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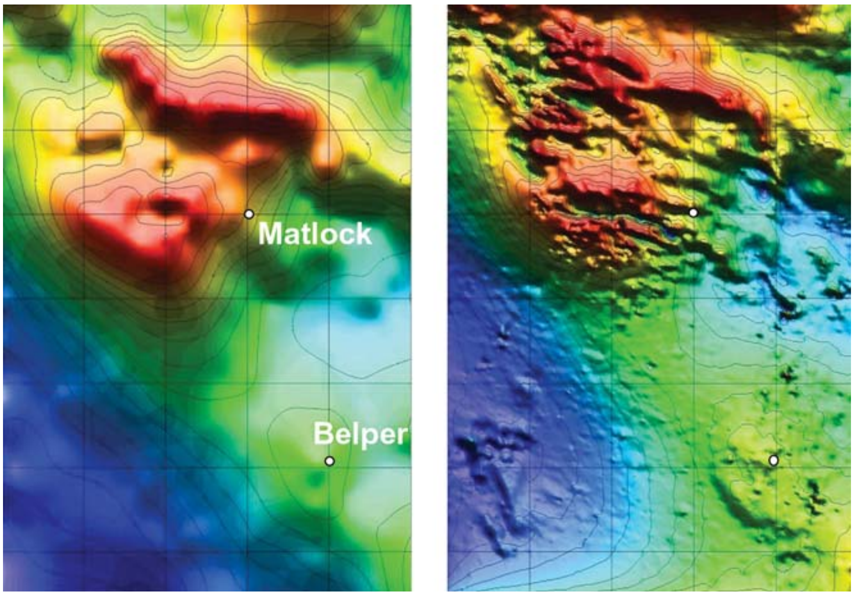
The High Resolution Airborne Resource and Environmental Survey- (Phase 1) (HiRES-1): background, data processing and dissemination and future prospects

Sustainable Energy and Geophysical Surveys Programme

Internal Report IR/03/112



BRITISH GEOLOGICAL SURVEY

INTERNAL REPORT IR/03/112

The High Resolution Airborne Resource and Environmental Survey- (Phase 1) (HiRES-1): background, data processing and dissemination and future prospects

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Keywords

HiRES-1; airborne geophysics, data processing, magnetics, radiometrics, VLF-EM

Front cover

Showing increased resolution of the HiRES-1 aeromagnetic data compared with the early (1950s/60s) coverage.

Bibliographical reference

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Foreword

This report marks the ‘closure’ of HiRES-1, the first phase of the High resolution airborne Resource and Environmental Survey of onshore UK conducted by the British Geological Survey (BGS) in collaboration with World Geoscience (UK) Ltd. (WGL). It collates and outlines the results of the numerous varied activities undertaken during the project and refers to texts giving more detailed descriptions of these activities. The report will serve as a central record of HiRES-1 and should be a useful starting reference for those wishing to pursue aspects of the project in greater detail.

Acknowledgements

We gratefully acknowledge the tremendous efforts made by our colleagues past and present to ensure that the HiRES-1 survey got off the ground successfully. Particular thanks are due to Mick Lee, Jon Busby and Geoff Kimbell who largely organized the project and, with the assistance of Jane Plant and Peter Cook (former Director BGS) made tireless efforts to secure funding to support its execution. We also thank our collaborators in this venture, WGL (now part of Fugro Airborne Surveys), who conducted the survey to high professional standards, often under very trying conditions. David Talbot and Mick Rainey undertook much of the original imaging of the radiometric data and, together with Catherine Emery, John Davis and Mick Strutt assisted very ably in numerous ground truthing campaigns. Further radiometric follow up was conducted by David Kestell as part of his MSc project and by Yerol Narayana during his Commonwealth post doctoral Fellowship at BGS. Barrie Chacksfield made a valuable contribution to the early processing of the magnetic data while Paul Williamson and Steve Rogers researched numerical methods of cultural noise suppression in the aeromagnetic data. This topic was further investigated by numerous Physics students undertaking their third year industrial projects (Martin Neal, Conrad Cooper, Adam Ryall, John Harris and David Short). Lastly, Geoff Kimbell's generous input to the design of the HiRES-1 GIS is gratefully acknowledged.

Contents

Summary

This report provides an overview of the HiRES-1 airborne geophysical survey of Central England. The BGS and World Geoscience (UK) Ltd. carried out the survey jointly in 1998. The three main survey data sets acquired were magnetic, radiometric (gamma ray spectrometry) and Very Low Frequency (VLF) electromagnetic. The main aim of the report is to provide information on the acquisition, processing and storage of the final data and map products produced by the HiRES-1 project. Additional descriptions of ground truthing activities, data licensing and dissemination are also provided.

A significant aspect of the project was the assessment of the potential of, and issues raised by, modern, multi-parameter, regional-scale airborne geophysical surveys in the UK context. Some of the main issues outlined in the report are:

- The practical difficulties of conducting extensive low level, fixed-wing geophysical surveying in the UK. Issues discussed include CAA regulatory permissions, flight height adjustments above conurbations and surveying near areas with dense air traffic.
- The processing challenges introduced by cultural (non-geological) influences on high resolution airborne magnetic data sets in the UK.
- The significant amounts of detailed geological and environmental information contained within the radiometric data.
- The weak application potential provided by passive (i.e. VLF) measurements, in contrast to active airborne electromagnetic techniques.

The future prospects for regional-scale, airborne geophysical surveys in the UK are considered. Such prospects are also influenced by a further set of trial airborne data, obtained in 1999, but not described here.

Further detail of the HiRES-1 survey, productivity, technical specifications and data pre-processing are contained in the survey logistics report prepared by WGL: 'British Geological Survey "Hi-Res Phase One" Airborne Geophysical Survey (Survey Details, Technical Specifications & Processing Summary)' (WGL 2000).

1 Introduction

Efforts to secure funding for a new phase of onshore UK airborne geophysical surveying began in 1986 when Dr Richard Haworth, then BGS Chief Geophysicist, submitted a proposal to the Department of Trade and Industry (DTI). The airborne survey proposed was not simply a new high resolution digital survey to replace the existing aeromagnetic data acquired several decades earlier (1955–65) but would include magnetic gradiometry, gamma spectrometry and Very Low Frequency electromagnetics (VLF-EM). The proposal was rejected by the DTI but throughout the next decade further, largely unsuccessful, attempts were made to attract sponsorship from other Government Departments and Agencies, including the Ministry of Defence.

Funding efforts were redoubled in 1996 with the launch of a new initiative aimed to create a consortium of potential UK airborne data users who would jointly fund the first phase of a national survey. This culminated with the consultation and strategy meeting ‘A new onshore airborne survey for Britain’ held by BGS at the Geological Society in London during the Spring of 1997. At this meeting the utility of new generation airborne geophysical data across numerous varied sectors (including resource exploration, environmental, health and epidemiological mapping) were addressed by invited speakers and discussed in depth.

Despite the large and enthusiastic participation, no offers of co-funding were made. However, soon afterwards World Geoscience (UK) Ltd (WGL), then one of the largest airborne survey contractors in the world, agreed to co-fund the first phase of an airborne survey in a collaborative research venture with BGS. It was agreed that the acquisition and processing costs would be shared equally. The intellectual property rights to the acquired data would also be shared equally by BGS and WGL for 10 years after completion of the survey, after which the full rights revert to BGS.

The start-up of survey operations was beset with problems. UK trade regulations demanded the use of a UK registered survey aircraft and so WGL subcontracted Cooper Aerial Surveys who were to operate a Twin Aerocommander 685. This aircraft had been modified by fitting a tail stinger to house the magnetometer sensor and, following an on-site inspection, the Civil Aviation Authority (CAA) declared that the modification did not meet internationally recognised standards and must undergo additional stress tests. Eventually the aircraft, kitted out with WGL geophysical instruments, commenced operations on 9th November 1997 but after acquiring 850km of data the aeroplane suffered a nose wheel problem and was grounded. This led to further complications with the CAA and the subcontract with Coopers was terminated in late November 1997.

WGL then submitted an application for their Australian registered Shorts Skyvan (VH-WGL), with a tail stinger modification approved by Australia Transport, to be allowed to operate in the UK and permission was granted. VH-WGL mobilised to Tollerton (Nottingham) Aerodrome on 2nd May 1998 and following further delays due largely to avionic and geophysical equipment problems and poor weather, production flying commenced on 21st May and the survey flying was completed on 6th September 1998.

2 The survey

2.1 SURVEY PARAMETERS

The HiRES-1 survey acquired 50,434 line-km of data and covers approximately 14 000 km^2 of central England, stretching from about Rhyl and Welshpool in the west to Lincoln and Stamford in the east and is bounded by BNG Eastings 310 to 510 km and Northings 315–385 km. (Figure 1).

This area was chosen for the first phase because it addresses many of the objectives of HiRES-1: it is prospective for hydrocarbons, coal, metalliferous and industrial minerals, it encompasses potential areas of relatively high radioactivity related to industrial radioactive waste or areas prone to high radon levels, and it displays a broad variety of geology and structure. To accommodate the change in regional geological strike across the area, flight line direction was east-west in the western half of the survey area (west of BNG Easting 400 km, Area 2) and southwest to northeast in the eastern survey area (Area 1, where the survey commenced). The CAA relaxed the rules concerning minimum flying heights (or rather minimum separations between aircraft and structures, people etc) and allowed us to fly at 90 m in 'open' areas and at 240 m over developed zones. Flight line separation was generally 400 m with tie line spacing at 1 200 m, except over three infill areas of special interest where flight line and tie line separations were effectively reduced to 200 m and 600 m respectively. These infill areas, chosen as the main survey neared completion, and their characteristics of interest are:

Derbyshire Dome (Area 4): an area of potential radon hazard and of current mining interest and also displaying complex high frequency magnetic signatures of shallow Carboniferous volcanics.

Melton Sheet (Area 5): at the time of the survey this was an area being geologically re-mapped in detail. It includes strong thorium anomalies related to Jurassic mudstones/ironstones and the area encompasses numerous magnetic granodiorite stocks.

Trent Trough (Area 6): an area already chosen for detailed Quaternary studies and displaying curvilinear radiometric anomalies revealing alluvial depositional patterns.

Originally about 2 000 line-km had been reserved for the infill work but following the operational difficulties encountered while flying near the busy international airports of Manchester and Liverpool it was decided to leave these urban areas unsurveyed and increase infill coverage (to a total of about 4 600 line-km).

Data acquired were total field magnetics, 1024 channel gamma spectrometry and two frequency VLF-EM. The flight path was filmed with a conventional video camera to assist in the subsequent identification of possible sources of cultural magnetic noise. Navigation and subsequent data location were achieved using a differential global positioning system (DGPS).

2.2 LOGISTICAL PROBLEMS

The CAA and local authorities are generally not familiar with extensive low level fixed wing geophysical surveys that are rarely flown in the UK, and hence permission to fly was not readily granted. It required some 12 months of intense lobbying of these authorities (mainly by WGL) to obtain the required permissions. Hopefully the situation will ease as more surveys are flown in the UK.

Survey planning was difficult because of the requirement to fly at low levels over a largely developed area comprising densely populated urban areas with numerous tall buildings

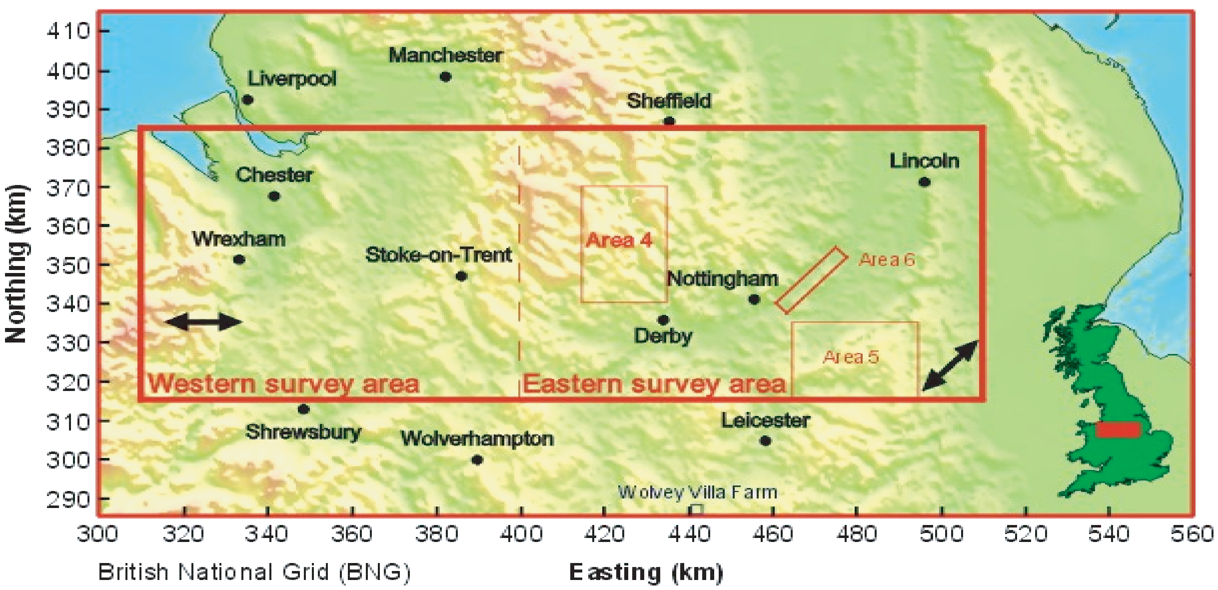


Figure 1 The HiRES-1 survey area in central England.

and other structures and overhead power cables. In addition there are at least fifteen operational airfields (commercial, private and military) within the survey boundary and certain of these (East Midlands, Manchester and the numerous RAF low flying fighter training bases in the East Midlands) are continually busy. The Midlands also appears to be a haven for microlite, hot air ballooning and parachuting enthusiasts.

