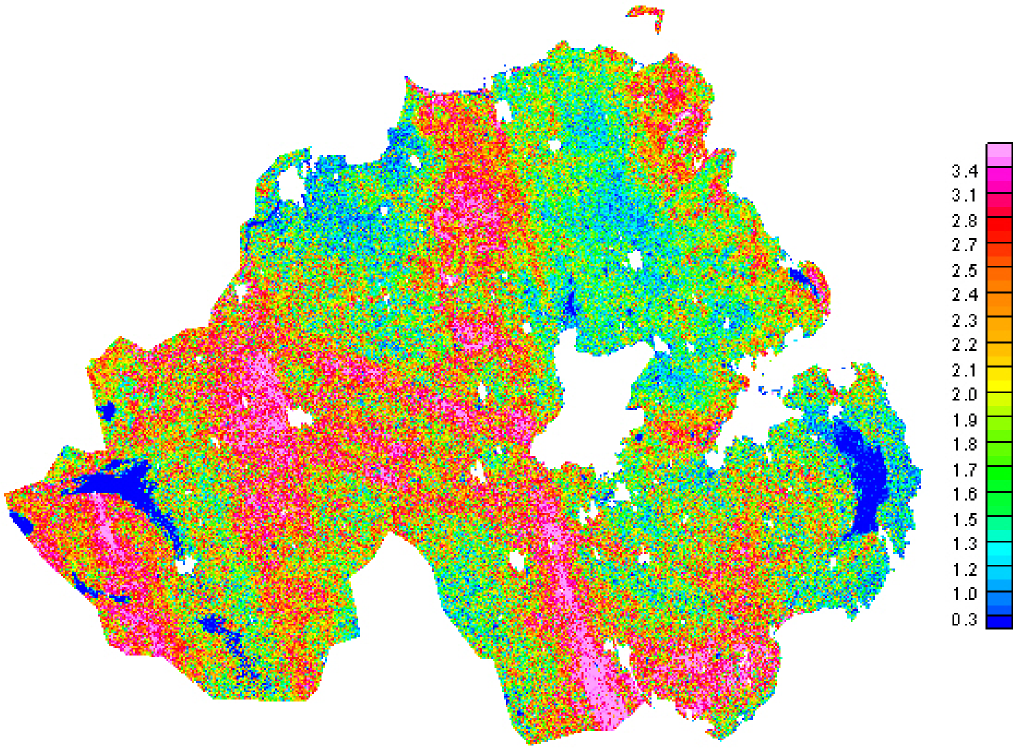


Figure 28. *^{137}Cs (KBqm^{-2}) for Northern Ireland, processed by season, masked above 100m.*

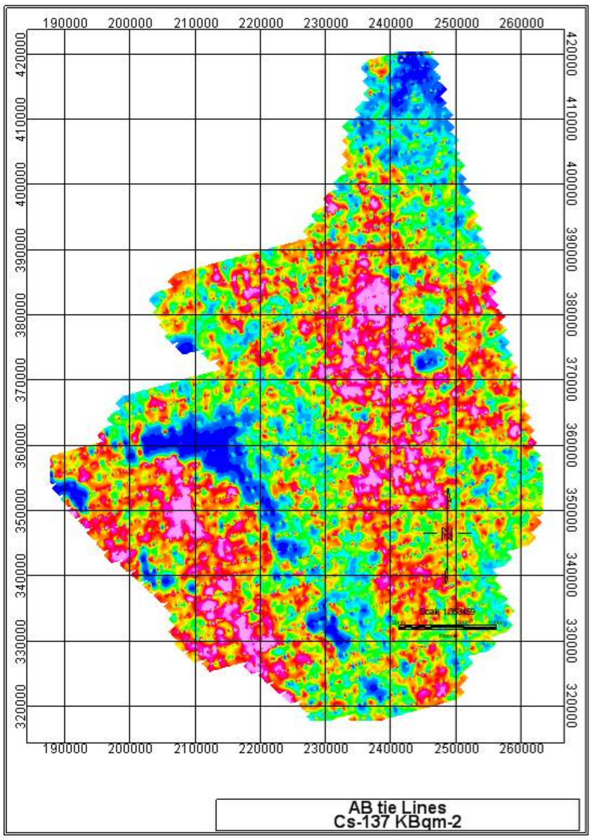


Figure 29. *^{137}Cs (KBqm^{-2}) for Block A and B tie-lines.*

To further illustrate this, a comparison of the ^{137}Cs survey results obtained using the 200 m survey line data and the 2000 m tie-line data, across the area defined by the tie-line survey is shown in Figure 30. Both data sets have been gridded using a Natural Neighbour technique and a grid interval of 500 m.

^{137}Cs data (KBqm^{-2}) and the FID channel were exported from the master Geosoft database as an XYZ file, and then converted to a table (.tbl). Headers were corrected in the table in line with the Geosoft conventions for tables. The final ^{137}Cs channel was then merged into the delivered radiometrics databases for each block using a single channel table look-up. These databases were themselves exported as Geosoft XYZ files for delivery to TELLUS.

The Version 1 Cs data was delivered as file Cs_revised.xyz on 12 September 2006. No README file was supplied. The initial standard sequence of radiometric channels (see Section 3) obtained from the Version 2 radiometric processing (see previous Section) is followed by the Cs channel in KBqm^{-2}. The Cs channel only has been masked to omit portions of the data set where the altitude (RALT) exceeds 100 m. The masking is achieved using dummy values for the Cs channel.

Subsequently, Version 2 Cs data was delivered in early March 2007. The file (Cs137_V2M_Revised_Alt(160)_Clip.XYZ) and README_channels_Rad_Cs.txt file are dated 02/03/2007. These data have been masked to omit portions of the data set where the altitude (RALT) exceeds 160 m.

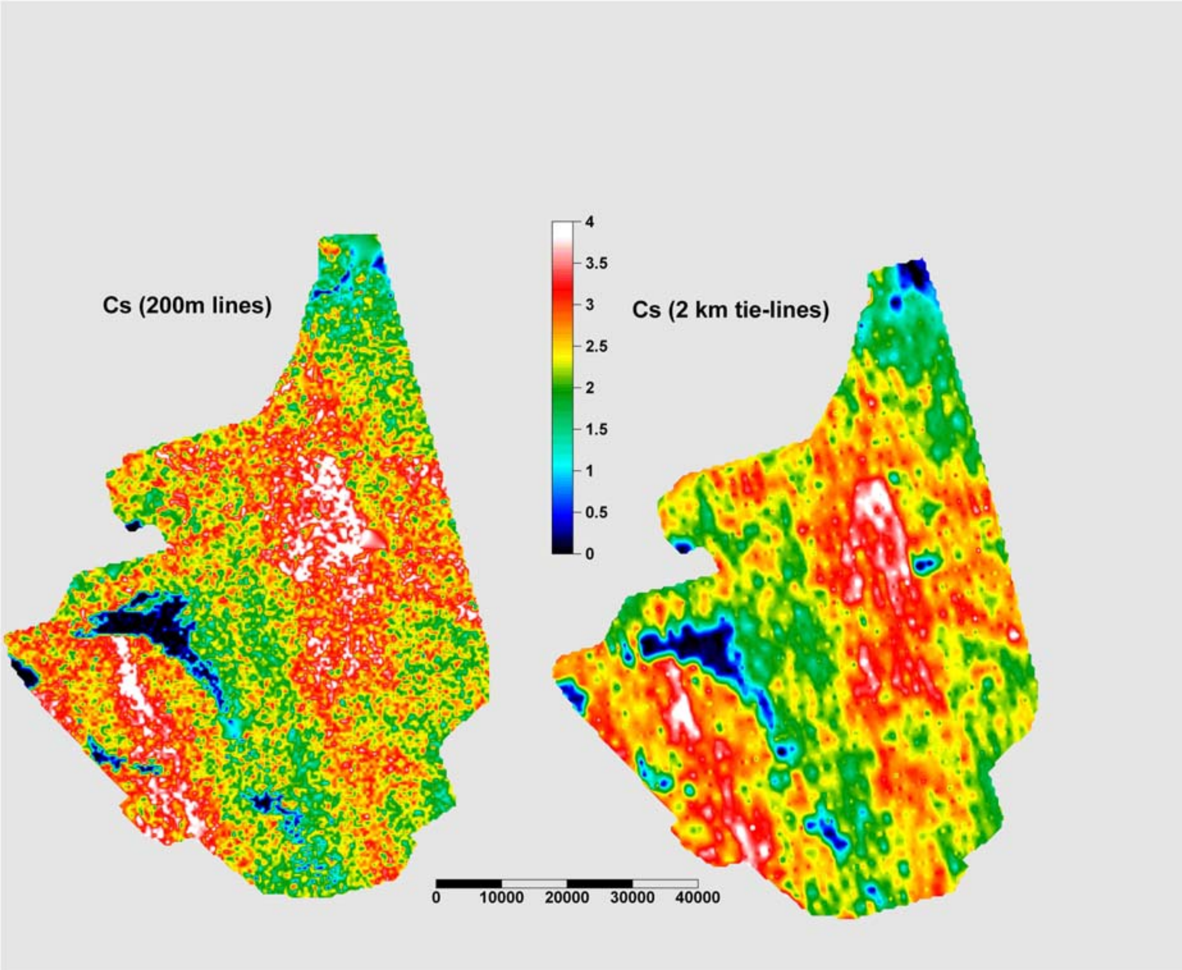


Figure 30. *Comparison of ^{137}Cs (KBqm^{-2}) for Block A and B tie-line area.*

Version 1 and Version 2 ^{137}Cs data is not yet calibrated to ground gamma spectrometry measurements. The assumption made in the PRAGA3 software is that there is an exponential vertical distribution of ^{137}Cs (highest at surface, decreasing down the soil profile). In reality, the distribution is likely to have sub-surface peaks, reflecting movement down the soil profile of ^{137}Cs and soil development since the peak of weapons testing fallout and the Chernobyl release of 1986.

Although out with the JAC remit, ground gamma spectrometry was carried out in May 2006, and October 2006. After assessment of this ground data, it is possible that the delivered TELLUS ^{137}Cs data will be adjusted to match ground values. This will result in a shift only, so the relative patterns of ^{137}Cs observed in Version 1 data will be maintained.

5.2.2 Further investigations

Following discussions with the client, it was suggested a processing sequence using the spectral averages from each individual block, might form a check on the results obtained above.

Each block was then individually processed in separate PRAGA3 projects. Within each season, all parameters for each block were kept identical with only the stripping ratios being changed between the seasons. Figure 31 shows floating blocks of this separately processed data, individually gridded and individually displayed using the standard Geosoft histogram equalisation display option. Hence colours (or strictly values) are not comparable block to block, but this does show that the same pattern exists when blocks are individually processed and displayed as floating blocks (i.e. no problems are created by overlapping data at block edges and ends) as when the data was processed by entire seasons. Note as the data are unmasked for height, high-fly areas show very low levels of ^{137}Cs because the method does not work at that height (see the Belfast area).

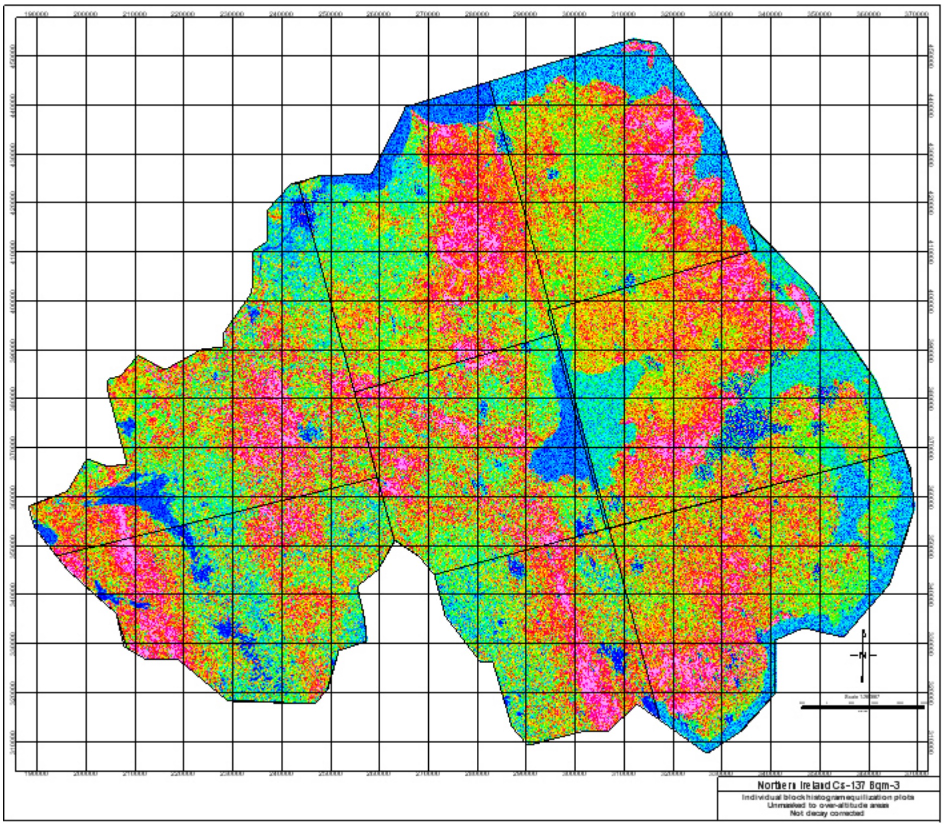


Figure 31. ^{137}Cs Floating blocks (blocks show individual histogram equalisation maps) with no correction for decay.

Block C1 has a band of higher ^{137}Cs that looks like the block boundary in the absence of a block boundary line. Figure 32 shows block C1 clipped to the ideal block showing that this Cs feature is within the block, not on the edge. The block also shows topography related Cs highs and Cs along the coast, which is clearly worth further investigation

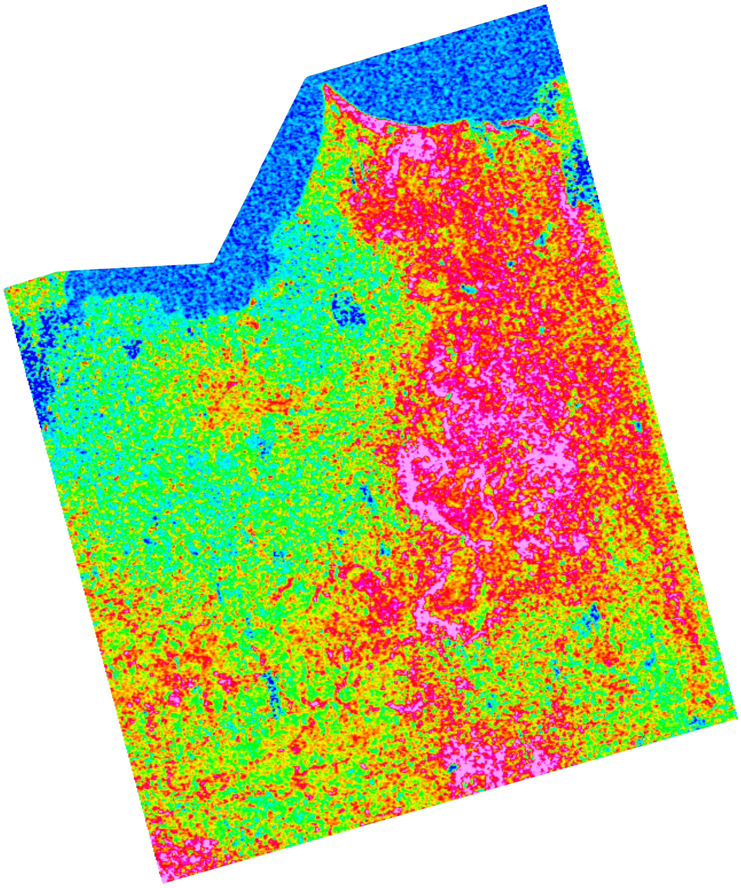


Figure 32. Block C1 ^{137}Cs, clipped to ideal block area.

During the PRAGA processing for ^{137}Cs, K, U and Th are also processed using the least squares fitting method. Although there would be more work to do to finalise these results (e.g. radon removal for the uranium channel) the results are very similar to the results produced using the standard window processing method used by JAC to deliver the K, U and Th data (Figures 33-36).

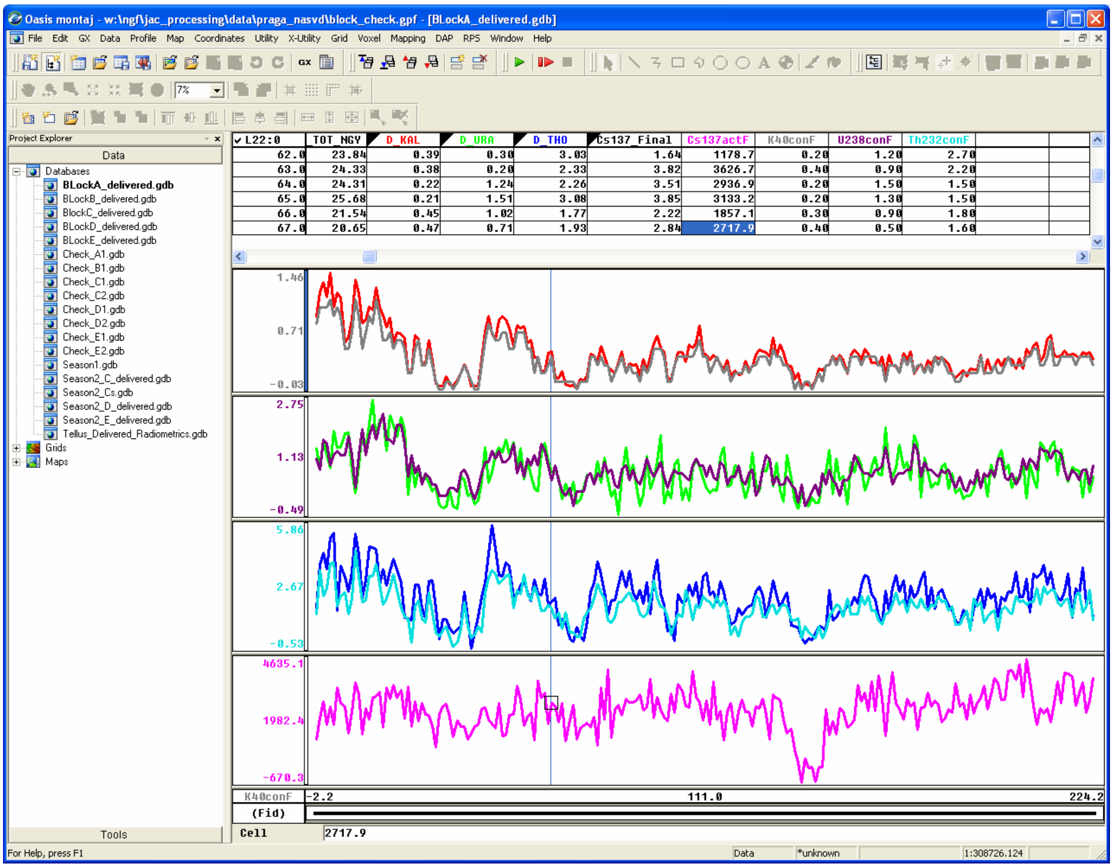


Figure 33. Example line profiles showing: Top panel- JAC processed K (red) Praga processed K (grey); JAC processed U (green) Praga processed U (purple); JAC processed Th (dark blue) Praga processed Th (Light blue). Panels set to scale the same for each profile.

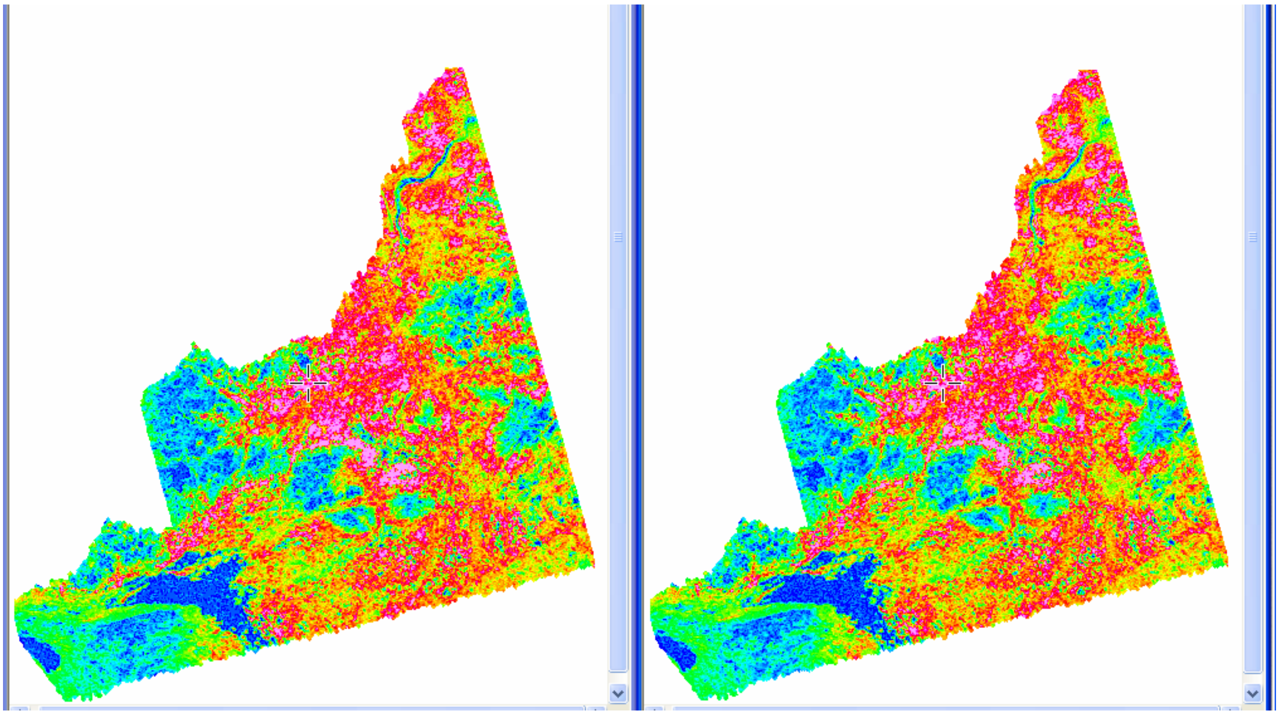


Figure 34. Left image: Praga processed K; Right image: JAC processed K.

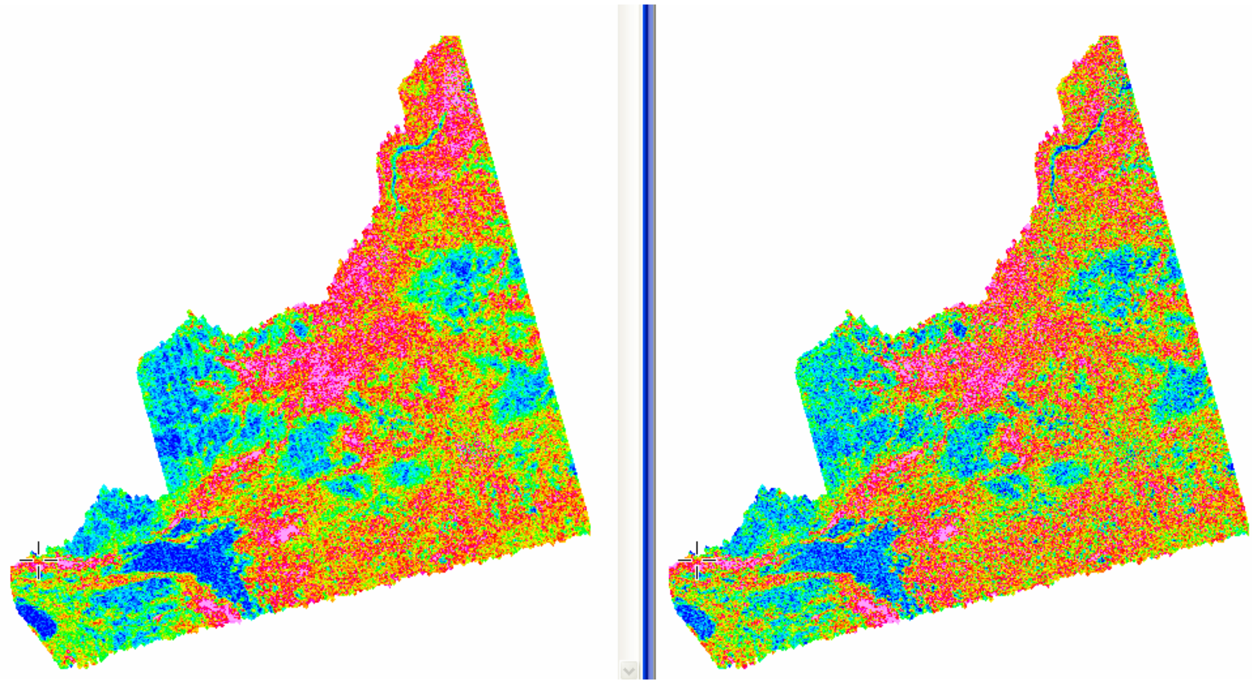


Figure 35. Left image: Praga processed U (radon not removed hence the stripes); Right image: JAC processed U.