Finally the weather throughout the survey period, and particularly during May and early June, was extremely poor with rain, low cloud and fog severely hampering progress. In fact June 1998 was the second wettest June on record in the UK.

Further details of the survey production and logistical problems encountered can be found in the logistics report prepared by WGL: 'British Geological Survey "Hi-Res Phase One" Airborne Geophysical Survey (Survey Details, Technical Specifications & Processing Summary)' (WGL 2000).

2.3 PUBLIC RESPONSE

In spite of both WGL and BGS running intensive media campaigns to alert the public in advance to the survey operations and the occasional presence of a low flying aircraft, we logged numerous direct complaints during the survey operations. Most of these, relating to early morning take-offs, were made by residents of Tollerton and parts of West Bridgford lying under the airfield approaches. Air traffic controllers at Tollerton claim to have received on average five complaints each day while the CAA at Gatwick also claim to have been inundated with irate callers. In addition to complaints BGS also received enquiries about the nature of the survey. These included whether the airborne data could reveal features of archaeological interest while a senior scientist at Coalite Chemicals in Derby was concerned that our survey aircraft had been commissioned by Friends of the Earth to monitor their industrial activities.

2.4 EQUIPMENT

Full technical specifications of the geophysical, navigational and avionics sytems employed during the survey can be found in the survey logistics report prepared by WGL: 'British Geological Survey "Hi-Res Phase One" Airborne Geophysical Survey (Survey Details, Technical Specifications & Processing Summary)' (WGL 2000). Here we outline the specifications of the geophysical and auxiliary equipment installed in the survey aircraft, Short Skyvan VH-WGL (Figure 2).

2.4.1 Magnetometer

Model	-	Scintrex CS-2
Operating Range	-	15 000–100 000 nT
Gradient Tolerance	-	40 000 nT/m
Cycle rate	-	10 Hz (equates to about 7 m traverse distance)

The caesium vapour magnetometer sensor was housed at the end of a 3 metre long kevlar tail stinger and held by a rotatable clamp that permits orientating the sensor head for optimum coupling with the local magnetic field direction.

2.4.2 Gamma Ray Spectrometer

Model	-	Picodas PGAM 1000 Ver. 6.11
Detector Volume (downward)	-	33.56 litres
Energy Channels Recorded	-	1024 Individual Channel Data
	-	256 Channel (summed) Spectrum
Lower Energy Threshold	-	180 KeV
Cycle Rate	-	1 Hz (equates to about 70 m traverse distance)

2.4.3 VLF_EM

Model	-	Scintrex/RMS Instruments TOTEM- 2A
Frequency range	-	15.0–25.0 kHz
Frequencies used	-	19.6 kHz (flight lines), 19.0 kHz (tie lines)
Parameters measured	-	Total field and vertical quadrature

Figure 2 Short Skyvan VH-WGL at Tollerton Aerodrome, with tail stinger housing the magnetometer sensor and radiometric calibration pads in the foreground.

The Totem 2-A VLF antennae array was mounted inside a fibre glass nose cone. The array comprised three coils measuring the three x,y,z VLF field components. The VLF system preamplifiers are also mounted in the nose cone.

2.4.4 Video flight path filming

Camera	-	Panasonic CCD
Monitor	-	Panasonic WV-5200 CRT
VCR	-	Panasonic AG5250
Power	-	28 VDC
Format	-	VHS PAL

The system comprised a colour video camera mounted in the nose of the aircraft, a monitor and a Video Cassette Recorder. A video tracking system interfaced to the data acquisition system via a video overlay interface board allowed data (aircraft position in decimal degrees/WGS-84 format, line number and fiducial) to be overlaid and recorded on the video cassette.

3 Data processing

Similar problems to those that beset the survey planning and operations, also created difficulties with data processing. Thus locally dense air traffic and variable weather conditions necessitated ‘patchy’ flying in some areas, with some lines requiring up to three days to complete. Some of these problems are illustrated in Figure 3.

Figure 3 shows that during flying operations in the eastern half of the survey area the temperature ranged between 10.9 and 27.7 degrees C (top right) while the relative humidity varied between 35.4 and 92.3%. Abrupt changes occurring along the NE trending flight lines illustrate how, on occasion, several sorties were required to complete one survey line. This may have been due to crowded air space or locally poor weather conditions and, more rarely, the requirement to refly parts of lines containing data that were out of specification.

Highly variable terrain clearance resulting from the requirement to overfly ‘developed areas’ at almost three times the regular survey elevation, combined with more rugged topography in places, posed extra challenges for the application of height attenuation corrections of the radiometric data and exacerbated the problems of miss-ties between flight and tie lines in the magnetic data. The survey area also contains a multitude of anthropogenic magnetic features and the excision of cultural magnetic noise proved to be a major and time consuming problem.

3.1 MAGNETIC DATA

3.1.1 Pre-processing by WGL

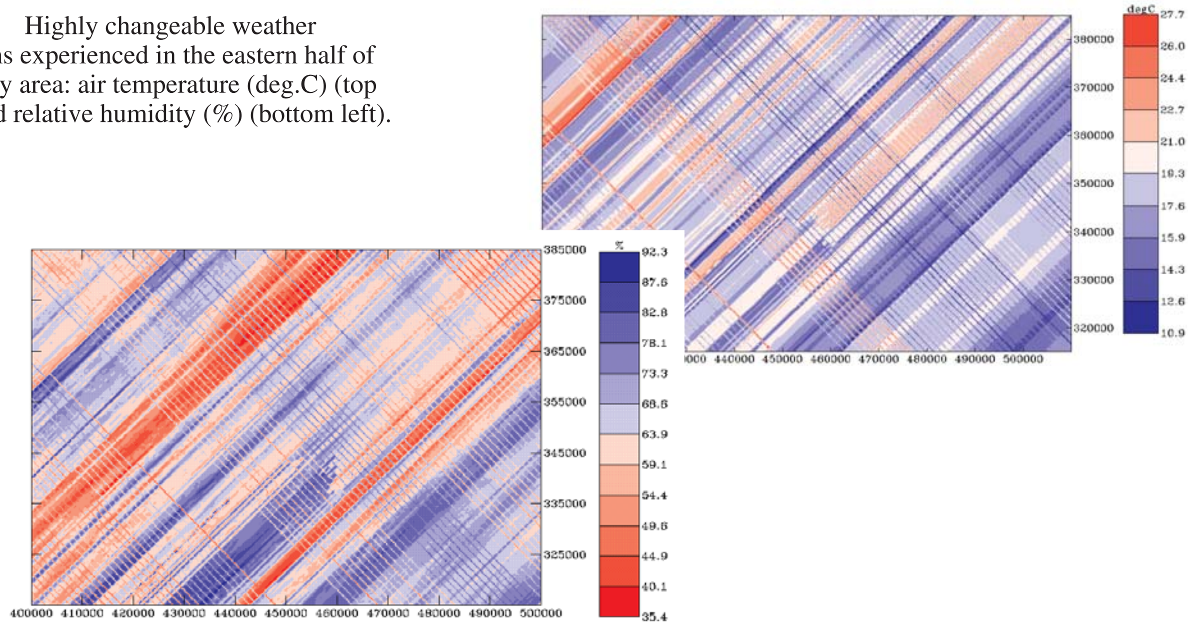
The initial, industry standard pre-processing steps applied by WGL comprised:

- Numerical removal of spikes from the raw data (by simple filtering).
- Interpolation to generate any ‘undefined’ magnetic values.
- Correlation of magnetic data with post-processed UTM coordinates.
- Compensation of the data (for the effects of aircraft movements, heading etc).
- Light filtering of base station recorded diurnal drift values followed by interpolation to the survey sample rate (10 Hz) and subtraction from observed magnetic values.
- Subtraction of the calculated IGRF (1995 Model) value from observed magnetic values. The IGRF values are computed using both GPS position and the exact date and time of acquisition.
- Application of parallax (lag) correction.

3.1.2 Levelling

The magnetic data were then levelled together. First, miss-tie values were determined, these being the differences in the magnetic value observed on tie lines and traverse lines at the crossover points. Differences that were due to altitude changes between tie and traverse lines were corrected by continuing observed values to the nominal survey elevation. Then, using a least squares fit algorithm, which also takes into account the statistical variation inherent in DGPS positioning, a series of corrections were applied to the traverse line data. These allowed the data to be levelled to the same base value. Following this a micro-levelling process was applied. This is a technique that is run on gridded data after tie line levelling to remove long wavelength discrepancies without degrading any high frequency content in the data. The line data were then reconstituted and the tie lines were re-levelled to the traverse lines to eliminate any ‘bulls-eyeing’ effect in the gridded data.

Figure 3 Highly changeable weather conditions experienced in the eastern half of the survey area: air temperature (deg.C) (top right) and relative humidity (%) (bottom left).



3.1.3 Automated suppression of cultural noise

WGL originally undertook to remove or suppress cultural magnetic noise using their proprietary technique based on the analytical signal. While this technique appears to perform well in areas of sparse cultural noise, it failed to discriminate between noise and shallow geological signal in parts of the HiRES-1 survey. As a result the magnetic response to outcropping basaltic sills and dykes in Area 4 was eliminated. Attempts by WGL to refine their suppression technique proved unsatisfactory and eventually it was agreed that BGS would complete the de-culturing process and map production in consideration of a reduction of the cash contribution by BGS.

3.1.4 Post- processing by BGS

3.1.4.1 Initial attempts at numerical supppression of cultural noise

Having received the magnetic data from WGL it was loaded into Geosoft Oasis Montaj and checked for completeness. We then experimented briefly to determine how effectively cultural noise could be removed from the line located data using Fourier-based filtering methods. We applied a variety of filters, both singularly and in combination:

- Non-linear
- Low-pass, High-pass and Band-pass
- Butterworth
- Gaussian
- Cosine

We concluded that while these filters successfully reduced the amplitude of the noise they also tended to stretch or smear its residual influence along line. More importantly, these filters also severely degraded shallow geological signal which displays spectral overlap with cultural noise anomalies. This spectral overlap is demonstrated by the aeromagnetic profile of Line 10920 (Figure 4) which shows numerous anomalies of cultural origin (reflecting a quarry complex (1), a large farm (2) etc) that posses similar amplitude and wavelength to the (negative) feature (3) that is due to shallow Carboniferous volcanics.

3.1.4.2 Manual de-culturing

We then investigated methods for manual de-culturing of the line data. Initially this involved the inspection of profile data (in Geosoft Oasis Montaj) and the identification by fiducial number of suspect anomalies (generally isolated, of high amplitude and short wavelength). The relevant flight path video was then examined for evidence of a possible source of cultural noise at this fiducial. If there was evidence (a farm building, railway line etc) then the affected portion of the total field profile was excised. This proved to be a very labour intensive task, involving the loading of numerous video tapes and fast forwarding etc to the required fiducial. Occasionally, too, we discovered that a source of cultural noise lay outwith the narrow field of view of the video camera (about 100 m diameter at the lowest survey flying height). To improve the efficiency of the process we then loaded scanned OS 1:25 k maps into the computer and, again within Geosoft Oasis Montaj, overlaid the flight paths on these maps and linked (using a common cursor display on three images displayed on a single screen) the total magnetic field profile(s), the gridded total field image and the OS map with flight path overlaid. An example of this graphic display is shown in Figure 5. Generally this proved to be a much quicker method of noise identification and removal, although there were instances where the somewhat dated maps did not show recent developments that created magnetic noise. Neither, of course, could the maps show mobile sources of noise such as large trucks and trains etc). To resolve this

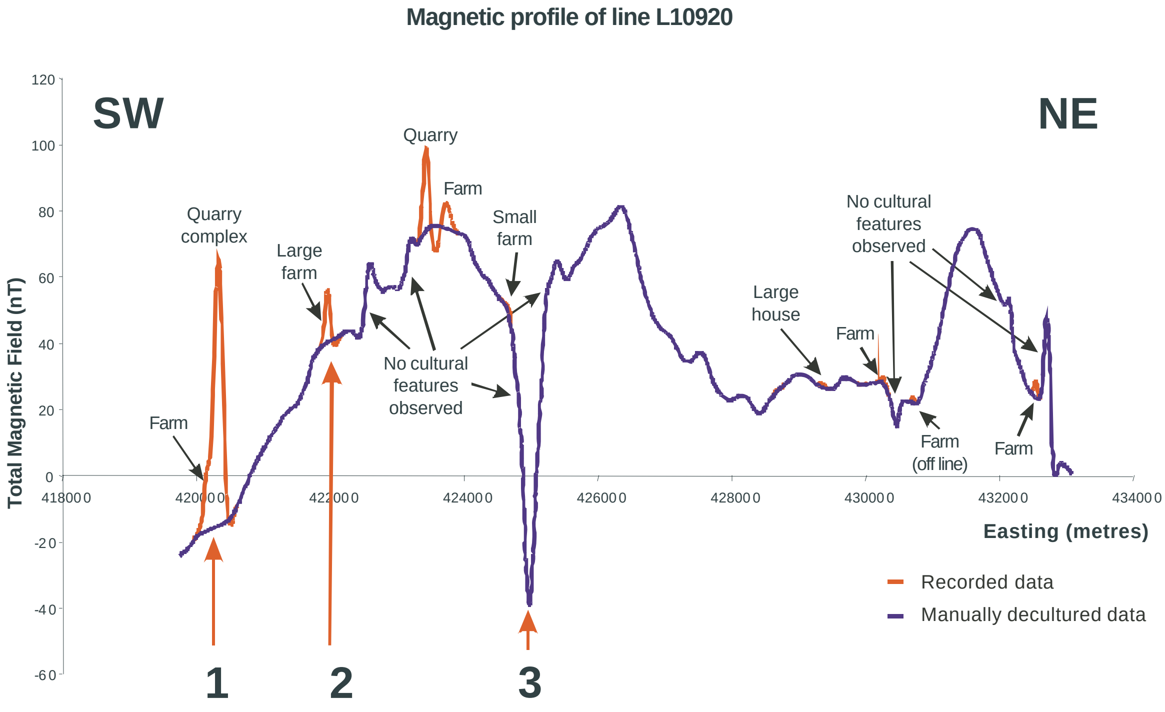


Figure 4 Showing the similarity in amplitude and wavelength between cultural anomalies (at 1 and 2 etc) and a shallow geological feature (at 3).

type of problem it was necessary to resort to examination of the video film.

As part of the manual de-culturing process three new data channels were created in the Geosoft magnetic database:

MagManFilt:	line data with sections excised.
MagManInt:	line data with excised sections replaced by minimum curvature interpolation.
10:	channel where '1' represents good data and '0' is poor data (ie data thought to be affected by cultural noise).

The amount of cultural noise on any one flight line ranged between about 7% and 70% and in total some 33% of the HiRES-1 aeromagnetic data have been excised. Figure 6 (top) shows the total field magnetic anomaly map of Area 4 following manual de-culturing, network levelling and microlevelling. Figure 6 (bottom) shows the magnetic noise that has been removed from the original data. The noise is not evenly distributed and is seen to comprise mainly isolated bi-polar features of amplitude less than about 20 nT, although several linear trends are also apparent. The white lines on the noise image map the routes of Transco high pressure gas mains which are clearly traced by noise features. These gas mains are not visible on either the in-flight video film or the Ordnance Survey maps. Comprehensive accounts of our approaches to the manual removal of magnetic noise can be found in Cuss (2001b) and Cuss (2003).

3.1.4.3 Further investigations of semi-automated cultural noise removal

Automated and semi-automated approaches to the removal or suppression of cultural noise were further investigated during the lengthy phase of manual de-culturing. The goal was to develop an automatic method of cultural noise suppression that removed about 95% of cultural anomalies while leaving as much shallow geological information in the data as possible. We found the application to line data of a carefully designed robust Gaussian filter (filter 1d) in the Generic Mapping Tools package (Wessel and Smith, 1991) almost met this target, The filter was shown to be very effective in removing spikes from the data while retaining underlying trends. Visual comparison of grids produced from unfiltered and filtered line data (Figure 7) showed that the filtering process used had very successfully removed cultural noise anomalies and had retained anomalies due to shallow geology to an acceptable degree. The filtered grid could be further enhanced by using a weighted difference grid to restore anomalies of geological (or suspected geological) origin that had been erroneously removed by filtering (Williamson, 2000). Figure 7 (right) compares very favourably with the product of manual de-culturing shown in Figure 6 (top). It should be noted, however, that close inspection of the filtered line data revealed that the process had introduced a considerable amount of noise while derivative grids (vertical gradient etc) produced from these filtered data were unsatisfactory. In spite of these drawbacks we feel

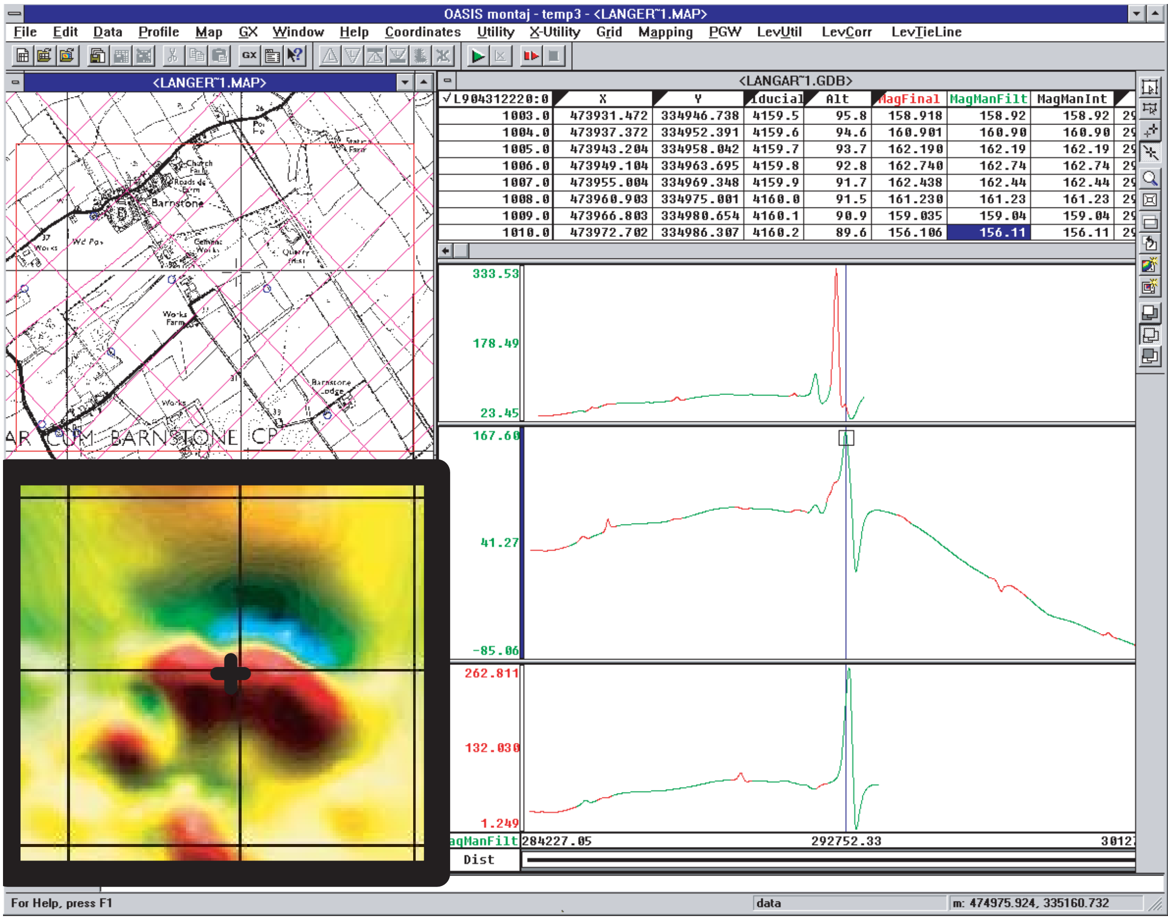
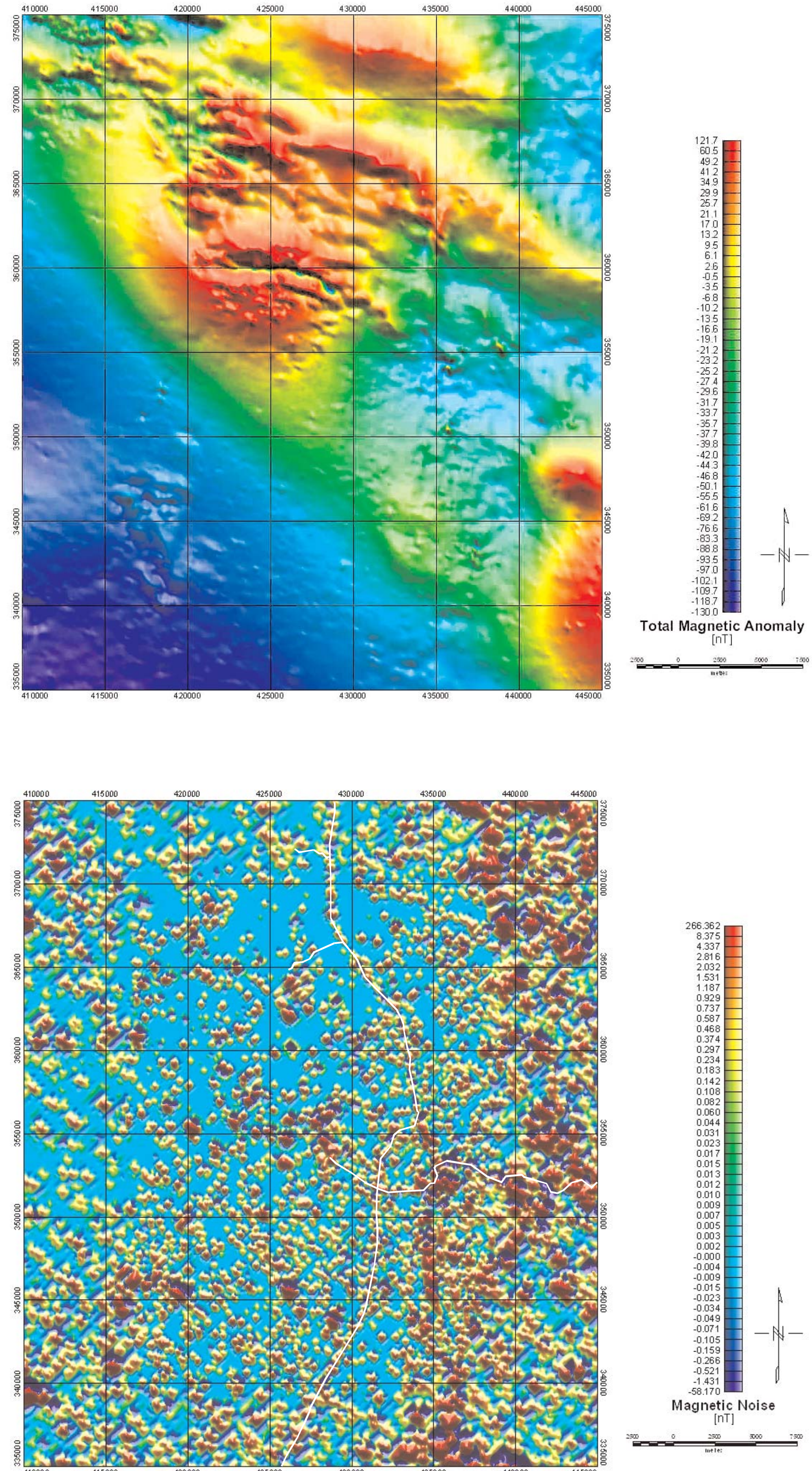


Figure 5 Graphic display provided by Geosoft Oasis Montaj software during the manual deculturing of aeromagnetic data using OS map information.

Figure 6
De-cultured total field magnetic map of Area 4 (top) and noise excised from the data set (bottom).



that the concept of restoring selected features (signal) to a filtered data set is worthy of further investigation.

Three MSci students from the Physics Department at Nottingham University investigated the application of wavelet analysis of line data as their third year project under the supervision of Dr Cuss. Their approach was moderately successful but again, as with the application of Fourier-based filtering methods, while cultural noise features were well suppressed new noise was introduced around such features. Again we concluded that the wavelet approach has promise and is worth pursuing with 3D (gridded) data and possibly extended to applications with measured magnetic gradiometer data.

We also briefly investigated the application of Artificial Neural Networks to automated de-culturing but this was not successful, possibly because we are not sufficiently familiar with such techniques.