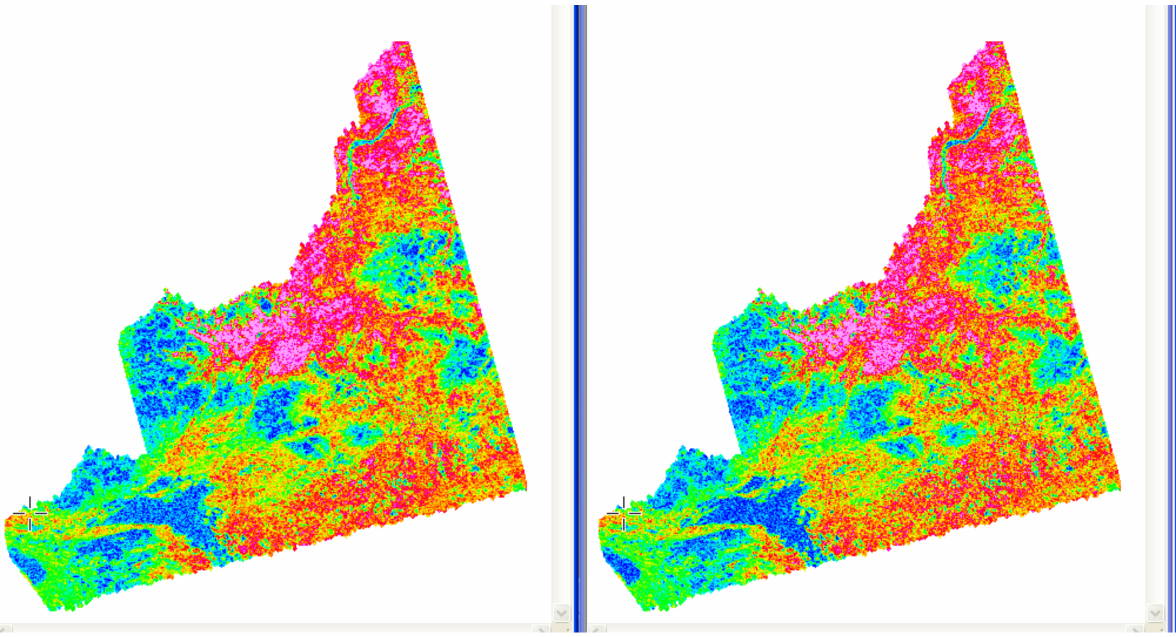


Figure 36. Left image: Praga processed Th; Right image: JAC processedTh.

5.3 ELECTROMAGNETIC PROCESSING

The Version 2 electromagnetic data comprise a combined data set (.xyz) across the whole survey area (8 Blocks). This, again, is in contrast to Version 1 data (.xyz) which comprised individual blocks.

Version 2 data have been combined across all 8 eight blocks using data processed within 8 individual, non-overlapping blocks. The overlapping/common lines (1214, 1215; 2214,2215; 3214,3125) allowed us to assess the level differences/issues arising from the 2-year acquisition of the data, using different frequencies. The motivation of Version 2 processing has been to deliver a ‘uniform’ set of EM data across all 8 blocks.

The Version 1 data were acquired as a 2-frequency (3125, 14368 Hz) data set across Blocks A, B, C1, D1 and E1 together with 4-frequency (900, 3005, 11962 and 24510 Hz) data set across Blocks C2, D2 and E2. The purpose of the Version 2 processing has been to amalgamate a low frequency data set (3125 and 3005 Hz) and a high frequency data set (14368 and 11962 Hz) across the whole 8 blocks. To our knowledge, this procedure has never before been required and/or attempted.

Prior to the production of Version 2 data, it was observed that – for reasons we were unable to establish – the data (EM coupling ratios) from Flight 102 (Block C1) were significantly out of level. It was therefore decided to adjust them by the following values:

	RE_3125	IM_3125	RE_14368	IM_14368
Flight 102	150	100	1200	50

Following this modification, the main procedures applied to the production of the Version 2 data were:

- Starting with the unlevelled coupling ratios from the 8 non-overlapping blocks (Version 1 data), the coupling ratios for low frequency (3125, 3005 Hz) were adjusted (an amplitude shift) to obtain a balanced result across the whole area. This was done separately for each of the two coupling ratios (real and imaginary). This was then repeated for the high frequency (14368 and 11962 Hz) data sets. The procedure was manual and iterative and required value judgements to be made. The procedure (the application of DC shifts to each of the coupling ratios within a Block) provided a balanced, composite data set of coupling ratios across the whole survey area.

- Following the descriptions of procedures applied to the Version 1 data, these data were then subjected to a) microlevelling, b) estimation of apparent resistivity and apparent depth and c) microlevelling of apparent resistivity and apparent depth.

In practice, the initial procedure required repeated feedback from the second stage calculation of apparent resistivities, in order to be successful. The main judgement made was in terms of the balance of apparent resistivities/conductivities across the whole survey area. This is because the coupling ratios depend on survey altitude and line-to-line and within-line altitude variations are inevitable making attempts to balance the values across block boundaries difficult and hazardous.

The rationale behind the procedure is straightforward. The procedure applies a constant offset to coupling ratio values within an entire block. Each (Version 1) data set has been separately levelled using a procedure that is not, and cannot be, exact. Within the 8 Blocks, a statistical ‘true’ value of the zero level of each data set is likely to exist. The procedures applied use manual method of adjustments to establish a more realistic (on balance) estimate of this zero level, for all 8 Blocks of data.

Considering the issues described above, wherever it was judged appropriate, the data of some blocks were adjusted by simple DC shifts, i.e., adding a single number to all data in a block to bring them in line with the overall level. The adjusted values, d_{adj}, are then related to the original values, d, through the relationship: $d_{adj} = d + c$, where c is the DC level shift. The adjustments applied to the data of all 8 blocks are summarised in the following table (Table 9):

	RE_LF (3125/3005)	**IM_LF (3125/3005)**	**RE_HF (14368/11962)**	**IM_HF (14368/11962)**
A	100	100	0	0
B	300	300	500	200
C1	0	100	0	0
D1	100	100	0	0
E1	0	100	0	0
C2	0	0	0	0
D2	0	0	300 (only if RALT<110m)	0
E2	0	0	0	0

Table 9. Definitions of dc offsets (in ppm) applied to the Version 1 coupling ratios, to provide Version 2 data at two frequencies (low=LF and high=HF).

It can be noted that in Block D2, an RALT condition was used. Block D2 contains a large number of high-fly zones (both large and small scale). The RALT condition was applied to allow a more-realistic zero-level to be maintained across these zones.

The Version 1 data, in the context of Version 2 data, still constitute a valuable resource since they are fully processed but the coupling ratios have not been adjusted across blocks. In this sense, they constitute ‘raw’ data used in the production of Version 2 data.

The data delivery is accompanied by a README_emap_v2.txt describing the data channels. The delivery includes 2 extra data channels that define the precise frequency (for each LF and HF) that should be associated with each measurement. The README_emap_v2.txt is shown below:

```
EMAP file (emap_v2.xyz) means Electromagnetic data (em) and Apparent Resistivity data (ap) from all blocks
(2005 and 2006 surveys)

        X:          Grid Easting (m)
        Y:          Grid Northing (m)
        LAT:        WGS84 latitude in decimal degrees
        LONG:       WGS84 longitude in decimal degrees
        FID:        Numerical sum of Julian day and seconds past previous midnight
        FLIGHT:     Flight number
        DATE:       Date of survey flight (YYYYMMDD)
        DAY:        Day number (Julian)
        TIME:       Time (HHMMSS.SS)
        DIR:        Flight direction (degrees clockwise)
        RALT:       Radar altitude (m)
        GPS_H:      GPS altitude (m) above geoid (WGS84)
        DTM:        Digital Terrain Model (m)
        PLM:        Power-line monitor (no units)

        RE_LF:      EM real (in-phase) component, low frequency (2005: 3125 Hz; 2006: 3005 Hz), ppm
        IM_LF:      EM imaginary (quadrature) component, low frequency (2005: 3125 Hz; 2006: 3005 Hz), ppm
        Low_Freq:   Low frequency (2005: 14368; 2006: 11962), Hz
        RE_HF:      EM real (in-phase) component, high frequency (2005: 14368 Hz; 2006: 11962 Hz), ppm
        IM_HF:      EM imaginary (quadrature) component, high frequency (2005: 14368 Hz; 2006: 11962 Hz), ppm
        High_Freq:  High frequency (2005: 14368; 2006: 11962), Hz


        LFApRes: EM apparent resistivity, low frequency (2005: 3125 Hz; 2006: 3005 Hz), ohm.m
        LFDepth: EM apparent depth, low frequency (2005: 3125 Hz; 2006: 3005 Hz), m
        HFApRes: EM apparent resistivity, high frequency (2005: 14368 Hz; 2006: 11962 Hz), ohm.m
        HFDepth: EM apparent depth, high frequency (2005: 14368 Hz; 2006: 11962 Hz), m

Note: The delivery includes 2 extra data channels that define the precise frequency (for each LF and HF) that
should be associated with each measurement.

Note: the apparent resistivity values have been clipped to a low amplitude value of 0.01 ohm.m.

Note: in _v2.xyz EMAP data sets, the EM coupling ratios (RE_LF, IM_LF, RE_HF and IM_HF) have been
microlevelled (see GTK special publication and recent microlevelling paper from Geophysics 2006).
Ideally they should have been labelled RE_LFmlev, IM_LFmlev, RE_HFmlev, IM_HFmlev. The resulting apparent
resistivities and apparent depths have also been microlevelled.

Other points concerning the data are discussed in the accompanying processing report.
```

5.3.1 Note on TELLUS EM data

The EM data and derived half-space models obtained across Northern Ireland are subject to a variety of distortions due to electromagnetic interference. The interference was most acute in Block D2 in the vicinity of Belfast, the Kilroot power station and associated power distribution routes. These are an inevitable consequence of acquiring active EM data in a populated region. The general distribution of EM distortions can be seen in Figures 37 and 38. The figures show the 3 kHz and 14 kHz apparent conductivity distribution as a 3D perspective view. High values (e.g. seawater) have been clipped to a value of 250 mS/m to aid visualisation. Individual spikes in the west of the survey area translate to a far more pervasive distribution, connected to the power distribution grid, in the east. Other high amplitude features are geological in origin (e.g. Omagh thrust and Moffat shales, assumed).