3.1.4.4 Downward continuation to the nominal survey height (90 m)

The HiRES-1 magnetic dataset were acquired over a wide range of survey heights, ranging between about 50 m and 480 m. It is important to 'project' this data as though it were acquired at the constant nominal ground clearance of 90 m. This was achieved using the routine CompuDrape, developed by Paterson, Grant and Watson Ltd. and marketed by Geosoft. This allows a relatively stable downward continuation of data to the 90 m level (the volume of data achieved at lower levels was insignificant). A careful study of the process was conducted with the following two conclusions:

Downward continuation to a common level is necessary to achieve a meaningful dataset

The process helps resolve extra features in data acquired at large terrain clearances, but downward continuation can be unstable and the process can introduce noise into the data.

We developed an efficient technique to 'drape' the HiRES-1 data to a constant 90 m altitude. The processing steps are as follows:

- Create a grid of the data acquired at varying elevation with a small grid-size (21 m, ie 3 fiducials) using a blanking distance of between 10 and 50 m.
- Apply CompuDrape to this grid.
- Re-sample the data back into the database.
- This process effectively filters out any features with wavelengths less than about 21 m.

3.1.4.5 Re-levelling of the de-cultured data

Data from the MagManInt channel (Section 3.1.4.2.) established in the Geosoft Oasis Montaj database (ie data with sections of noise excised and with minimum curvature interpolation applied to replace the missing observations) were found to be unsuitable for both gridding and levelling. The problems associated with gridding such data are outlined in the section below. Re-levelling of lines containing interpolated data was found to propagate any errors introduced by the interpolation procedure throughout the dataset. We therefore used the data in the MagManFilt channel (ie data with noise removed but with no interpolation applied to replace missing values) for the re-levelling procedure. This is outlined below:

- Full levelling was applied to flight-tie line intersections, excluding those where the magnetic gradient exceeded 20 nT/fid or where null values existed.
- Empirical levelling (microlevelling) was applied using Fast Fourier Transform decorrugation.
- A Butterworth filter was applied with the following parameters:
  - Cut off wavelength equal to one quarter of line spacing
  - Filter order equal to 8
  - High pass
  - Application of directional cosine with centre direction of 90 degrees (for E-W lines) or 135 degrees (for SW-NE lines) and degree of cosine equal to 0.5

The error grid created by this process was re-imported into Geosoft Oasis Montaj and filtered to remove noise. The microlevelling error was then subtracted from the line data in the database and the grid of the resulting channel (error) was subtracted from the grid of magnetics to create the final magnetic images.

A thorough investigation was conducted to determine whether re-levelling was necessary. This study showed that only flight-tie line intersections were retained in the non-affected (ie lacking cultural noise) magnetic data and that only these points were active during re-levelling. It was seen that very little alteration occurs at these crossover points as the original levelling was so good. Therefore it was concluded that re-levelling was not necessary. In fact, the re-levelling process can introduce new errors. We therefore concluded that only one stage of levelling is necessary, to be undertaken prior to manual de-culturing. Microlevelling was still seen to be necessary.

3.1.5 Gridding of data

Gridding of interpolated line data (MagManInt) (Section 3.1.4.2.) produced 'blurs' where the unrealistically smooth (minimum curvature interpolated) values perturbed the values on adjacent lines. We concluded that such data should be used ONLY for 2D line based work where continuous data is required. The final magnetic map was created from the microlevelled MagManFilt channel. The standard Geosoft Oasis Montaj minimum curvature routine was applied using grid cell sizes of 80 m (for 400 m spaced data) and 50 m for 200 m spaced data.

A 'definitive grid' of the de-cultured magnetic data was created for the whole HiRES-1 area. This was achieved by:

- Producing 80 m cell size grids of Areas 1 and 2, and 50 m cell size grids of Areas 4, 5, and 6.
- Microlevelling all these grids.
- Masking the overlap area between the Area 4, 5 and 6 grids and Area 1, thereby leaving a 1 km border of overlapping data (to allow grid knitting).
- Merge the grids. It should be noted that when using Geosoft Oasis Montaj, if a 'tight' grid is merged with a 'loose' grid (eg when. merging a 50 m cell size grid into an 80 m cell size grid), then the loose grid is re-interpolated to the tighter grid spacing. This has no detrimental effect. Clearly care has to be taken regarding the order of merging, otherwise the 'tight' grid will be de-sampled to the 'loose' grid cell size.

A full suite of grids was produced using scripts in Geosoft Oasis Montaj and the in-house Regional Geophysics grid software. The full suite, listed below, was produced for each area (1, 2, 4, 5, 6) and also for the whole area combined. Table 1 shows all grids produced for Area 1, identified by the

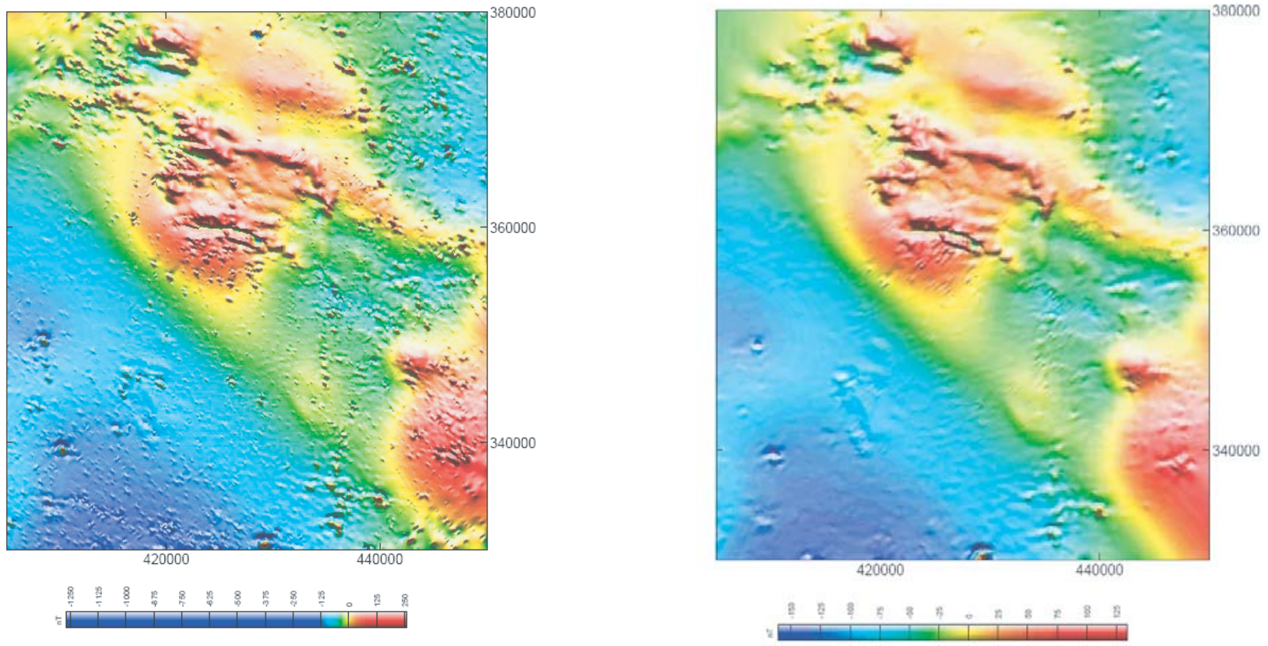


Figure 7 50 m grids of (left) unfiltered Area 4 data and (right) numerically filtered data, with some anomalies known to be due to shallow geological sources restored (from Williamson, 2000).

prefix A1 or a1. Grids for Areas 2, 4, 5, and 6 have the prefix A2/a2, A4/a4 etc while grids of the whole survey area combined are identified by the prefix H1. Some of these grids have not been retained but these can easily be regenerated.

The final complete Geosoft Oasis Montaj magnetic database and most of the derived grids are currently awaiting import into the BGS Corporate database (Oracle). In addition the complete HiRES-1 databases and most of the magnetic grids named below have been loaded onto the Geosoft Oasis Montaj server at Kwnts18/users/HiRES.

3.2 GAMMA SPECTROMETER DATA

3.2.1 Pre-processing by WGL

The radiometric data were processed using both the standard IAEA window processing method and WGL's proprietary Spectra Plus technique. The IAEA method comprises:

- Energy calibration to remove spectral drift in the 1024 channel data and ensure the K, U and Th series gamma peaks are correctly matched throughout the dataset.
- Re-window the 1024 channel data using the IAEA standard energy windows and sum the energy-corrected data for each window.
- Lightly filter radar altimeter, temperature and pressure values to remove spikes.
- Coordinate the data with post processed UTM coordinates.
- Apply parallax corrections.
- Calculate the equivalent terrain clearance at standard temperature and pressure (STP).
- Remove aircraft background.
- Remove cosmic background.
- Remove radon background.
- Apply stripping corrections to remove contributions from the other radionuclides to each of the K, U and Th energy windows. The coefficients applied were derived from measurements with the BGS transportable calibration pads (produced by the Geological Survey of Canada, Grasty *et al*, 1991) that contain known concentrations of K, U and Th.
- Apply height attenuation corrections by correcting all data to a single height at standard temperature and pressure.

The Picodas PGAM 1000 system has analogue to digital converters associated with each detector and consequently the total dead time, arising from the time taken by the system to process pulses from the detectors, is negligibly small and may be disregarded.

WGL also processed the data using their proprietary 256 channel radiometric processing technology — Spectra Plus™. This uses the full recorded spectra after alignment by energy calibration. It relies on mathematical modelling of the expected detector response to the radiation field using Monte Carlo photon transport code. Normally the method produces the unit response for each radionuclide at a given height. These response functions are then fitted to the measured spectra to provide radionuclide concentrations for each 1 second spectrum. This technique reduces statistical noise compared to conventional windows processing.

With the HiRES-1 data it appears that WGL applied only the full Spectra Plus processing to the ^{137}Cs data, which were provided as estimated activities in kBq.m^{-2}. The natural K, U and Th data (along with Total Count) were delivered as both corrected window and Spectra Plus versions in counts s^{-1}.

3.2.2 Post processing by BGS

The final stage of processing involved the conversion of the corrected counts per second to ground concentrations (% K, ppm eU, ppm eTh and air absorbed dose rate nG.h^{-1}). This conversion, which allows direct comparison and merging of the results from different airborne systems, was undertaken by BGS using data from flights over an 8 km calibration range in the Vale of Belvoir. The ground concentrations of K, U and Th were established by a large number of measurements (over 3000) with an Exploranium

Table 1 The full suite of magnetic grids produced for Area 1 (identified by the prefix A1 or a1).

Grid name	Description	Geosoft database channel or derived grid
A1_1950s.grd[1]	Early magnetic data from the 1950/60s surveys (400 m grid cell)	
A1_Alt.grd	Radar altimeter (ground clearance)	Altitude
A1_MagBefore.grd	Magnetics before manual deculturing	Magnetics
a1_bef.sg[2]	Same as A1_MagBefore.grd in standard grid format	A1_MagBefore.grd
A1_MagDC.grd	Downward continued magnetics before deculturing	MagDC
a1_bef_hg.sg	Horizontal magnetic gradient of uncleaned data	a1_bef.sg
A1_rGauss.grd	Robust Gaussian filtered raw magnetics	
A1_cl.grd	Magnetics after manual deculturing (pre-microleveling)	MagFilt
A1_Noise.grd	Noise removed by the deculturing process	Noise
A1_leverr.grd	Leveling error derived from FFT[3] decorrugation	lev_err
A1_leverrfilt.grd	Filtered leveling error to retain geological signal	leverr_filt
A1_ml_grid.grd	Magnetics simply microleveled from error grid	ml_grid
A1_MagFinal.grd	Final magnetics fully microleveled from filtered error	Mag_ml
a1.sg	Same as A1_MagFinal.grd in standard grid format	A1_MagFinal.grd
a1+.sg	Same as a1.sg with nulls filled by interpolation	a1.sg
a1_hg.sg	Horizontal magnetic gradient of cleaned data	a1.sg
a1_rtp.sg	Magnetics reduced to the pole	a1+.sg
A1_5x5conv.grd	5x5 convolution filter on final magnetics	A1_MagFinal.grd
A1_AGC.grd	Automatic gain control of final magnetics	A1_MagFinal.grd
A1_ASig.grd	Analytic signal of the final magnetics	A1_MagFinal.grd
a1_grav.sg	Pseudogravity grid derived from magnetics	a1+.sg
A1+_res0200.grd	Residual of upward continuing magnetics by 200 m	a1+.sg
A1+_res0500.grd	Residual of upward continuing magnetics by 500 m	a1+.sg
A1+_res1000.grd	Residual of upward continuing magnetics by 1 km	a1+.sg
A1+_res2000.grd	Residual of upward continuing magnetics by 2 km	a1+.sg
a1+up0200.sg	Upward continued magnetics by 200 m	a1+.sg
a1+up0500.sg	Upward continued magnetics by 500 m	a1+.sg
a1+up1000.sg	Upward continued magnetics by 1 km	a1+.sg
a1+up2000.sg	Upward continued magnetics by 2 km	a1+.sg
a1r_1vd.sg	First vertical derivative of reduced to pole magnetics	a1_rtp.sg
a1r_2vd.sg	Second vertical derivative of reduced to pole magnetics	a1_rtp.sg
a1r_hg.sg	Horizontal gradient of reduced to pole magnetics	a1_rtp.sg
A1r_res0200.grd	Residual of upward continuing RTP magnetics by 200 m	a1_rtp.sg
A1r_res0500.grd	Residual of upward continuing RTP magnetics by 500 m	a1_rtp.sg
A1r_res1000.grd	Residual of upward continuing RTP magnetics by 1 km	a1_rtp.sg
A1r_res2000.grd	Residual of upward continuing RTP magnetics by 2 km	a1_rtp.sg
a1up0200.sg	Upward continued reduced to pole magnetics by 200 m	a1_rtp.sg
a1up0500.sg	Upward continued reduced to pole magnetics by 500 m	a1_rtp.sg
a1up1000.sg	Upward continued reduced to pole magnetics by 1 km	a1_rtp.sg
a1up2000.sg	Upward continued reduced to pole magnetics by 2 km	a1_rtp.sg

[1] Geosoft Oasis Montaj grids are suffixed .grd
[2] USGS standard grids are suffixed .sg
[3] Fast Fourier Transform

GR-320 portable gamma spectrometer. Continuous measurements along traverses were supplemented by static data and the collection of surface soils and shallow cores for laboratory analyses. Together the data provided detailed information on K, U and Th contents of the surface materials on both a small scale (meters to 10s of meters) and over a larger scale of several kilometres.

The Lower Jurassic mudstones and limestones of the calibration range provided radionuclide concentrations that either met or were close to recommended values (Grasty and Minty, 1995). A section of the calibration range that gave relatively constant K, U and Th contents was used for the conversion of the airborne data.

The calibration range meets most of the ideal requirements of such sites, ie:

- It is relatively flat at a nearly constant height of 50 m above Ordnance Datum.
- There are no hills within 1km
- It is close to a large expanse of water to allow measurements of background radiation; Rutland Water, one of Europe's largest reservoirs, is about 25 km (6 minutes flying time) away
- It is generally free of flight restrictions. The site is open agricultural land, although it is crossed by one power line and there is potential conflict, especially at weekends, with a nearby parachute club.
- The range is easy to navigate as it runs parallel to a straight stretch of minor road for much of its length.
- It meets the 8 km suggested length, providing over 100, 1 Hz measurements

- It is readily accessible for ground measurements with no access problems, although growing crops can hamper ground traverses during the summer
- Radionuclide contents are uniform. Mean K is 1.0%, eU 1.6 ppm and eTh 7.2 ppm. Relative to the suggested values of Grasty and Minty (1995) of respectively ^{3} 1%, ^{3} 3 ppm and ^{3} 6 ppm, the eU concentration is a little low, but K and eTh exceed minimum recommended values.

Separate conversion factors were used for the IAEA windows-based and Spectra Plus data sets. These gave similar results but, since the Spectra-plus data were less noisy, these were used in most subsequent analyses, presentations and interpretations of the data.

The conversion assumes uniform distribution of the radionuclides. In general this is probably a reasonable assumption, but it will not hold true in all circumstances. Locally higher concentrations may behave more like point sources or distribution may be patchy. Particular horizons are known to have significantly elevated levels of one or more radionuclides; for example Carboniferous marine bands are thin layers that often display relatively high uranium content. Where these come close to surface the depth distribution of radionuclides will not be uniform. Because of this non-uniformity, radionuclide concentrations should be regarded only as estimates of actual ground values. They are in any case an average of the ground activities within the footprint seen by the detector and this covers more than 10^4 m^2 for every 1 second measurement.

3.3 VLF_EM DATA

3.3.1 Background

The HiRES-1 VLF data were acquired as a ‘low priority’ marginal cost supplementary data set for mapping variations of electrical resistivity in subsurface formations. The history of airborne techniques shows that VLF is usually used only as an accessory tool in multi-parameter surveys; it is very rarely flown as a primary airborne geophysical technique.

The VLF survey instrument used, the Scintrex Totem 2A, can simultaneously record signals at two frequencies. The use of two VLF transmitters allows the directional dependence of resistivity contrasts to be examined. The Totem 2A has 3 orthogonally mounted coils that measure the total field strength and the vertical (Hz) quadrature (ie 90 degrees out-of-phase with the primary field) component of the VLF field. The total field is a superposition of the primary and secondary (i.e. the field generated by resistivity contrasts) fields. The primary field magnitude is established in an undisturbed zone. This entails an initial instrument calibration (gain setting) at high altitude prior to the survey. This initial calibration (to achieve an instrument null) defines the 100% primary field magnitude for the survey. All data subsequently obtained are relative to the primary field magnitude established by the calibration.

The VLF measurements are made in orthogonal coordinates relative to the flight direction. The flight direction is referred to as LINE. The 3 sensors record data according to the following definitions:

- LINE sensor: maximally coupled with an H field in the direction of flight.
- ORTHO sensor: maximally coupled with an H field direction at 90 degrees to the direction of flight.
- ERECT sensor: maximally coupled with a vertical field.

The system uses two VLF frequencies. The first VLF frequency uses the LINE sensor as principal (horizontal) axis. The second VLF frequency uses the ORTHO sensor as principal (horizontal) axis.

Using these principal axes each VLF frequency is used to record:

- TOTAL FIELD: the change in magnitude of the vector sum of the principal axis field and the in-phase components of the other 2 orthogonal fields (i.e. 1 horizontal and 1 vertical).
- VERTICAL QUADRATURE: the magnitude of that component of the ERECT axis field in quadrature with the principal axis field.

The use of two frequencies allows an additional parameter to be obtained:

- GRADIENT: the difference in magnitude of the TOTAL FIELD at the lowest sensor and the TOTAL FIELD at the upper sensor. The vertical sensor separation is 5 cm.

Immediately prior to the start of HiRES-1 acquisition, tests to optimise VLF frequency selection were carried out by recording horizontal field data at Keyworth using the Scintrex IGS-2 instrument. Based on these trials and a study of field polarisations we recommended use of the following VLF transmitters:

- Area 2 (Western Area (E-W flight lines)): 16 kHz for LINE and 23.4 kHz for ORTHO.
- Areas 1, 4, 5 and 6 (Eastern Area (SW-NE flight lines)): 16 kHz or 19.6 kHz for LINE and 23.4 kHz or 19 kHz for ORTHO.

While WGL followed our recommendations for operations in the Eastern Area (including the infill flying) ie. 19.6 kHz for LINE and 19.0 kHz for ORTHO they omitted to change frequencies for the Western Area coverage. Similarly these frequencies were retained for the tie line flying whereas, for consistency, the original LINE/ORTHO designations should have been ‘reversed’.

It became clear that WGL had very little experience of acquiring/processing VLF data.

3.3.2 Pre-processing by WGL

The VLF data supplied by WGL comprise eight columns, the first four columns being raw data and the second four columns processed data. The first two columns are TOTAL FIELD and VERTICAL QUADRATURE records for the LINE data. The LINE data were maintained throughout the survey as 19.6 kHz (VLF-1). The second two data columns comprise TOTAL FIELD and VERTICAL QUADRATURE records for the ORTHO data and these were maintained throughout the survey as 19 kHz (VLF-2).

The four columns of raw data are followed by the four corresponding columns of processed data. According to WGL the only processing applied to the raw data is the application of a first difference filter. A simple backward difference filter, with a sign change based on line direction, is applied to the successive raw data values (d) along a flight line. The processed data (pd) is simply:

$$pd(i) = d(i) - d(i-1)$$

The pd series is a time-derivative with the time-interval being successive fiducials of 0.1 second. In a spatial sense, the pd series is also a horizontal spatial derivative across a nominal separation of 7 m, approximately the distance travelled by the survey aircraft in 0.1 s. Although the difference filter removes the DC component, the use of a first difference filter is only one processing stage that can be applied to the raw data.

3.3.3 Further processing by BGS

3.3.3.1 Data decimation

The sampling rate of the VLF data was 10 Hz, corresponding to a traverse interval of about 7 m. Since there is considerable attenuation of high wavenumber features at the nominal flight elevation of 92 m, data sampling at 7 m constitutes oversampling and results in excessively large data files. We therefore decimated the raw data at an interval of seven data points (resulting in a sampling interval of about 50 m) and data files with the additional prefix -sep were generated. Comparisons of full and decimated raw data confirm that the decimation factor of seven is totally acceptable and results in no loss of information.

3.3.3.2 Flight dates

It is important to identify the dates when data were acquired since VLF transmissions vary with time (e.g. the transmitter may be switched off for maintenance or its output may be reduced). Base station records are available and can be checked to indicate transmitter performance at any time on any particular day. In the WGL databases the line number is shown as a 5 digit code with the first digit signifying the HiRES-1 survey area (1, 2, 4, 5 or 6). Digits 2 to 4 indicate the 3 digit line number while the final digit indicates whether or not the line was completed in a single pass. Final digits > 0 indicate the number of sorties required to complete the line (multiple sorties usually resulting from locally bad weather or crowded air space near commercial/military airfields). The dates of acquisition of lines or individual sections of lines were extracted from the HiRES-1 data files. Single line data acquired on different days presents a problem that is probably unique to the VLF survey.

3.3.3.3 Acquisition- and resulting processing problems revealed:

Variable gain setting?

Along individual survey lines the raw data (in particular from Area 1) obtained on different days can be seen to be of very different quality, displaying a high level of amplitude variance. This is particularly true of the in-line data. The variability of the data is not fully understood. From an examination of base station records, it seems that VLF transmitter effects are unlikely to be the cause of the observed behaviour. The high amplitude variance recordings have the characteristic of an excessive gain factor in the acquisition system. A further problem with multi-phase data acquisition along a single line is the appearance of major discontinuities (in particular in the in-line Total field data) associated with flight line end/start positions.

Null data

A further common data problem encountered is that of null data, where all data are effectively zero. Examination of the concurrent VLF base station recording usually indicated that both VLF transmitters were active and hence the cause of such null data is likely to be simple operator error (eg the VLF unit was not switched on).

The problem of variable survey altitude

The magnitude and form of the VLF response from a given resistivity anomaly varies with altitude. The magnitude of both recorded components decreases with increasing altitude. The detailed behaviour requires assessment using two and three dimensional plane-wave electromagnetic modelling and such work, in relation to the HiRES-1 data, has been undertaken.

The variation in flight elevation/ground clearance during the survey is clearly relevant. Such variations can result from either topography or aircraft manoeuvres (e.g. during the transition from rural to urban areas necessitating a 3 fold increase in ground clearance). Theoretically the magnitude of the response should decrease although it is generally difficult to observe this effect in the survey data. In terms of processing the VLF data it was thought prudent to investigate the application of a cut- off altitude rule for data acceptance. From our analysis to date we consider that only VLF data acquired below an altitude of 180 m (ie twice the nominal flight height) is useful.

3.3.4 Rapid data assessment by statistical analysis

One of the main features of the raw data is the ‘level’ offsets that need to be addressed in a data processing strategy. This initial problem is essentially one of correctly levelling the data sets. To help achieve this a rigorous statistical analysis of all the HiRES-1 VLF decimated data on a line by line basis was undertaken. The most useful parameters were found to be the mean, range and root mean square (rms). Data means can be positive or negative. The range of the data is defined as the range between maximum and minimum values along each line. The rms value is the normal statistical measure of the average amplitude of the energy level of the data. The statistical analysis highlighted problem areas in the data sets (eg null values, datum shifts etc) and allowed a rapid assessment of data quality.

The results highlighted ‘null’ data in the large data sets from Areas 1 and 2. These data obviously had to be eliminated. The data from Areas 1 and 2 form large data sets acquired on a multitude of days. The range and rms distributions show a high degree of skew. The results indicate likely problems with some individual lines and line sequences of the data. Very high range and rms values for a line can be used to eliminate some of the problem data. The data from Areas 4, 5 and 6 appear to be of better quality. These data sets are much more self-consistent and contain no null data. In contrast to the data from Areas 1 and 2 (that were acquired over many days) all three statistics in all four measured components display stability and low variance.

The procedures (range and rms values) used for poor quality line elimination differ for each component. Our statistical results show that the Total field components, both in-line and orthogonal, present the greatest problem.

Survey flight orientations were SW-NE in Areas 1, 4, 5 and 6 and W-E in Area 2. The flight orientations had an influence on the degree of coupling with the two VLF transmitters. The average rms value, calculated for the total lines obtained across an area (following rejection of null data) can be used to indicate the energy of individual components. The rms figures can be considered, to some

Figure 8 The regional scale resistivity distribution in Area 2 (the Western Area) as revealed by VLF-EM measurements.