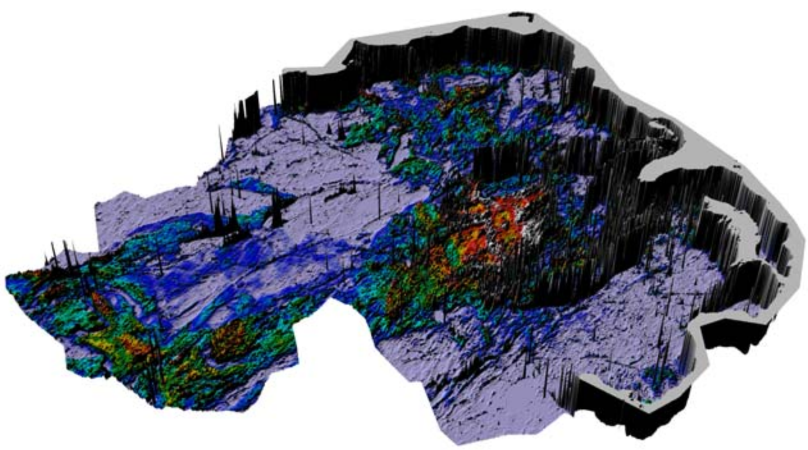


Figure 37. 3D perspective view of 3 kHz apparent conductivity.

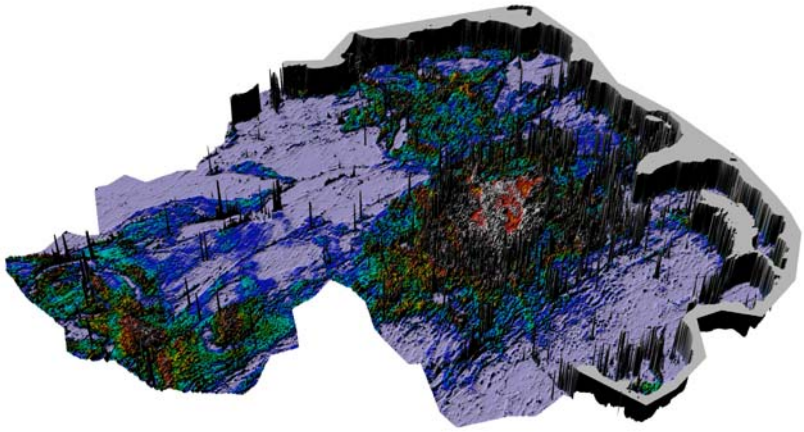


Figure 38. 3D perspective view of 14 kHz apparent conductivity

5.3.2 The Season 2 4-frequency electromagnetic data set

The Season 2 data were acquired as a 4-frequency (912, 3005, 11962 and 24510 Hz) data set across Blocks C2, D2 and E2. The combined data set (.xyz) across the 3 blocks includes data that were processed within 3 individual non-overlapping blocks. These data provide the complete 4-frequency data set from Season 2, including the lowest and highest frequencies that were not included in the Version 2 data set that covered the whole of Northern Ireland.

The main procedures applied to the production of the 4-frequency data set were:

Starting with the unlevelled coupling ratios from the 3 non-overlapping blocks, the coupling ratios for each frequency were adjusted (an amplitude shift) to obtain a balanced result across the whole area. This was done separately for each of the two coupling ratios (real and imaginary). The procedure was manual and iterative and required value judgements to be made. The procedure (the application of DC shifts to each of the coupling ratios within a Block) provided a balanced, composite data set of coupling ratios across the whole survey area.

Following the aforementioned adjustments the data were then subjected to: a) microlevelling, b) estimation of apparent resistivity and apparent depth and c) microlevelling of apparent resistivity and apparent depth.

In practice, the initial procedure required repeated feedback from the second stage calculation of apparent resistivities, in order to be successful. The main judgement made was in terms of the balance of apparent resistivities/conductivities across the whole survey area. This is because the coupling ratios depend on survey altitude and line-to-line and within-line altitude variations are inevitable making attempts to balance the values across block boundaries difficult and hazardous.

The rationale behind the procedure is straightforward. The procedure applies a constant offset to coupling ratio values within an entire block. Each data set has been separately levelled using a procedure that is not, and cannot be, exact. Within the 3 Blocks, a statistical 'true' value of the zero level of each data set is likely to exist. The procedures applied use manual method of adjustments to establish a more realistic (on balance) estimate of this zero level, for all 3 Blocks of data.

Considering the issues described above, wherever it was judged appropriate, the data of some blocks were adjusted by simple DC shifts, i.e., adding a single number to all data in a block to bring them in line with the overall level. The adjusted values, d_{adj}, are then related to the original values, d, through the relationship: $d_{adj} = d + c$, where c is the DC level shift. The adjustments were only applied to data obtained at a flying altitude less than 120 meters, so that high-fly zones with low signal did not increase in value and produce erroneous conductive zones. The adjustments applied to the data of all 8 blocks are summarised in the following table:

RALT<120m	**RE09**	**IM09**	**RE3**	**IM3**	**RE12**	**IM12**	**RE25**	**IM25**
C2	-50	200	50	50	0	0	300	300
D2	-50	200	50	50	0	0	300	300
E2	0	0	0	0	0	0	0	0

Table 10. Definitions of dc offsets (in ppm) applied to the Version 1 coupling ratios, to provide Version 2 data at 4 frequencies.

The data delivery is accompanied by a README_emap_s2_4f.txt describing the data channels. The README_emap_s2_4f.txt is shown below:

```
EMAP file (EMAP_Season2_4f_060207.xyz) means Electromagnetic data (em) and
Apparent Resistivity data (ap)
from Season 2 blocks (2006 survey) for all 4 frequencies.
The data cover Tellus Blocks C2, D2 and E2.

        X:          Grid Easting (m)
        Y:          Grid Northing (m)
        LAT:        WGS84 latitude in decimal degrees
        LONG:       WGS84 longitude in decimal degrees
        FID:        Numerical sum of Julian day and seconds past previous midnight
        FLIGHT:     Flight number
        DATE:       Date of survey flight (YYYYMMDD)
        DAY:        Day number (Julian)
        TIME:       Time (HHMMSS.SS)
        DIR:        Flight direction (degrees clockwise)
        RALT:       Radar altitude (m)
        GPS_H:      GPS altitude (m) above geoid (WGS84)
        DTM:        Digital Terrain Model (m)
        PLM:        Power-line monitor (no units)

        RE09:       EM real (in-phase) component, 912 Hz, ppm
        IM09:       EM imaginary (quadrature) component, 912 Hz, ppm
        RE3:        EM real (in-phase) component, 3005 Hz, ppm
        IM3:        EM imaginary (quadrature) component, 3005 Hz, ppm
        RE12:       EM real (in-phase) component, 11962 Hz, ppm
        IM12:       EM imaginary (quadrature) component, 11962 Hz, ppm
        RE25:       EM real (in-phase) component, 24510 Hz, ppm
        IM25:       EM imaginary (quadrature) component, 24510 Hz, ppm


        F1ApRes: EM apparent resistivity, frequency 1 (912 Hz), ohm.m
        F1Depth: EM apparent depth, frequency 1 (912 Hz), m
        F2ApRes: EM apparent resistivity, frequency 2 (3005 Hz), ohm.m
        F2Depth: EM apparent depth, frequency 2 (3005 Hz), m
        F3ApRes: EM apparent resistivity, frequency 3 (11962 Hz), ohm.m
        F3Depth: EM apparent depth, frequency 3 (11962 Hz), m
        F4ApRes: EM apparent resistivity, frequency 4 (24510 Hz), ohm.m
        F4Depth: EM apparent depth, frequency 4 (24510 Hz), m

Note: the apparent resistivity values have been clipped to a low amplitude value of 0.01 ohm.m.

Note: in _s2_4f.xyz EMAP data sets, the EM coupling ratios (RE09, IM09, RE3, IM3, RE12, IM12, RE25
 and IM25) have been microlevelled (see GTK special publication and recent microlevelling paper from
 Geophysics 2006).
Ideally they should have been labelled RE09mlev, IM09mlev, RE3mlev, IM3mlev, RE12mlev, IM12mlev,
RE25mlev, IM25mlev. The resulting apparent resistivities and apparent depths have also been microlevelled.

Other points concerning the data are discussed in the accompanying processing report.
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5.4 MAGNETIC PROCESSING

Magnetic data often require microlevelling to remove high frequency corrugation observed line to line, with wavelengths of the order of 1 to 2 times line spacing. The JAC philosophy is not to filter data any more than is deemed necessary and so microlevelling is not routinely performed. However, microlevelling was requested for Tellus and so a robust method of microlevelling was investigated. There are a number of ways in which microlevelling can be performed, with two common methods being:

1) Frequency domain decorrugation (see Geosoft Technical Note; Microlevelling Using FFT Decorrugation)
2) Regional/residual separation (see Geosoft Technical Note; Microlevelling using Bi-directional Gridding)

Technique (1) employs a directional cosine filter with a wavelength of a harmonic of line spacing. The limitations of the technique are well understood by JAC. However, it is designed to work on regularly spaced data. The twin magnetometer set-up of the aircraft means that for Tellus Season 1 data (2 frequency EM configuration), considering left and right magnetometers as separate flight lines results in a line spacing of 23 – 177 – 23 – 177 etc; for the Season 2 configuration, line spacing is 10.7 – 189.3 – 10.7 – 189.3 etc. The irregular nature of the line spacing means that the filter length has to be chosen based on the smaller of the two line spacings, which results in the non-identification of corrugation in the 200m spaced data.

Technique (1) performs a directional cosine filter on a grid of magnetic data. Convention states that grid cell size can be between 1/4 and 1/5 line spacing, and is usually set at 50 metres for 200m line-spaced data. Such a grid cell size means that individual representation of left and right, or left and nose, data is not achieved and that each grid cell is represented by an average of the twin magnetometer sensor. This means that the separate left and right/nose magnetometers are not being independently microlevelled and the results are often worse than the starting data.

Technique (2) is also a grid-based technique, which employs bi-directional gridding and filtering of the resultant grid. The end result is a grid of high frequency data; which is made up of high frequency geology/cultural magnetic signal, and line-to-line noise. As this technique also has the pitfalls of large grid-cells compared with sensor separation, it is also limited in application to twin magnetometer datasets.

One way of dealing with microlevelling twin-sensor data is to separate left and right/nose magnetometer data and to microlevel these independently and combine the datasets once microlevelled. This is problematic for a number of reasons:

- Data can be separated as left and right/nose; as parallel lines are not flown in the same direction the flight pattern means that the majority of lines are then spaced by 200m, but in the extreme case lines are separated by 223m (or 210.7 for nose), and 177m (or 189.3) depending on the direction of adjacent lines. Therefore data have to separated as being west and east of the ideal flight line.
- The recombining of separately microlevelled data does not result in well microlevelled data. Microlevelling aims to remove very small line-to-line corrugations, usually less than 1 nT in magnitude. The microlevelling of the two sensor data separately results in very small differences in results, which are apparent when the data are recombined.

Therefore it was concluded that it was not possible to microlevel separate left and right/nose magnetometer data, and that microlevelling would have to be performed on a single magnetometer measurement.

5.4.1 Adopted procedure

To achieve evenly spaced line based data with a common track for all three geophysical methods, the following was done:

- Season 1 configuration (left/right): The magnetic field was predicted at the centre of the aircraft as the mean of the left and right magnetometers. Testing using a number of ways of prediction showed that this was the most robust method. The mean of magnetics (MAG_MID) was achieved and the difference between the left and right magnetometers gives the cross-plane magnetic gradient (GRAD_PERP), which has to be corrected for the direction of travel. Both of these are required for microlevelling.
- Season 2 configuration (left/nose): It is desirable to achieve consistent tracks for all three geophysical methods. The mean between the left and nose magnetometers would achieve a flight line 5.35 m parallel to that of the EM and radiometrics. Therefore the nose magnetometer is used for MAG_MID, and the difference between the left and nose magnetometer is used to determine the magnetic gradient (GRAD_PERP).

The following procedure is used to achieve the microlevelled result. This is a modification of the Geosoft Technical Note on Microlevelling using Bi-directional Gridding.