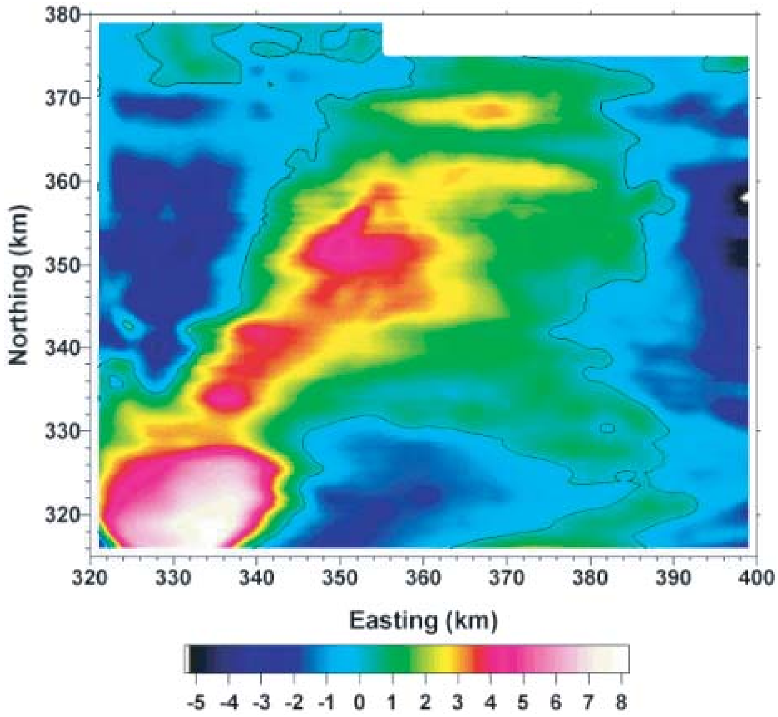
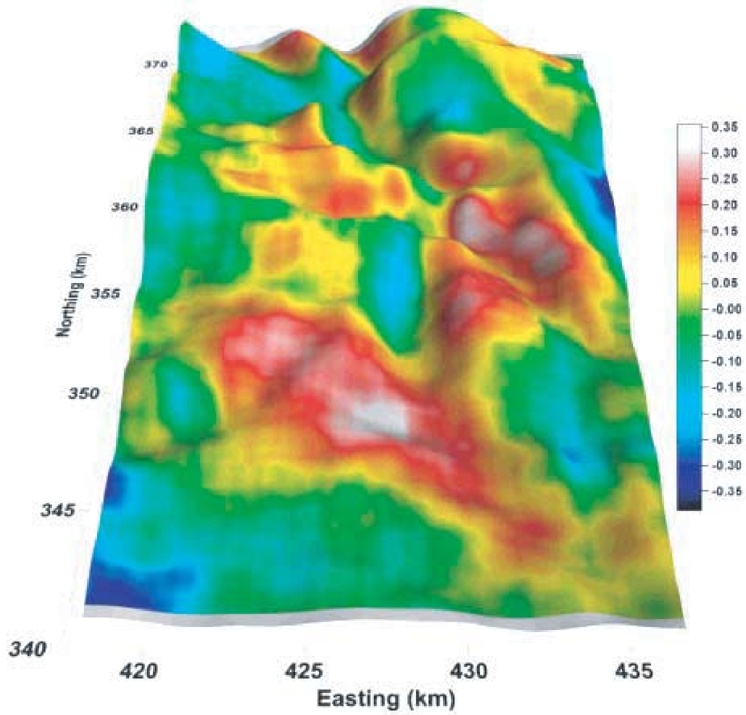


Figure 9 The VLF quadrature vertical field (19.6 kHz) over the Derbyshire Dome (Area 4). The data are shown as colour contours draped on topography.



extent, as a signal-to-noise level. It seems clear that the in-line data components (VLF-I), for both areas, provide a greater received signal when compared to their orthogonal counterparts.

3.3.5 Summary of the BGS processing scheme developed for the VLF data

Processing applied to individual survey *lines* comprises:

- mean removal
- linear trend removal
- rejection of lines with rms values < 0.1 (null data from Areas 1 and 2 only)
- rejection of lines with range values > rangec, where rangec varies with VLF component and Area (see Beamish, 1999b).

The processing applied to individual *points* comprises:

- Rejection of data with radar altitudes > radarc where radarc varies from 170 m (Areas 1, 2, 4, 6) to 150 m (Area 5).
- Following processing, the scattered data have been

converted to a regular grid using a minimum curvature algorithm. The grid interval used (identical in x and y) was 200 m (one half the survey line separation of 400 m).
- In some cases, a simple (matrix) smoothing of the gridded data was undertaken. The method is based on a simple weighted average using 3 parameters. The first parameter refers to the weight of the matrix centre; the second two parameters then refer to the number of rows and columns on either side of the centre, used in forming the weighted average. In Areas 1 and 2, where zones of 'no data' occur, this method of smoothing is not appropriate for a 'final' assessment of the data.

3.3.6 Summary of VLF results

Area 1 (Eastern Area): the data quality is too poor and variable to warrant further processing.

Area 2 (Western Area): apart from obvious problem zones (those of null data or excessive ground clearance), the data display spatially persistent features at both high and low wavenumber scales (Figure 8). A main central trend (NE–SW) of positive values may be geologically controlled. A peculiar circular feature appears in the SW of the area; this does not appear to have an expression in the quadrature Z component. High wavenumber components occur throughout the area.

Area 4 (Derbyshire Dome infill): a large part of the NW–SE gradients in the quadrature Z component appear to be topographically related (Figure 9). An exception to this appears to be a WNW–ESE swathe of positive values and this large scale anomaly may be geologically controlled.

Area 5 (Melton Sheet infill): the clearest and most persistent anomalies appear in the Total field data. A major positive anomaly is defined with particularly strong gradients to the SW, where it becomes negative. The feature does not appear to be simply related to topography.

Area 6 (Trent Valley infill): the anomaly pattern is dominated by along flight line variations with very little coherence of anomalies in a perpendicular direction. The data do not appear to contain useful geological information. The observed response may be the 'natural' consequence of airborne VLF surveying above a zone of relatively high population density. The flight parameters of > 100 m altitude and a line separation of 400 m could well produce a superposition of responses from non-geological sources.

Of the 2 frequencies acquired the highest signal-to-noise was obtained from VLF-1 (in-line 19.6 kHz from Rugby). The orthogonal VLF-2 data at 19 kHz (not recommended by BGS) appears to have provided lower amplitude data sets with the appearance of noise. The VLF-2 data do not appear to provide geologically useful information.

Further details of the VLF equipment and data acquisition and a comprehensive account of the statistical analyses, the processing strategy developed and some example results can be found in Beamish 1999a, b, c.

4 Video cassettes

WGL were contracted to acquire video coverage of all flight and tie lines in the survey area, with the exception of the overflights of the Capenhurst nuclear facility where they were expressly forbidden to film. The main reason for the video acquisition was to assist in the identification of magnetic cultural noise features. A total of 65 video films were delivered to BGS at the end of the survey. These are numbered one to sixty seven, there being one film missing (number 39) while number 43 was omitted from the numbering sequence. The missing video (39) contains the whole of Flight 41 of August 2, 1998, amounting to about 900 km.

Detailed examination of the video coverage of Area 4, made during the early process of manual de-culturing of magnetic data, revealed numerous sections with no video coverage. These are detailed in Table 2 below.

Thus a total of 1270.4 km (equating to about five hours) of video coverage is missing from the Area 4 survey alone. The most common causes of missing footage are:

- The operator failing to insert a fresh video (video number 6 was used for 3 survey flights over three days).
- The tape finishing while still on-line.
- The operator forgetting to re-start recording, having paused the video camera at the end of line to minimise filming of the turns.

The videos are generally of good quality and it appears that care was taken to keep the perspex lens cover clean. As noted above, the field of view is restricted to a diameter roughly equivalent to the flying height and so, with 400 m line spacing, there is a considerable interline area for which there is no video coverage. The use of a wide angle lens is to be recommended for future work.

The videos were copied in house and one complete set is deposited in the Secure Files Store (N113) at BGS Keyworth.

Table 2 Missing video coverage of Area 4 (Derbyshire Dome).

Line number	Start fiducial	End fiducial	Length of missing video (km)[1]
L1107			40
L1108	all		86.1
L1109	all		86.9
L1113	all		90.1
L1114	all		90.9
L1011	all		87.7
L1098	2030	2293	18.4
T7048	all		99.4
L1070	all		55.7
L1071	all		56.5
L1072	6067	6668	47.5
L1077	10407	10805	28.5
L1078	52	119	5
L1084	4130.5	4377	16
L1119	710	728	1.25
L1115	446	719	18
L1068	1594.6	1721.3	9.9
L1148	3630	3850	16.85
L1141	9044.3	9082	2.6
L1059	1881.6	1909	2
L1060	all	47.7	
L1129	all		101.8
L1130	all		101.8
L1138	4710	4875	11.9
L1087	3183	3641	30.7
L1089	707	713.6	0.5
L1086	3642	3669	2.2
L1053	1333.4	1632	23.1
L1052	1633	1647.2	1
L1037	7980	7995	1.1
L1150	1992.6	2040	3.3
L1169.1	8412.4	8452	3
L1167.1	1530.9	1861	23.7
L1205.1	1862	1912.2	3.5
T7052	1	289	23.4
T7052	901	1082	14.7
T7067	8260	8508	17.7

[1] Distances have been estimated assuming that the flight speed remained constant along each line.

5 Data QC

Basic QC tests were made immediately following delivery of the final digital data from WGL in October 1999. These included close examination of flight path plots to ensure complete coverage with no line deviation or separation exceeding those specified in the contract. Images of the gridded radiometric and magnetic data (including the numerous transforms) were examined closely. The VLF data were subjected to a rigorous statistical analysis as described above.

Following the purchase of the Geosoft Airborne QC Toolkit in early 2003, the opportunity was taken to run the full suite of tests on the HiRES-1 data. The results are summarised in Table 3 below:

We produced an A0 sized map of the complete HiRES-1 survey area that flags all the out of specification parameters. Following the quantitative QC tests we concluded that the HiRES-1 survey was generally flown within the specifications listed in the contract, with the exception of very limited areas that WGL should have re-flown. The principal causes of out-of-specification flying were related to the requirement to overfly developed areas at 240 m and to maintain a safe clearance over rugged terrain. These conditions forced the pilot to exceed the nominal specified flying height and occasionally resulted in marginally excessive sampling distances.

Table 3 Results of full QC tests on the HiRES-1 data.

QC test	Result	Contract specification	Computing time (s)
Total surveyed line distance	50 434 km	50 000 km	9
Statistics of all channels			45
Altitude deviation	39% or 14 850 km of data out of specification	Not to exceed 90 m +/-10 m for > 1 km[1]	5
Alt. Dev. (Area 4)	57% out of specification	Not to exceed 90 m +/-10 m for > 1 km	
Flight path deviation	0.3% or 146 km of data out of spec	Not > 80 m off intended track for > 5 km	5
Flight line separation[2]	0.3% out of spec (150 km) out of spec	Not to exceed 400 m +/- 10% for > 5 km	130
Flight line separation (Area 4))	0.5% or 183 km out of ± 40 m spec	Not to exceed 400 m +/- 10% for > 5 km	
Sample separation[3]	31% or 12 113 km out of 8 m spec	~ 8 m	5
Sample separation	0.9% or 34 km out of 9 m spec	~ 8 m	5
Sample separation	All within 10 m	~ 8 m	5
Diurnal variation	Not tested	Not > 5 nT in 5 mins (non-linear)	
Magnetic noise	< 1 km of data out of spec	Not > +/-0.2 nT over 5 km	10

[1] Except to avoid breaches of air safety regulations (over 'developed' areas) or otherwise where the aircraft/crew would be put at risk.
[2] Excludes infill areas
[3] Stated as 8 m in contract.

6 Ground truthing activities

Ground follow up was made of a number of features seen in the HiRES-1 radiometric data and these investigations are continuing. Their aim is to confirm the cause of anomalies and establish in more detail their extent and significance. These investigations are outlined below. Anomalous features in the magnetic data are generally well understood and have not been investigated further in the field to date. Similarly, anomalous indications in the VLF data have not been followed up on the ground since these are generally of regional extent.

6.1 RADIOMETRIC GROUND TRUTH AND OTHER INVESTIGATIONS

A range of different features have been examined including both natural occurrences, accumulations of natural radioactivity due to human activity and those resulting from anthropogenic radionuclides such as ^{137}Cs. The nature of this work is outlined below:

- Relatively high Th and U associated with the Marlstone Rock Formation, both naturally and relating to ironstone extraction. The Marlstone is also associated with higher indoor radon concentrations
- Higher U values related to the Carboniferous Limestone in Derbyshire, another radon associated unit.
- Limited ground investigations related to the use of radiometric and other data for soil mapping
- A study of levels of U and Th in the vicinity of the Hilts Quarry landfill site near Crich in Derbyshire
- Generally higher levels of natural radioactivity associated with colliery spoil, power station fly ash and an iron foundry site. Figure 10 compares the HiRES-1 thorium response over the Staveley Foundry waste site (left) with that measured by ground traverses (right). Clearly the anomaly has been confirmed. The high thorium values probably reflect the presence of zircon-rich moulding sands.
- Accumulations of ^{137}Cs in inter-tidal areas and uplands of NW England and North Wales. The former is derived from Sellafield discharges, the latter from nuclear weapons testing fallout and the Chernobyl accident.
- Investigation in south west Derby to locate an intense anomaly detected at a flying height of 240 m. This work failed to locate the source which was subsequently proved to be a temporarily unshielded ^{60}Co sample, the size of a cricket ball, used for testing the integrity of steel mouldings.