5.4.1.1 Stage 1: Microlevelled magnetic gradient

The bi-directional grid approach of microlevelling yields best results when the starting magnetic grid is as good as possible. Bi-directional gridding results are usually enhanced when gradient information is used in the calculation of the grid. The cross-plane gradient can be used for these purposes and results in enhanced features, especially for features such as dykes that cross-cut the flight line obliquely. Using minimum curvature these features can appear as a series of peaks, whereas a gradient enhanced bi-directional grid shows a clear ridge feature.

Magnetic gradient data (GRAD_PERP), once corrected for flight direction (i.e. adjusted gradient so that they are all west-east), are often noisy. In low magnetic gradient regions this is due to the signal-to-noise ratio, i.e. the resultant gradient is dominated by the noise in both magnetometers as the recording is at the threshold of resolution. In addition to this level of noise, there are often “stripes” along entire line lengths. These features are resultant from magnetic correction errors and operation of non-magnetically clean devices on the aircraft. One example of the latter cause is the operation of full tank pumps mid-flight. These are not operated on line, but result in magnetic level shifts between flight lines.

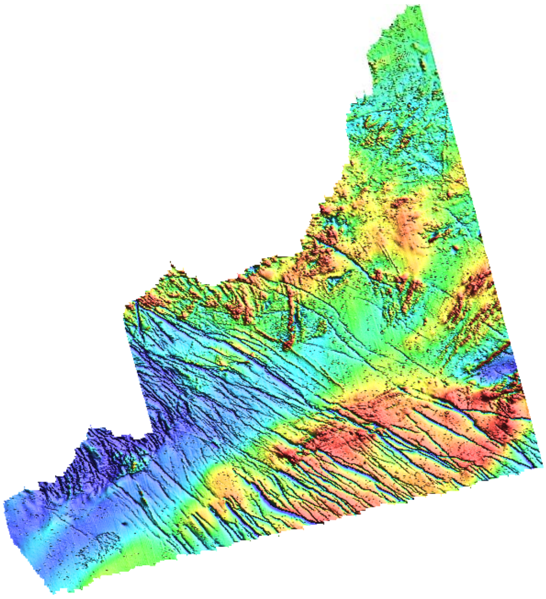
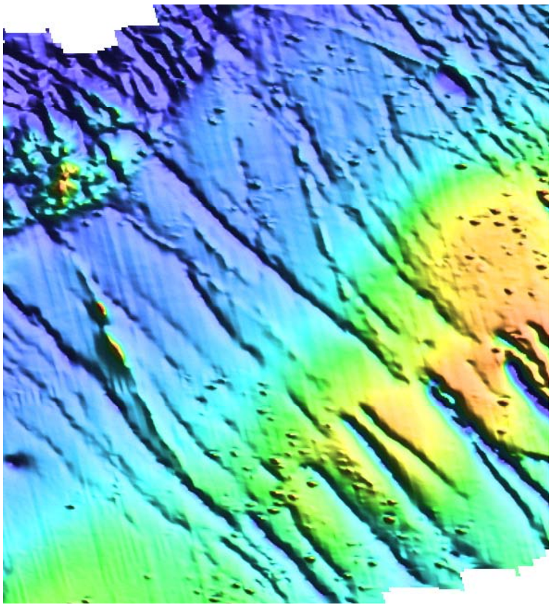
The microlevelling procedure is shown with examples in Stage 2 below. Magnetic gradient data are microlevelled using this procedure. Before levelling, gradient data is lightly filtered by a 5-point moving average spatial filter.

5.4.1.2 Stage 2: Achieving a grid of microlevelling error

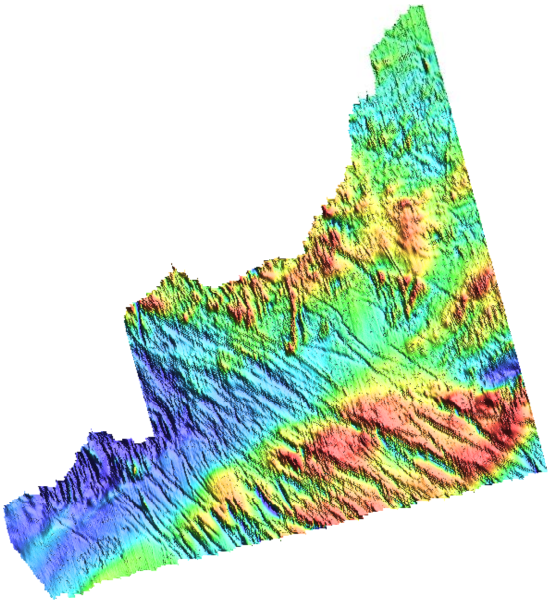
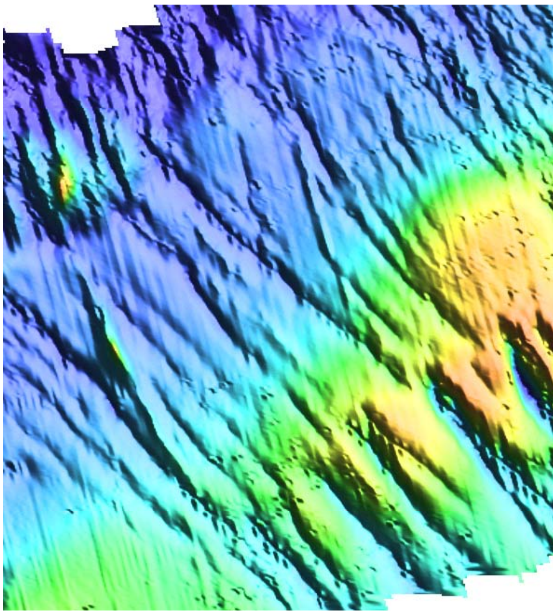
Magnetometer data are lightly filtered with a 5-point moving average spatial filter; this removes high frequency noise that is of shorter wavelength than the flying altitude, which is not possible to be observed.

The following outlines the microlevelling process with example images shown from Area A of Season 1.

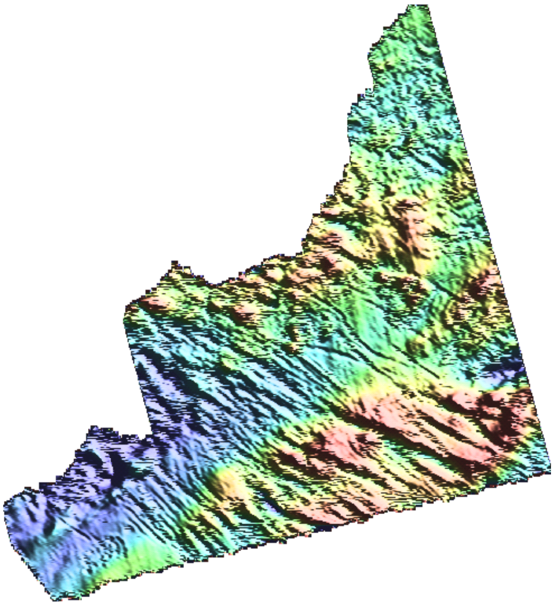
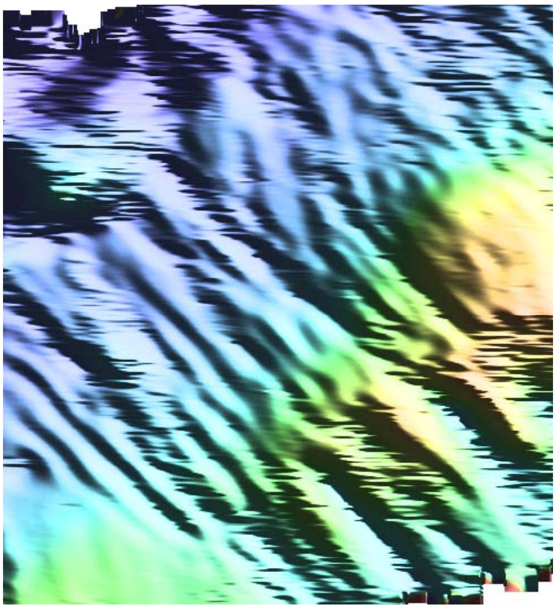
1) Magnetic data are gridded using the cross-plane gradient data to achieve a gradient-enhanced bi-directional grid with a cell size of 50m [Lev1.grd]:

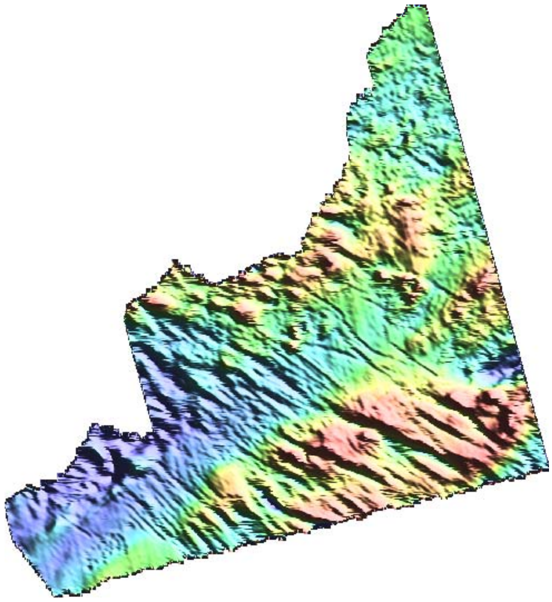
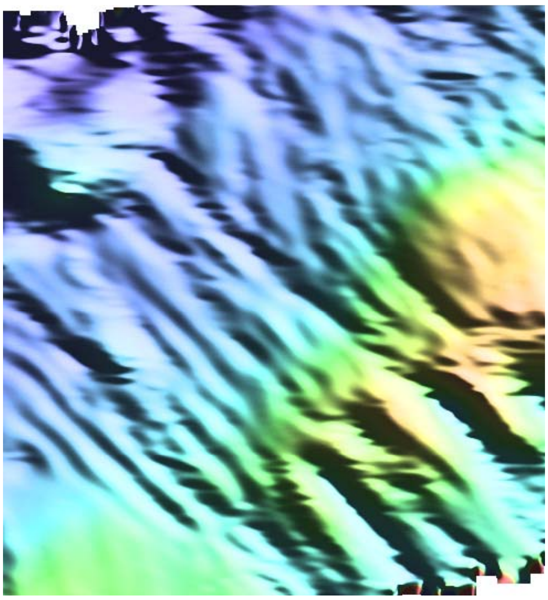
2) A second, almost identical grid is created but with a low pass filter of 4 times line separation (800m) [Lev2.grd]. This result often appears noisy:

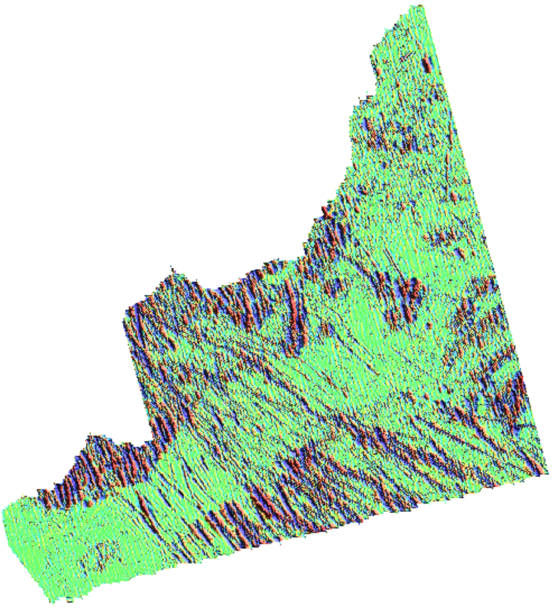
3) The Lev2.grd result is re-gridded with the same low-pass filter. The grid is also extended by a few grid cells. Care has to be taken that the grid extension does not introduce any artefacts into the final results. The re-gridding process works along the x and y axis of the grid, and results in artefacts in these orientations. These are less apparent for survey data oriented east-west or north-south, but the artefacts do not affect the final result [Lev3.grd]:

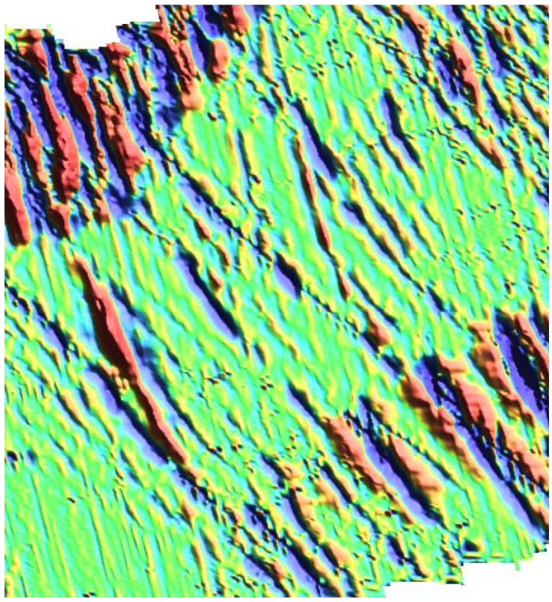



4) The Lev3.grd result is filtered for 5 passes using a 3 × 3 convolution filter [Lev4.grd], this can be seen to represent the regional magnetic field:

5) The final noise grid [Lev5.grd] is achieved by removing the regional field [Lev4.grd] from the low-pass filtered result [Lev2.grd]:





The resultant noise grid is similar to that achieved by Fourier-domain decorrugation, but the artefacts created by high amplitude, isolated or localized features are much reduced.

5.4.1.3 STAGE 3: SEPARATING SIGNAL FROM NOISE

The success of the bi-directional grid method of microlevelling is dependent on how signal and noise are isolated. The noise grid [Lev5.grd] still includes a lot of geological information, as can be seen by the obvious retention of dykes. The simple removal of the noise grid only reduces amplitude of these features slightly, but over the high amplitude magnetic anomalies of the Antrim basalts, considerable geological information would be removed.

The levelling error grid [Lev5.grd] is sampled back into the Oasis montaj database, as shown by the red profile in Figure 39. The result has an unrealistic high frequency noise component, which is removed by an 80-fiducial low-pass filter, as shown by the green profile in Figure 39.

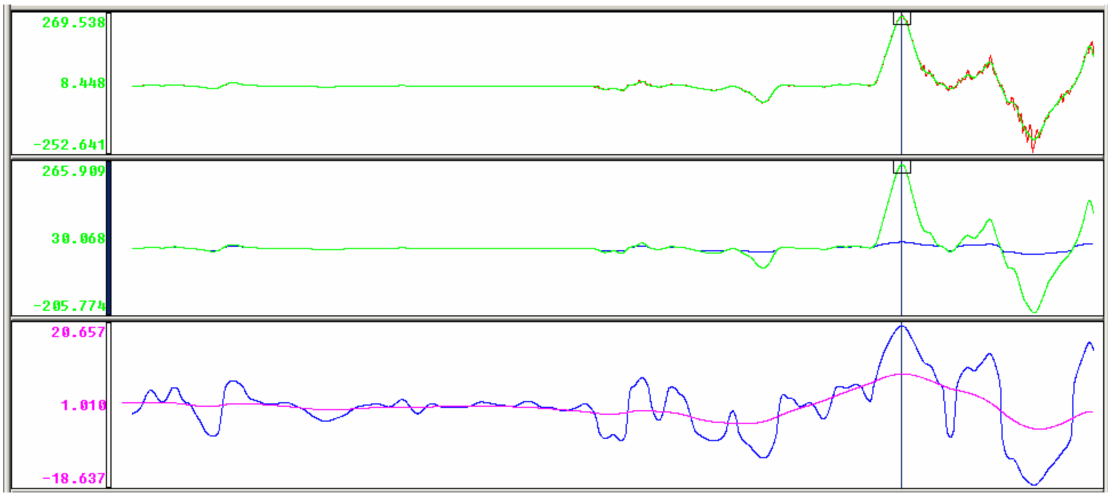


Figure 39 The separation of magnetic signal (both geological and anthropogenic) and levelleling noise. The top profile shows the imported levelling error in red, which is filtered in order to create the green profile. These data are then processed in order to reduce the amount of noise above 5 nT in amplitude, creating the blue profile shown in the middle and bottom profiles. The final estimate of levelling error is shown in magenta in the bottom profile, this is a B-spline as fitted to the blue profile data.

The problem with over-estimation of levelling error is most apparent in Area C2 where large estimates are generated in and around the basalt area. For area C the range of microlevelling error is –713 to 583 (range of 1300nT). Examination of the resultant data shows that the method attempts to remove the strong feature that outlines this area. This is clearly incorrect. Figure 39 shows that large levelling errors are estimated over the basalt areas, as highlighted by the cursor.

Examination of data from the low gradient areas shows that microlevelling errors are generally restricted to ± 5nT. Therefore an approach to "damp" the microlevelling error was investigated. A simple clip was seen as inappropriate as derivative images are likely to highlight the edges of the clip. Data above 5 nT are damped by the square root of the magnetic value above 5 nT. This greatly reduces the high amplitude features, as shown in Figure 39 by the blue profile.

A tight B-spline is fitted to the damped result to yield the microlevelling error for each line, as shown by the magenta profile in Figure 39. This long wavelength result is a good representation of all noise sources encountered.

The adopted methodology was consistent for all 8 of the survey blocks. This is important in retaining frequency characteristics between blocks. Although Northern Ireland is a relatively small area, it has considerable variation in magnetic signature; this ranges from the high frequency, high amplitude anomalies of the Antrim basalts (Area C2) to the very low wavelength features seen in Area B. The latter is complicated further by the localised, high amplitude anomalies created by the dykes of this region.

5.5 SUMMARY OF VERSION 2 DATA FILES

The files delivered as Version 2 ASCII (.xyz) data are listed in Table 11.

	Data file and date	Readme file and date
Magnetic data	Mag_Version_2_260906.xyz 26/09/2006	Mag_Version_2_Readme.txt 26/09/2006
Radiometric data	Tellus_Radiometric_Data_v2.xyz 03/11/2006	README_Tellus_Radiometric_Data_v2.txt 03/11/2006
EM 2f data	EMAP_Version2_151206.xyz 15/12/2006	README_emap_v2.txt 15/12/2006
EM 4f data	EMAP_Season2_4f_060207.xyz 06/02/2007	README_emap_s2_4f.txt 06/02/2007
Cs-137 data	Cs137_V2M_Revised_Alt(160)_Clip.XYZ 02/03/2007	README_channels_Rad_CS.txt 02/03/2007

Table 11. Version 2 delivered data files

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Geosoft Technical Note on Microlevelling using FFT Decorrugation http://www.geosoft.com/resources/technotes/pdfs/microleveling%20tech%20note.pdf

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Appendix 1

Listing of the IGRF used in the processing of the Tellus magnetic data.

```
/-----------------------------------------------------------------------------
/
/ IGRF
/
/ International Geomagnetic Reference Field
/
/ Reference:   Geomagnetic Field Models and Synthesis Software
/              Geomagnetic Data Group
/              National Geophysical Data Center
/              Code E/GC1
/              325 Broadway
/              Boulder, Colorado, 80303
/              Phone 303-497-6478
/              Web site: www.ngdc.noaa.gov
/              E-mail: smclean@ngdc.noaa.gov
/
/-----------------------------------------------------------------------------

year 1945
 -30634.0    0.0   12.6    0.0
  -2240.0 5806.0   -0.2    0.2
  -1215.0    0.0  -23.0    0.0
   2972.0 -1700.0   1.2  -22.6
   1588.0  497.0   -1.8  -21.8
   1274.0    0.0    3.8    0.0
  -1833.0 -512.0   -9.0    5.4
   1225.0  185.0    9.2    8.6
    926.0   -5.0   -7.2  -12.4
    980.0    0.0   -1.0    0.0
    771.0  155.0    4.8    3.2
    544.0 -280.0   -2.4   -5.2
   -408.0  -68.0    1.2    3.4
    300.0 -158.0    2.0   -5.2
   -286.0    0.0    6.2    0.0
    341.0  -14.0    2.8    1.2
    207.0   80.0   -1.2    4.2
    -25.0  -65.0    4.4   -6.0
   -156.0 -114.0   -0.8    2.8
    -88.0   83.0    2.4   -2.0
     68.0    0.0   -2.2    0.0
     67.0    9.0   -3.4   -2.0
      6.0  118.0    1.8   -3.6
   -244.0   18.0   -3.4    6.8
    -12.0   -9.0    4.0    0.4
     14.0  -12.0   -1.2   -1.0
   -100.0  -42.0   -1.6    4.2
     72.0    0.0   -1.0    0.0
    -61.0  -42.0    2.6   -0.4
      6.0  -39.0   -1.8    4.2
      6.0    2.0    2.0   -1.6
    -44.0   -1.0    1.2   -1.4
     -2.0   25.0    0.6    1.4
     18.0  -19.0   -1.8    0.2
     27.0  -23.0   -3.2    0.2
     15.0    0.0    0.2    0.0
      5.0   -7.0   -0.2    1.8
    -12.0    9.0    0.8   -2.2
    -21.0    0.0   -2.0   -0.6
     18.0  -13.0   -0.6    1.2
     16.0    5.0   -1.6    0.2
    -14.0   26.0   -0.6    0.2
      1.0    1.0    1.2   -1.4
     10.0  -19.0    0.6   -0.6
year 1950
 -30571.0    0.0   12.8    0.0
  -2241.0 5807.0   21.4   -2.2
  -1330.0    0.0  -20.4    0.0
   2978.0 -1813.0   3.4  -16.6
   1579.0  388.0   -2.4  -25.0
   1293.0    0.0    3.0    0.0
  -1878.0 -485.0  -15.4   -0.4
   1271.0  228.0    4.4    1.4
    890.0  -67.0    1.4   -1.2
    975.0    0.0   -2.2    0.0
    795.0  171.0   -0.2   -0.8
    532.0 -306.0   -4.4    6.2
   -402.0  -51.0    2.0    1.4
    310.0 -184.0   -3.6  -13.0
   -255.0    0.0    4.6    0.0
    355.0   -8.0    1.0    4.4
    201.0  101.0    7.2    2.0
     -3.0  -95.0   -2.0    1.0
   -160.0 -100.0   -3.2   -2.2
    -76.0   73.0    1.6    0.8
     57.0    0.0   -2.0    0.0
     50.0   -1.0    1.4   -1.2
     15.0  100.0   -2.2    0.2
   -261.0   52.0    2.2   -1.2
      8.0   -7.0    0.8   -1.8
      8.0  -17.0    1.0    2.2
   -108.0  -21.0    0.6    0.0
     67.0    0.0    2.6    0.0
    -48.0  -44.0   -3.6   -1.6
     -3.0  -18.0    1.0   -3.8
     16.0   -6.0   -2.4    2.4
    -38.0   -8.0   -1.6    1.4
      1.0   32.0   -3.2   -0.6
      9.0  -18.0   -0.2   -0.4
     11.0  -22.0    0.6    2.0
     16.0    0.0   -2.2    0.0
      4.0    2.0    2.6    2.0
     -8.0   -2.0    1.0    0.6
    -31.0   -3.0    0.2    2.6
     15.0   -7.0   -0.2   -2.6
      8.0    6.0    3.8   -0.2
    -17.0   27.0    0.4    1.4
      7.0   -6.0   -1.2    2.0
     13.0  -22.0   -0.2    0.6
year 1955
 -30507.0    0.0   19.2    0.0
  -2134.0 5796.0   -5.6   -3.2
  -1432.0    0.0  -22.8    0.0
   2995.0 -1896.0   2.4  -10.4
   1567.0  263.0    1.0  -10.8
   1308.0    0.0   -0.2    0.0
  -1955.0 -487.0   -6.4   13.2
   1293.0  235.0   -1.0   -1.0
    897.0  -73.0   -3.6  -11.4
    964.0    0.0   -0.4    0.0
    794.0  167.0    2.0   -3.4
    510.0 -275.0   -3.6    0.6
   -392.0  -44.0    0.0    9.0
    292.0 -249.0   -5.0   -1.0
   -232.0    0.0   -0.8    0.0
    360.0   14.0   -0.4   -0.4
    237.0  111.0   -1.6    2.0
    -13.0  -90.0   -4.2   -5.0
   -176.0 -111.0    4.6    1.0
    -68.0   77.0    0.8    1.2
     47.0    0.0    0.0    0.0
     57.0   -7.0   -0.2   -1.2
      4.0  101.0   -1.4    1.0
   -250.0   46.0    1.8    1.8
     12.0  -16.0   -1.8   -2.0
     13.0   -6.0   -1.8   -0.8
   -105.0  -21.0   -0.6    1.0
     80.0    0.0   -1.6    0.0
    -66.0  -52.0    2.8   -0.2
      2.0  -37.0    0.4    2.4
      4.0    6.0    1.4   -2.8
    -46.0   -1.0    5.2    0.8
    -15.0   29.0    2.2   -0.2
      8.0  -20.0    1.4    0.8
     14.0  -12.0   -1.6   -1.2
      5.0    0.0    0.2    0.0
     17.0   12.0   -2.6   -1.0
     -3.0    1.0    0.0   -3.4
    -30.0   10.0    3.4   -1.0
     14.0  -20.0   -3.8    0.2
     27.0    5.0   -3.4    0.0
    -15.0   34.0    1.8   -2.2
      1.0    4.0    2.8   -1.2
     12.0  -19.0   -1.4    0.2
year 1960
 -30411.0    0.0   15.4    0.0
  -2162.0 5780.0    8.6   -0.8
  -1546.0    0.0  -23.2    0.0
   3007.0 -1948.0  -2.0  -13.6
   1572.0  209.0    4.4  -19.0
   1307.0    0.0   -2.0    0.0
  -1987.0 -421.0  -10.2    3.4
   1288.0  230.0    0.8    2.0
    879.0 -130.0   -4.6   -7.0
    962.0    0.0   -1.0    0.0
    804.0  150.0    0.0   -0.4
    492.0 -272.0   -2.6    0.6
   -392.0    1.0    0.4    2.4
    267.0 -254.0   -3.0   -3.0
   -236.0    0.0    3.4    0.0
    358.0   12.0    0.0    1.4
    229.0  121.0    5.0    1.4
    -34.0 -115.0    0.6   -2.2
   -153.0 -106.0   -0.8    1.8
    -64.0   83.0    0.4   -0.4
     47.0    0.0   -0.4    0.0
     56.0  -13.0    1.0    0.4
     -3.0  106.0    2.2   -1.2
   -241.0   55.0    2.6    2.6
      3.0  -26.0    0.2   -1.2
      4.0  -10.0   -0.6    0.4
   -108.0  -16.0   -0.6    1.8
     72.0    0.0    0.6    0.0
    -52.0  -53.0   -1.0   -1.6
      4.0  -25.0    0.0   -0.4
     11.0   -8.0    0.4    1.2
    -20.0    3.0   -1.2    0.6
     -4.0   28.0   -0.4   -0.4
     15.0  -16.0   -0.4   -1.4
      6.0  -18.0   -1.0    1.2
      6.0    0.0    1.4    0.0
      4.0    7.0    0.2    0.0
     -3.0  -16.0   -0.2    0.8
    -13.0    5.0   -0.2    0.8
     -5.0  -19.0    1.0    0.6
     10.0    5.0   -0.4   -0.2
     -6.0   23.0    1.0    0.2
     15.0   -2.0   -0.8   -0.2
      5.0  -18.0   -0.2    0.2
year 1965
 -30339.0    0.0   15.3    0.0
  -2123.0 5758.0    8.7   -2.3
  -1654.0    0.0  -24.4    0.0
   2994.0 -2006.0   0.3  -11.8
   1567.0  130.0   -1.6  -16.7
   1297.0    0.0    0.2    0.0
  -2036.0 -403.0  -10.8    4.2
   1289.0  242.0    0.7    0.7
    843.0 -176.0   -3.8   -7.7
    958.0    0.0   -0.7    0.0
    805.0  149.0    0.2   -0.1
    492.0 -280.0   -3.0    1.6
   -392.0    8.0   -0.1    2.9
    256.0 -265.0   -2.1   -4.2
   -223.0    0.0    1.9    0.0
    357.0   16.0    1.1    2.3
    246.0  125.0    2.9    1.7
    -26.0 -123.0    0.6   -2.4
   -161.0 -107.0    0.0    0.8
    -51.0   77.0    1.3   -0.3
     47.0    0.0   -0.1    0.0
     60.0  -14.0   -0.3   -0.9
      4.0  106.0    1.1   -0.4
   -229.0   68.0    1.9    2.0
      3.0  -32.0   -0.4   -1.1
     -4.0  -10.0   -0.4    0.1
   -112.0  -13.0   -0.2    0.9
     71.0    0.0   -0.5    0.0
    -54.0  -57.0   -0.3   -1.1
     -0.0  -27.0   -0.7    0.3
     12.0   -8.0   -0.5    0.4
    -25.0    9.0    0.3    0.2
     -9.0   23.0   -0.0    0.4
     13.0  -19.0   -0.2    0.2
     -2.0  -17.0   -0.6    0.3
     10.0    0.0    0.1    0.0
      9.0    3.0    0.4    0.1
     -3.0  -13.0    0.6   -0.2
    -12.0    5.0    0.0   -0.3
     -4.0  -17.0   -0.0   -0.2
      7.0    4.0   -0.1   -0.3
     -5.0   22.0    0.3   -0.4
     12.0   -3.0   -0.3   -0.3
      6.0  -16.0   -0.5   -0.3
year 1970
 -30220.0    0.0   24.0    0.0
  -2068.0 5737.0   11.0  -12.4
  -1781.0    0.0  -24.2    0.0
   3000.0 -2047.0   2.0   -4.0
   1611.0   25.0    4.2  -18.6
   1287.0    0.0   -2.2    0.0
  -2091.0 -366.0  -10.6    6.6
   1278.0  251.0   -3.6    2.2
    838.0 -196.0   -1.6   -5.4
    952.0    0.0   -1.2    0.0
    800.0  167.0   -1.8    4.8
    461.0 -266.0   -4.6    0.2
   -395.0   26.0   -2.0    2.6
    234.0 -279.0   -3.6   -1.8
   -216.0    0.0   -0.4    0.0
    359.0   26.0   -0.6    1.0
    262.0  139.0    0.4    1.8
    -42.0 -139.0   -3.4   -2.6
   -160.0  -91.0    0.2    1.6
    -56.0   83.0    1.4    1.0
     43.0    0.0    0.4    0.0
     64.0  -12.0    0.4   -0.2
     15.0  100.0    2.6   -0.2
   -212.0   72.0    2.8    0.6
      2.0  -37.0   -0.2   -0.8
      3.0   -6.0    0.6    0.4
   -112.0    1.0    0.2    2.0