Ground gamma spectrometry has been carried out over all these features using a portable Exploranium GR320 spectrometer coupled with a GPS receiver. Data were normally displayed and logged on a Husky palmtop computer. Measurements have been made on continuous traverses and at static sites with the instrument mounted on a tripod. At selected sites surface samples and soil/sediment cores were collected for laboratory investigation. The use of the airborne

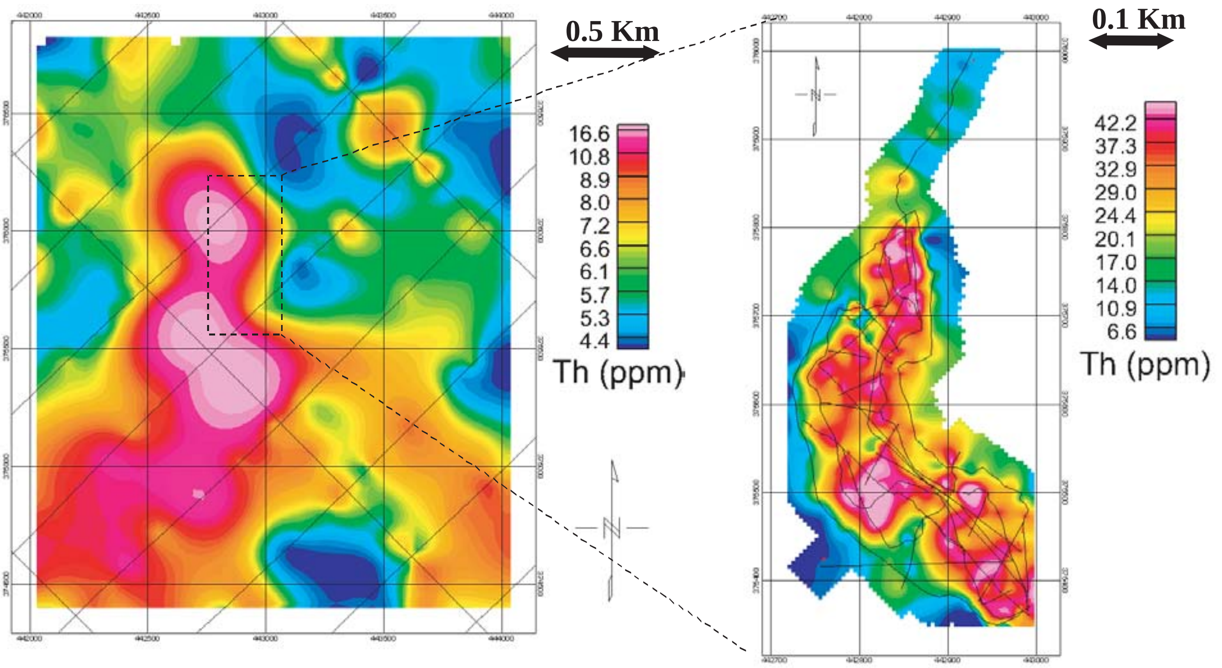


Figure 10 The HiRES-1 thorium response over the Staveley Foundry waste site (left) compared to that measured by ground traverses (right).

radiometric data for environmental studies, with examples from the UK and Germany, has recently been summarised in a joint paper with GTK (Lahti and Jones, 2003).

Initial ground truth work was carried out as part of an MSc project (Kestell, 2000). This highlighted a number of sites but focused on two power stations (Cotham and Ratcliffe-on-Soar), a disused colliery and the former iron foundry site at Staveley. The power station work confirmed that the higher radioactivity was associated with the storage/disposal of fly ash. At Ratcliffe this had not been proved because the radiometric feature is some distance from the power station.

Investigation of ^{137}Cs formed part of a post-doctoral fellowship (Narayana, 2001). This used the depth profiles of ^{137}Cs in inter-tidal sediments (tidal flat and salt marsh), and the spectral shape of surface measurements, to estimate sedimentation rates in the Dee Estuary. The project also carried out more limited work on Moel Famau in the Vale of Clwyd, North Wales. Here the ^{137}Cs distribution is related to topography and reflects rainfall causing deposition of airborne contaminants from nuclear weapons fallout and the Chernobyl accident.

Higher natural radioactivity associated with colliery spoil has been investigated in North Nottinghamshire at the former Warsop Vale and Shirebrook collieries. Detailed ground gamma spectrometry was carried out and the data confirmed by laboratory analysis of samples. The radiometric feature conforms well to the extent of colliery spoil, but this is not necessarily well defined on Ordnance Survey mapping. Thus the radiometric anomaly can better define the spoil distribution at surface.

Variation in natural radioactivity, particularly K, was shown to be potentially useful in mapping soil types or soil parent material as part of a DEFRA-funded study carried out with Cranfield University (Mayr *et al*., 2001). The background U and Th distribution around Hilts Quarry was investigated on behalf of a major engineering company (BGS, 2002). U levels are naturally higher in the Carboniferous Limestone around the site.

The higher U in the Carboniferous Limestone is associated with higher indoor radon values. The possible use of the airborne U data to map variations in radon levels is being investigated by ground gamma and soil gas radon measurements along airborne flight lines. Work is also in progress on other formations associated with elevated radon concentrations, such as the Marlstone Rock.

7 Data licensing and spin-offs

HiRES-1 data have been licensed for use in a soils mapping R&D project in the Melbourne area of Derbyshire, undertaken on behalf of a UK Government Department (Mayr *et al*, 2001). Similarly, a block of HiRES-1 data covering part of the Peak District has been licensed by a mining company for use in a LINK project (FIESTA) investigating sustainable methods of mining in an environmentally sensitive area (Cuss and Busby, 2003). To date five academic licenses to use HiRES-1 data have been issued and a further license has been taken out by a remote sensing consultancy.

HiRES-1 data have also been included in a short thematic geoscience atlas for the area around Crich, Derbyshire, that was commissioned by a major engineering company. The report incorporates the geochemistry of uranium and thorium in soils, stream sediments and stream waters and airborne gamma spectrometry (BGS, 2002). Following a presentation of the HiRES-1 data, a UK defence research establishment commissioned surface geophysical surveys over a test site in Dorset to assess to what extent the data could be used to characterise soils (Rainey *et al*, 2000).

8 Data dissemination

The results of the HiRES-1 survey, together with those from a subsequent trial airborne survey undertaken in 1999 in collaboration with the Geological Survey of Finland (Beamish *et al*, 2000a and 2000b), have been widely disseminated by publication in scientific and general interest journals, by oral and poster presentation at international geoscience conferences and by presentations to fellow scientists, distinguished visitors to the BGS and local interested groups etc. Wider use of the data within BGS has been promoted by the establishment of a comprehensive GIS that is available via the Intranet. In addition we have produced a reference set of selected HiRES-1 images at A3 size in a hard copy Image Atlas (BGS, 2004). We have also published HiRES-1 pages on the Intranet and updated these at regular intervals. Further details are shown below:

8.1 PUBLICATIONS

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- Beamish, D, and Mattsson, A. 2001b. The role of airborne EM methods for environmental applications in different geological terrains European Association of Geoscientists & Engineers 63rd Conference, Amsterdam. Extended Abstract/Oral Presentation.
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- Cuss, R J, Williamson, J P, and Peart, R J. 1999. Manual and automated removal of cultural noise from high-resolution aeromagnetic data acquired over highly developed areas Annual General Meeting of the American Geophysical Union, San Franscisco. Poster Presentation.
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- Narayana, Y. 2001a. Distribution and enrichment of 137Cs in Dee Estuary saltmarsh COGER Meeting, Imperial College, London.
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- Talbot, D K, Jones, D G, Roberts, P D, and Strutt, M H. 1999. An airborne gamma spectrometric and geophysical survey of parts of central and northern England and north Wales COGER Meeting, Nottingham.

8.3 PRESENTATIONS TO COLLEAGUES AND DISTINGUISHED VISITORS TO BGS

Presentations were made to the following:

- The BGS Board
- The Chief Executive of the NERC (Professor John Lawton)
- Directors of Centres and Surveys
- Rt Hon Kenneth Clarke MP
- Mr Chris Mullins MP
- Rt Hon Mr Brian Wilson MP
- Director and Deputy Director of BRGM
- BGS Keyworth, Edinburgh and Wallingford.

8.4 PRESENTATIONS TO OTHER INTERESTED GROUPS

These included:

- Regional Advisory Panel (East Midlands).
- Various environmental groups (East Midlands and Nottinghamshire County Council).
- Nottingham University Evening Class ‘Geology and Man’.
- Vale of Belvoir Probus meeting.
- Rushcliffe Borough Council.
- Open University Geological Society (North West Branch).

8.5 HIRES-1 CUSTOMISED GIS

A customised GIS was established and populated with HiRES-1 data and a wide assortment of other thematic layers. The GIS was designed for use with the ArcView GIS software developed by ESRI. A series of images (122 in total) of magnetic, radiometric and VLF data are included, together with a customised dialog that facilitates toggling between the different displays. An example GIS screen image showing part of the radiometric ternary plot of the HiRES-1 area together with two of the customised interactive imaging dialog and backdrop imaging dialog menus is shown in Figure 11. The geophysical data are also loaded in the GIS as grids, and further dialogs enable the user to generate displays interactively from the gridded data within the GIS. The options include colour and/or shaded relief imaging, contouring, slope or aspect of a grid, ternary (RGB) imaging and restricted colour display determined by set thresholds. The tools can be used with user-defined grids as well as the initial set of grids supplied. The broad functionality of the GIS is demonstrated by Figure 12 which shows a contrasting series of images of data from Area 4. The GIS can be accessed via:

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or
\\kwnts9\programmes\LR\IGSS\HiRES-GIS\HiRES-1_GIS\hires-1_gis.apr

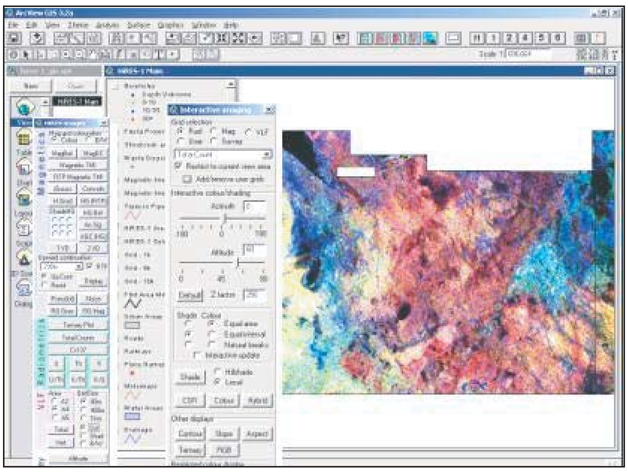

Figure 11 Screen capture of the customised HiRES-1 GIS showing part of the radiometric ternary image and the backdrop and interactive imaging dialog menus.

It is anticipated that the availability of the HiRES-1 GIS will encourage wide use of the data by fellow geoscientists within BGS. Full details can be found in Cuss and Kimbell (2001).

8.6 HIRES-1 HARD COPY ATLAS

In addition to the comprehensive series of images populating the GIS, we have produced an A3 sized Image Atlas containing a limited selection (29) of hard copy images of some of the most significant features detected during the survey. This publication, entitled ‘Airborne Geophysical Survey of the North Midlands: Selected Maps and Images’ (BGS, 2004) comprises the following maps:

GENERAL AND RADIOMETRICS MAPS:

Map 1:	Survey line path	
Map 2:	Survey altitude	Colour shaded-relief, north-northeast illuminated
Map 3:	Digital elevation model	Colour shaded-relief, northeast illuminated
Map 4:	Bedrock geology	
Map 5:	Tectonic elements	
Map R1:	Radiometric total count	Colour image
Map R2:	Radiometric Potassium	Colour image
Map R3:	Radiometric Uranium	Colour image
Map R4:	Radiometric Thorium	Colour image
Map R5:	Radiometric ternary image	Ternary image
Map R6:	Radiometric ratios, U:K	Colour image
Map R7:	Radiometric ratios, U:Th	Colour image
Map R8:	Radiometric ratios, Th:K	Colour image
Map R9:	Radiometric Caesium 137	Colour image

AEROMAGNETIC MAPS:

Map M1:	Magnetic total field anomaly (colour shaded-relief, NNE illuminated).
Map M2:	Magnetic total field anomaly (colour shaded-relief (reduced to pole) NNE illuminated).
Map M3:	Magnetic total field anomaly (grey shaded-relief (reduced to pole) horizontal gradient NNE illuminated).
Map M4:	Magnetic total field anomaly (grey shaded-relief (reduced to pole) horizontal gradient, automatic gain control, NNE illuminated).
Map M5:	Magnetic total field anomaly (colour shaded-relief (reduced to pole) residual based on 200 m upward continuation, NNE illuminated).
Map M6:	Magnetic total field anomaly (colour shaded-relief, before manual de-culturing, NNE illuminated).
Map M7:	Magnetic total field anomaly (colour shaded-relief , anthropogenic (cultural noise) magnetic signal, NNE illuminated).
Map M8:	Magnetic total field anomaly (colour shaded-relief, reduced to pole, Area 1: Eastern survey area, N illuminated).
Map M9:	Magnetic total field anomaly (colour shaded-relief, reduced to pole, Area 2: Western survey area, NE).
Map M10:	Magnetic total field anomaly (colour shaded-relief, reduced to pole, Infill Area 4: Derbyshire Dome, N illuminated).

Map M11: Magnetic total field anomaly (colour shaded-relief, reduced to pole, Infill Area 5: Melton Mowbray Area, N illuminated).

Map M12: Magnetic total field anomaly (colour shaded-relief, reduced to pole, Infill Area 6: Trent Valley, N illuminated).

Map M13: Magnetic total field anomaly (colour shaded-relief, reduced to pole, horizontal gradient Infill Area 4: Derbyshire Dome, N illuminated).

Map M14: Magnetic total field anomaly (colour shaded-relief, reduced to pole, 200 m upward continuation, Infill Area 4: Derbyshire Dome, N illuminated).

Map M15: Magnetic total field anomaly (colour shaded-relief, reduced to pole, residual based on 200 m upward continuation, Infill Area 4: Derbyshire Dome, N illuminated).

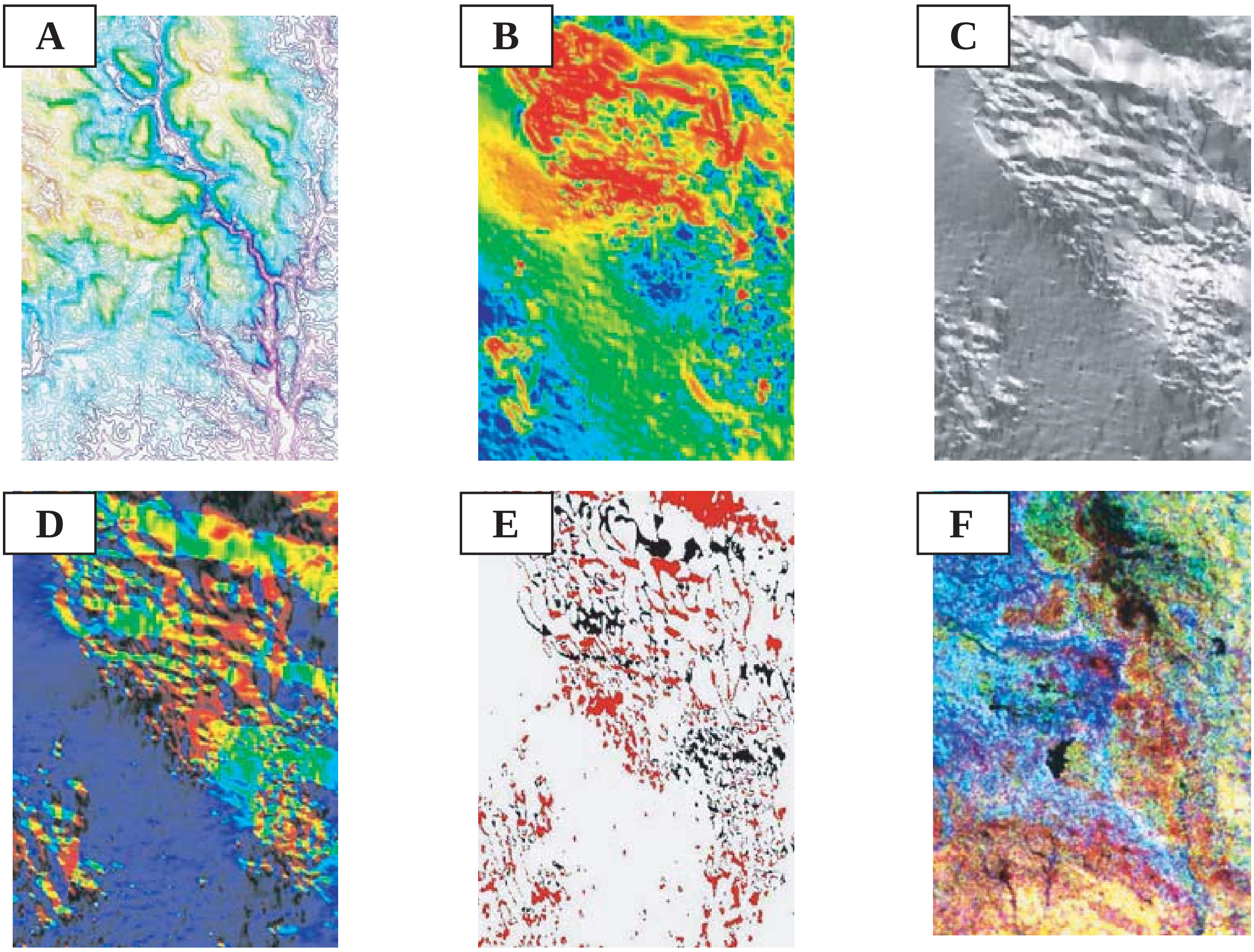

Figure 12 Examples of image display for Area 4 data using the ‘Other displays’ option of the Interactive imaging dialog. A. Colour contours of topography, B. Slope of reduced-to-pole magnetic field, C. Grey-scale aspect image of RTP magnetic field, D. Colour aspect image, E. Trend identification. F. Radiometric ternary image.

9 Academic collaboration

BGS hosted Dr Narayana from India, a post doctoral Commonwealth Fellow, for one year. During this time he investigated the distribution of ^{137}Cs (as first revealed by the HiRES-1 survey) in the Dee Estuary and the Vale of Clwyd. (Narayana 2001b, Narayana et al (In Prep-a), Narayana et al (In Prep-b).

In addition a total of seven MSc, MSci or M.Phys. students have worked with HiRES-1 data and prepared dissertations covering a variety of topics:

- Manual methods of de-culturing aeromagnetic data (Neal 2000).
- Towards automated de-culturing of aeromagnetic data: (Cooper 2002), (Harris *et al* 2001).
- The health significance and the origin of selected radiometric anomalies (Kestell 2000).
- A GIS based examination of the correlation between EM and radiometric anomalies (Stevenson 2000).

10 The future for regional airborne geophysical surveys in the UK

The HiRES-1 survey provides the only regional scale high resolution airborne geophysical coverage of onshore UK. However, the area covered by the survey is only 6% of the UK land area. Elsewhere the lack of modern, multi-component airborne data represents one of the most serious gaps in the geoscience knowledge base of the UK, and a national high resolution airborne survey has been a stated NERC and BGS objective for many years. The utility of airborne data in the UK has been clearly demonstrated following the HiRES-1 survey and the subsequent airborne trials conducted in collaboration with GTK (Beamish *et al*, 2000a and 2000b). These surveys have, for instance, mapped numerous anomalies of both natural and artificial radionuclides at regional and local scales while the magnetic data are currently being applied to mineral exploration in an environmentally sensitive area and also to geological and structural mapping. The collaborative work with GTK has demonstrated in particular the importance of frequency domain airborne EM data for locating and investigating potential pollution from colliery spoil, landfill sites and sewage farms. A recent (March 2003) drilling campaign has confirmed the presence at depth of highly conductive pore fluids adjacent to colliery spoil heaps, as predicted by the trials airborne data and subsequent surface geophysical follow-up. It is essential that such EM data be collected during all future regional surveys.

We believe the case for a national, strategic high resolution survey is clear: to provide important new data sets to underpin decision making on land-use planning, the detection and mitigation of natural and man-made geo-hazards, and the sustainable development of natural resources. All of these objectives will support the stated NERC 5 year strategy as detailed in the document 'Science for a Sustainable Future' (NERC, 2002).

National coverage would take between 8 and 10 years to complete and cost in the region of £20M, including data acquisition and post-processing etc. While it is difficult to justify this cost for a single application the value across all sectors makes a compelling case.

10.1 DRIVERS

The main drivers for acquiring regional scale airborne data include:

- Existing and planned EU environmental directives governing groundwater protection, radon hazard, integrity of landfill sites, sewage treatment, agricultural activities and mine waste.
- Resource exploration (for hydrocarbons, industrial and bulk minerals, groundwater etc)
- Geological and structural mapping, in particular the characterisation of Quaternary deposits to gain information on climate change, soil types etc

10.2 POTENTIAL SPONSORS

It is likely that the heavy investment required to complete national coverage in a systematic and efficient manner can only be provided through Science Budget funding supported by central government departments and/or agencies such as DTI, DEFRA, the Environment Agency, the Department of Health, the National Radiological Protection Board. Large commercial concerns (e.g. Experian, Landmark, Sitescope) may be prepared to co-fund such surveys where we can demonstrate that the data have direct commercial potential.

10.3 POTENTIAL BARRIERS TO FURTHER REGIONAL SCALE COVERAGE

We see two major potential barriers:

- Failure to secure sufficient funding for a systematic national programme.
- CAA restrictions on survey flying height. Ideally ground clearance over 'open' or undeveloped areas should not exceed about 60 m. The CAA will look more favourably upon requests to allow flying at this height if the airborne survey is deemed to be for the public good. This would clearly be the case if the survey were to be supported by central government funding.

Probably less significant barriers relate to:

- Highly variable UK weather conditions
- Crowded air space
- The need to increase flying altitude over rugged topography and urban areas
- Cultural noise in developed areas

11 Conclusions

Following a lengthy campaign to secure funding, the HiRES-1 survey was eventually flown between May and September 1998. Numerous 'new' problems were encountered, largely related to airborne surveying in a densely populated and heavily industrialised nation. These included the requirement to overfly 'developed' zones at nearly three times the nominal survey flying height, the need to orchestrate survey operations with commercial and military flying in busy air spaces and the plethora of cultural noise acquired in the magnetic data. The highly variable weather conditions experienced during the survey also presented further challenges at both data acquisition and processing stages. In spite of these difficulties we were able to acquire two high quality datasets. A recent quantitative QC check of the HiRES-1 data made using the Geosoft Airborne Data QC Tool Kit shows that, apart from ground clearance, the vast majority of the data are within specification for all of the six tests run.

Data processing challenges included the need to excise some 33% of the aeromagnetic data which are affected by cultural noise. Currently only manual de-culturing yields a fully satisfactory result but automated and semi-automated alternatives to this onerous and time consuming task have shown promise and are worthy of further investigation and refinement before we acquire extensive new data sets. The VLF technique was employed as a low priority 'piggy back' option to obtain, at marginal cost, information on the shallow distribution of earth resistivity. It is clear that WGL were not familiar with VLF acquisition and we were required to develop new routines for checking and processing the VLF data. The VLF data from Area 1, where the survey commenced, is deemed unusable. However the situation improved with time and information of probable geological significance was obtained over Areas 2, 4 and 5. Subsequent UK trials with the GTK Twin Otter active airborne EM system have demonstrated the fundamental significance of multi-frequency EM and we plan to acquire such data in all future surveys. As part of the HiRES-1 survey we established an 8km long radiometric calibration range in the Vale of Belvoir. This meets most of the ideal requirements specified by the industry and has allowed us to convert the corrected observed counts per second into concentrations of the three radioelements in the ground. This will facilitate direct comparisons between data acquired with different equipment. The HiRES-1 radiometric data has demonstrated that, in certain areas, contrary to popular belief, useful signal can be measured at ground clearances in excess of 250 m.

To date the radiometric data have proved the most useful of the three HiRES-1 data sets acquired. They have mapped radon prone areas of relatively high natural (lithological) concentrations of Uranium and Thorium in addition to anomalous distributions of ^{137}Caesium, the artificial radioelement derived from atomic power generation, nuclear weapons testing and the Chernobyl accident of 1986. Anomalous levels of radioelements related to industry (coal burning power stations, steel foundry waste etc) have also been observed and subsequently confirmed by ground follow-up activities. The radiometric data, in particular ^{40}K concentrations, also show great promise for remote soil characterisation. The magnetic data have assisted structural mapping, delineating previously unrecognised faults and inversion features that may have hydrocarbon significance. These data, together with the radiometric data, have also been used in a LINK project investigating new methods of mineral exploration in environmentally sensitive areas.

The HiRES-1 survey and the subsequent GTK trials have demonstrated the broad spectrum of applications of airborne geophysical data, even when acquired in a densely populated and heavily industrialised nation. We believe there is a compelling case to complete national coverage with modern high resolution equipment and techniques.

References

Most of the references listed below are held in the Library of the British Geological Survey at Keyworth, Nottingham. Copies of the references may be purchased from the Library subject to the current copyright legislation.

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