     72.0    0.0   -0.2    0.0
    -57.0  -70.0    0.2   -1.4
      1.0  -27.0    0.0    0.2
     14.0   -4.0    0.4   -0.2
    -22.0    8.0    1.6    0.4
     -2.0   23.0    0.4   -0.2
     13.0  -23.0   -0.2    0.0
     -2.0  -11.0   -0.6   -0.2
     14.0    0.0    0.0    0.0
      6.0    7.0    0.0   -0.2
     -2.0  -15.0    0.2   -0.2
    -13.0    6.0    0.2   -0.4
     -3.0  -17.0   -1.0   -0.4
      5.0    6.0   -0.2    0.0
      0.0   21.0    0.0   -0.6
     11.0   -6.0   -0.2   -0.8
      3.0  -16.0   -0.4   -0.2
year 1975
 -30186.0    0.0   25.61    0.00
  -2036.0 5735.0    9.97  -10.19
  -1898.0    0.0  -24.95    0.00
   2997.0 -2124.0   0.73   -2.95
   1551.0  -37.0    4.29  -18.94
   1299.0    0.0   -3.75    0.00
  -2144.0 -361.0  -10.44    6.94
   1296.0  249.0   -4.06    2.48
    805.0 -253.0   -4.20   -4.97
    951.0    0.0   -0.21    0.00
    807.0  148.0   -2.00    5.02
    462.0 -264.0   -3.86    0.82
   -393.0   37.0   -2.09    1.71
```

235.0	-307.0	-3.09	-1.02
-204.0	0.0	0.26	0.00
368.0	39.0	-0.68	1.19
275.0	142.0	1.13	2.35
-20.0	-147.0	-1.63	-1.96
-161.0	-99.0	-0.49	1.34
-38.0	74.0	0.96	1.09
46.0	0.0	0.15	0.00
57.0	-23.0	0.51	-0.49
15.0	102.0	2.04	-0.12
-210.0	88.0	2.84	-0.19
-1.0	-43.0	-0.03	-1.28
-8.0	-9.0	0.87	0.75
-114.0	-4.0	-0.08	1.73
66.0	0.0	0.03	0.00
-57.0	-68.0	-0.01	-1.36
-7.0	-24.0	0.03	-0.11
7.0	-4.0	0.57	0.27
-22.0	11.0	0.89	0.27
-9.0	27.0	0.29	-0.71
11.0	-17.0	0.31	0.07
-8.0	-14.0	-0.45	0.83
11.0	0.0	0.24	0.00
13.0	4.0	0.34	-0.20
3.0	-15.0	0.05	-0.35
-12.0	2.0	0.16	-0.16
-4.0	-19.0	-0.35	-0.30
6.0	1.0	-0.32	0.44
-2.0	18.0	0.58	-0.34
9.0	-6.0	-0.34	-0.63
1.0	-19.0	-0.09	0.26

year 1980

-29992.0	0.0	23.0	0.0
-1956.0	5604.0	10.6	-21.4
-1997.0	0.0	-15.2	0.0
3027.0	-2129.0	3.6	-12.4
1663.0	-200.0	5.6	-21.8
1281.0	0.0	3.8	0.0
-2180.0	-336.0	-5.6	4.8
1251.0	271.0	-1.4	2.6
833.0	-252.0	0.4	-8.8
938.0	0.0	-0.2	0.0
782.0	212.0	-0.4	4.2
398.0	-257.0	-7.0	1.4
-419.0	53.0	-1.4	3.0
199.0	-297.0	-6.0	-0.2
-218.0	0.0	0.6	0.0
357.0	46.0	-0.2	0.2
261.0	150.0	-1.6	-0.4
-74.0	-151.0	-4.0	-0.8
-162.0	-78.0	0.2	0.6
-48.0	92.0	0.0	0.6
48.0	0.0	0.8	0.0
66.0	-15.0	-0.2	-0.2
42.0	93.0	1.6	-0.6
-192.0	71.0	1.2	-0.4
4.0	-43.0	0.0	-1.4
14.0	-2.0	0.6	-0.4
-108.0	17.0	1.2	0.6
72.0	0.0	0.6	0.0
-59.0	-82.0	-0.4	0.0
2.0	-27.0	0.0	0.2
21.0	-5.0	0.6	0.8
-12.0	16.0	1.2	1.4
1.0	18.0	0.6	-0.2
11.0	-23.0	-0.4	0.4
-2.0	-10.0	0.4	0.8
18.0	0.0	0.6	0.0
6.0	7.0	0.0	0.0
0.0	-18.0	0.0	-0.6
-11.0	4.0	0.0	0.2
-7.0	-22.0	-0.4	-0.6
4.0	9.0	-0.4	0.4
3.0	16.0	0.2	-0.8
6.0	-13.0	-0.4	-0.6
-1.0	-15.0	-1.0	1.0

year 1985

-29877.0	0.0	23.2	0.0
-1903.0	5497.0	10.0	-24.5
-2073.0	0.0	-13.7	0.0
3045.0	-2191.0	3.4	-11.5
1691.0	-309.0	7.0	-20.2
1300.0	0.0	5.1	0.0
-2208.0	-312.0	-4.6	5.3
1244.0	284.0	-0.6	2.3
835.0	-296.0	0.1	-10.8
937.0	0.0	0.1	0.0
780.0	233.0	-0.6	3.8
363.0	-250.0	-7.8	2.2
-426.0	68.0	-1.4	2.5
169.0	-298.0	-6.8	0.9
-215.0	0.0	1.3	0.0
356.0	47.0	0.1	0.1
253.0	148.0	-1.5	-0.2
-94.0	-155.0	-3.2	-0.1
-161.0	-75.0	0.1	0.6
-48.0	95.0	-0.1	0.0
52.0	0.0	1.4	0.0
65.0	-16.0	-0.3	-0.4
50.0	90.0	1.7	-1.1
-186.0	69.0	0.6	-0.8
4.0	-50.0	0.0	-2.3
17.0	-4.0	0.9	-0.5
-102.0	20.0	1.2	-0.1
75.0	0.0	0.2	0.0
-61.0	-82.0	-0.6	0.2
2.0	-26.0	-0.5	1.0
24.0	-1.0	0.8	1.1
-6.0	23.0	1.0	1.9
4.0	17.0	0.4	0.3
9.0	-21.0	-0.5	0.2
0.0	-6.0	-0.1	0.9
21.0	0.0	0.7	0.0
6.0	7.0	0.0	0.1
0.0	-21.0	0.3	-1.0
-11.0	5.0	0.4	0.1
-9.0	-25.0	-0.3	-0.8
2.0	11.0	-0.3	0.2
4.0	12.0	0.1	-0.8
4.0	-16.0	-0.5	-0.1
-6.0	-10.0	-0.8	1.3

year 1990

-29775.4	0.0	18.0	0.0
-1851.0	5410.9	10.6	-16.1
-2135.8	0.0	-12.9	0.0
3058.2	-2277.7	2.4	-15.8
1693.2	-380.0	-0.0	-13.8
1314.6	0.0	3.3	0.0
-2240.2	-286.5	-6.7	4.4
1245.6	293.3	0.0	1.6
806.5	-348.5	-5.9	-10.6
938.9	0.0	0.5	0.0
782.3	248.1	0.6	2.6
323.9	-239.5	-7.0	1.8
-422.7	87.0	0.5	3.1
141.7	-299.4	-5.5	-1.4
-211.0	0.0	0.6	0.0
352.5	47.2	-0.1	-0.1
243.8	153.5	-1.6	0.5
-110.8	-154.4	-3.1	0.4
-165.6	-69.2	-0.0	1.7
-37.0	97.7	2.3	0.4
60.7	0.0	1.3	0.0
63.9	-15.8	-0.2	0.2
60.4	82.7	1.8	-1.3
-177.5	68.3	1.3	0.0
2.0	-52.5	-0.2	-0.9
16.7	1.8	0.1	0.5
-96.3	26.9	1.2	1.2
76.6	0.0	0.6	0.0
-64.2	-81.1	-0.5	0.6
3.7	-27.3	-0.3	0.2
27.5	0.6	0.6	0.8
0.9	20.4	1.6	-0.5
5.7	16.4	0.2	-0.2
9.8	-22.6	0.2	0.0
-0.5	-5.0	0.3	-0.0
22.4	0.0	0.2	0.0
5.1	9.7	-0.7	0.5
-0.9	-19.9	-0.2	-0.2
-10.8	7.1	0.1	0.3
-12.4	-22.1	-1.1	0.3
3.8	11.9	-0.0	0.4
3.8	11.0	-0.0	-0.5
2.6	-16.0	-0.5	-0.3
-6.0	-10.7	-0.6	0.6
4.4	0.0	0.0	0.0
9.9	-20.8	0.0	0.0
0.8	15.4	0.0	0.0
-12.0	9.5	0.0	0.0
9.3	-5.7	0.0	0.0
-3.9	-6.4	0.0	0.0
-1.4	8.6	0.0	0.0
7.3	9.1	0.0	0.0
1.5	-6.6	0.0	0.0
-5.5	1.9	0.0	0.0
-3.6	0.0	0.0	0.0
-3.9	1.3	0.0	0.0
2.4	0.4	0.0	0.0
-5.3	3.1	0.0	0.0
-2.4	5.6	0.0	0.0
4.4	-4.2	0.0	0.0
3.0	-0.5	0.0	0.0
1.2	-1.5	0.0	0.0
2.2	3.8	0.0	0.0
2.9	-0.5	0.0	0.0
0.0	-6.2	0.0	0.0

year 1995

-29682.0	0.0	17.6	0.0
-1789.0	5318.0	13.0	-18.3
-2197.0	0.0	-13.2	0.0
3074.0	-2356.0	3.7	-15.0
1685.0	-425.0	-0.8	-8.8
1329.0	0.0	1.5	0.0
-2268.0	-263.0	-6.4	4.1
1249.0	302.0	-0.2	2.2
769.0	-406.0	-8.1	-12.1
941.0	0.0	0.8	0.0
782.0	262.0	0.9	1.8
291.0	-232.0	-6.9	1.2
-421.0	98.0	0.5	2.7
116.0	-301.0	-4.6	-1.0
-210.0	0.0	0.8	0.0
352.0	44.0	0.1	0.2
237.0	157.0	-1.5	1.2
-122.0	-152.0	-2.0	0.3
-167.0	-64.0	-0.1	1.8
-26.0	99.0	2.3	0.9
66.0	0.0	0.5	0.0
64.0	-16.0	-0.4	0.3
65.0	77.0	0.6	-1.6
-172.0	67.0	1.9	-0.2
2.0	-57.0	-0.2	-0.9
17.0	4.0	-0.2	1.0
-94.0	28.0	0.0	2.2
78.0	0.0	-0.2	0.0
-67.0	-77.0	-0.8	0.8
1.0	-25.0	-0.6	0.2
29.0	3.0	0.6	0.6
4.0	22.0	1.2	-0.4
8.0	16.0	0.1	0.0
10.0	-23.0	0.2	-0.3
-2.0	-3.0	-0.6	0.0
24.0	0.0	0.3	0.0
4.0	12.0	-0.2	0.4
-1.0	-20.0	0.1	-0.2
-9.0	7.0	0.4	0.2
-14.0	-21.0	-1.1	0.7
4.0	12.0	0.3	0.0
5.0	10.0	0.2	-1.2
0.0	-17.0	-0.9	-0.7
-7.0	-10.0	-0.3	-0.6
4.0	0.0	0.0	0.0
9.0	-19.0	0.0	0.0
1.0	15.0	0.0	0.0
-12.0	11.0	0.0	0.0
9.0	-7.0	0.0	0.0
-4.0	-7.0	0.0	0.0
-2.0	9.0	0.0	0.0
7.0	7.0	0.0	0.0
0.0	-8.0	0.0	0.0
-6.0	1.0	0.0	0.0
-3.0	0.0	0.0	0.0
-4.0	2.0	0.0	0.0
2.0	1.0	0.0	0.0
-5.0	3.0	0.0	0.0
-2.0	6.0	0.0	0.0
4.0	-4.0	0.0	0.0
3.0	0.0	0.0	0.0
1.0	-2.0	0.0	0.0
3.0	3.0	0.0	0.0
3.0	-1.0	0.0	0.0
0.0	-6.0	0.0	0.0

year 2000

-29615.	0.	14.6	0.0
-1728.	5186.	10.7	-22.5
-2267.	0.	-12.4	0.0
3072.	-2478.	1.1	-20.6
1672.	-458.	-1.1	-9.6
1341.	0.	0.7	0.
-2290.	-227.	-5.4	6.0
1253.	296.	0.9	-0.1
715.	-492.	-7.7	-14.2
935.	0.	-1.3	0.
787.	272.	1.6	2.1
251.	-232.	-7.3	1.3
-405.	119.	2.9	5.0
110.	-304.	-3.2	0.3
-217.	0.	0.0	0.
351.	44.	-0.7	-0.1
222.	172.	-2.1	0.6
-131.	-134.	-2.8	1.7
-169.	-40.	-0.8	1.9
-12.	107.	2.5	0.1
72.	0.	1.0	0.
68.	-17.	-0.4	-0.2
74.	64.	0.9	-1.4
-161.	65.	2.0	0.0
-5.	-61.	-0.6	-0.8
17.	1.	-0.3	0.0
-91.	44.	1.2	0.9
79.	0.	-0.4	0.
-74.	-65.	-0.4	1.1
0.	-24.	-0.3	0.0
33.	6.	1.1	0.3
9.	24.	1.1	-0.1
7.	15.	-0.2	-0.6
8.	-25.	0.6	-0.7
-2.	-6.	-0.9	0.2
25.	0.	-0.3	0.
6.	12.	0.2	0.1
-9.	-22.	-0.3	0.0
-8.	8.	0.4	0.0
-17.	-21.	-1.0	0.3
9.	15.	0.3	0.6
7.	9.	-0.5	-0.4
-8.	-16.	-0.7	0.3
-7.	-3.	-0.4	0.7
5.	0.	0.0	0.
9.	-20.	0.0	0.0
3.	13.	0.0	0.0
-8.	12.	0.0	0.0
6.	-6.	0.0	0.0
-9.	-8.	0.0	0.0
-2.	9.	0.0	0.0
9.	4.	0.0	0.0
-4.	-8.	0.0	0.0
-8.	5.	0.0	0.0
-2.	0.	0.0	0.
-6.	1.	0.0	0.0
2.	0.	0.0	0.0
-3.	4.	0.0	0.0
0.	5.	0.0	0.0
4.	-6.	0.0	0.0
1.	-1.	0.0	0.0
2.	-3.	0.0	0.0
4.	0.	0.0	0.0
0.	-2.	0.0	0.0
-1.	-8.	0.0	0.0

year 2005

-29556.8	0.	8.8	0.
-1671.8	5080.0	10.8	-21.3
-2340.0	0.	-15.0	0.
3047.0	-2594.9	-6.9	-23.3
1656.9	-516.7	-1.0	-14.0
1335.7	0.	-0.3	0.
-2305.3	-200.4	-3.1	5.4
1246.8	269.3	-0.9	-6.5
674.4	-524.5	-6.8	-2.0
919.8	0.	-2.5	0.
798.2	281.4	2.8	2.0
211.5	-225.8	-7.1	1.8
-379.5	145.7	5.9	5.6
100.2	-304.7	-3.2	0.0
-227.6	0.	-2.6	0.
354.4	42.7	0.4	0.1
208.8	179.8	-3.0	1.8
-136.6	-123.0	-1.2	2.0
-168.3	-19.5	0.2	4.5
-14.1	103.6	-0.6	-1.0
72.9	0.	-0.8	0.
69.6	-20.2	0.2	-0.4
76.6	54.7	-0.2	-1.9
-151.1	63.7	2.1	-0.4
-15.0	-63.4	-2.1	-0.4
14.7	0.0	-0.4	-0.2
-86.4	50.3	1.3	0.9
79.8	0.	-0.4	0.
-74.4	-61.4	0.0	0.8
-1.4	-22.5	-0.2	0.4
38.6	6.9	1.1	0.1
12.3	25.4	0.6	0.2
9.4	10.9	0.4	-0.9
5.5	-26.4	-0.5	-0.3
2.0	-4.8	0.9	0.3
24.8	0.	-0.2	0.
7.7	11.2	0.2	-0.2
-11.4	-21.0	-0.2	0.2
-6.8	9.7	0.2	0.2
-18.0	-19.8	-0.2	0.4
10.0	16.1	0.2	0.2
9.4	7.7	0.5	-0.3
-11.4	-12.8	-0.7	0.5
-5.0	-0.1	0.5	0.4
5.6	0.	0.0	0.
9.8	-20.1	0.0	0.0
3.6	12.9	0.0	0.0
-7.0	12.7	0.0	0.0
5.0	-6.7	0.0	0.0
-10.8	-8.1	0.0	0.0
-1.3	8.1	0.0	0.0
8.7	2.9	0.0	0.0
-6.7	-7.9	0.0	0.0
-9.2	5.9	0.0	0.0
-2.2	0.	0.0	0.
-6.3	2.4	0.0	0.0
1.6	0.2	0.0	0.0
-2.5	4.4	0.0	0.0
-0.1	4.7	0.0	0.0
3.0	-6.5	0.0	0.0
0.3	-1.0	0.0	0.0
2.1	-3.4	0.0	0.0
3.9	-0.9	0.0	0.0
-0.1	-2.3	0.0	0.0
-2.2	-8.0	0.0	0.0