Mineral Industry Sustainable Technology

MIST

Project MA/3/01/001

Geophysical Rapid Archaeological and Mineral Surveys

GRAMS

Project Official Title:
Feasibility Study for the application of new integrated technology to the detection, delineation and characterisation of archaeological sites with potential for mineral development.

Final Report:
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MA3/1/001

Feasibility Study for the application of new integrated technology to the detection, delineation and characterisation of archaeological sites with potential for mineral development.

1.1 Executive Summary

The project aim was to test the capabilities of the geophysical survey system known as the multi-sensor platform (MSP) to establish the ability of the system to collect high-quality geophysical data from a wide range of different geophysical sensors in a fast and cost-effective manner. If these tests were successful, they would provide a compelling argument for the widespread use of this technology in geophysical surveys.

The test sites were chosen to provide extremely different challenges to the system. The first, Bull's Lodge, overlies a well-known sand and gravel deposit where the principal problem was to perform deep penetration electromagnetic surveys to map variations within the sand and gravel body, but also its base, at depths of up to 20 metres. The second site was Wroxeter roman city, where the primary objective was to produce a magnetic survey of the archaeological structures. This is an exacting task demanding very high data quality from the magnetic measurement, and excellent navigational accuracy since the features under investigation may be less than 1m across.

The project started on September 1st 2003 and within 3 weeks the MSP system was upgraded and adapted for the new types of surveys, and deployed in the field for 3 weeks of continuous fieldwork. The field period was blessed with excellent dry weather and no major interruptions to the overall survey plan. Support from project partners with the logistics throughout this period was excellent. Quality Assurance checks on the data during acquisition in the field led to an expectation that the required quality of data was being achieved, and the survey targets were being located.

The Bull’s Lodge data provide comprise a set of five separate electromagnetic surveys with increasing depths of penetration. Viewed sequentially they provide images of the subsurface as a series of horizontal slices at increasing depths sub-surface. These clearly show the presence of a resistive body corresponding to the known location of the sand and gravel. More importantly, the data also indicate lateral variations within the sand and gravel layer. Two resistivity imaging profiles were recorded across the survey site. These are completely independent of the MSP data, but confirm the resistivity structures located by the MSP electromagnetic survey. The imaging profiles were located to pass through borehole locations, and the resistivity images also correlate with the borehole data.

At the Wroxeter site the MSP operated with a substantially different sensor package, mainly using an array of six magnetometers. Data acquisition was as rapid as had been anticipated. Data processing was more time consuming than had been anticipated due to the necessity to correct each magnetometer sensor for its own individual offset and heading errors. Having completed this, the resulting magnetic map shows the location of the archaeological features as detected on previous surveys. English Heritage carried out a separate magnetic survey of the same area using similar sensors but in a more conventional mode of operation. Their data have higher resolution than those from the MSP, and neatly illustrate the trade-off between the different survey methods.

Overall the project has demonstrated the versatility of the MSP and its ability to produce rapid, high quality data acquisition in a wide range of environments. The dense data sampling over extensive areas offers the possibility of developing new interpretation and imaging methods to exploit the wealth of detail in the data. Such methods will provide new tools to examine the 3D variation of the shallow sub-surface for a wide variety of applications.
1.2 Project Aims and Objectives

To test the feasibility of the use of the geophysical multi-sensor platform (MSP) to perform rapid, cost-effective geophysical surveys of potential sites of mineral extraction. Such surveys must be of high enough resolution to detect small, weak anomalies due to archaeological features, but also penetrate deeply over a large area to provide an assessment of the mineral potential. Specific objectives are thus:

- Adapt the current MSP for the purposes of the two surveys.
- Survey a site with known archaeology and pre-existing geophysical data.
- Survey a known mineral deposit with economic significance and show the data are relevant to that deposit.
- Assess the quality of the results with regard to both the geophysical resolution and accuracy of the data, and the value of the data for the particular application.

Leicester will enhance their existing MSP system with new equipment, supplied and given technical support from Geomatrix. Detailed geophysical surveys will be carried out at sites chosen by Hanson and English Heritage to test the capabilities of the MSP system with respect to its depth of penetration (mineral application, Hanson) and small-scale resolution and accuracy (archaeological application, English Heritage).

The survey of a known mineral deposit will be at the Bull's Lodge Sand and Gravel deposits near Chelmsford, Essex. This is worked by Hanson plc who will provide background information including results of major drilling campaigns, and site access and logistics. This site also has some known archaeological features.

The survey of a known archaeological site will take approx 1 week. This will be the Wroxeter Roman city near Shrewsbury. English Heritage will supply their own pre-existing data for this site, and mount a comparison survey using their own newly developed equipment.

From November to February Leicester will process, analyse and interpret the data using in-house software and that supplied and supported by Geosoft. During the interpretation there will be liaison with the relevant party, Hanson or English Heritage.

Leicester will produce a final report with recommendations by the end of February. MIRO will help to manage the project, and to disseminate the results both as a report and CD, and as a website.

Expected Results:

- Case histories for geophysical surveys of two contrasting sites.
- A report detailing the potential for development of this system for (a) increased resolution (b) range of measurements and (c) optimum efficiency for a range of different survey applications.
1.3 Project Partners

Department of Geology, University of Leicester

Established nearly 50 years ago, has a well-established spectrum of taught courses and a Research Grade of 4. The geophysics group is one of the major active sections of the department with an international reputation. The university as a whole lies in the top 20 UK research institutions.

Geomatrix Earth Science Ltd

Formed 3 years ago from the merger of Geometrics UK and Earth Science Systems, the company has a history of sales and supply of geophysical equipment over some 20 years. Increasingly the company is involved in technical development and innovation. Based in Milton Keynes, they provide services to (mainly non-hydrocarbon) exploration geophysics throughout Europe.

Hanson plc.

Major multinational company which has extensive interests in aggregate production, in UK and overseas. This project connects with the UK aggregate section of the company, based in Kent.

Mineral Industry Research Organisation (MIRO)

MIRO is an industry funded research and information organisation for the international minerals industry, that specialises in assisting member organisations to locate, develop and transfer innovative technology. MIRO was established in the early 1970's and is a non-profit making organisation limited by guarantee. MIRO's main functions are:

- To provide a means of co-operation amongst its members to solve common technical problems.
- To obtain information and data for the industry and act as a point of contact between its' members and national governments and international bodies.
- To provide an industry focus and co-ordination for research and technical development projects.
- To assist the transfer of technology aimed at improving the finding, extraction and environmental production of minerals.

Geosoft Europe Ltd.

The European component of the worldwide Geosoft company which provides and supports the Geosoft software system for processing and displaying geological and geophysical data. Their software is a key product for major companies and institutions such as RTZ and BGS, and is an accepted industry standard.

English Heritage

The national body charged with care and development of heritage issues, particularly for this study, the detection and investigation of archaeological features which may be threatened by development.
1.3.1 Contact Details for Lead Participants from each project partner

**Name and address of the leading project partner**

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1.4 Project Workplan

MIST Feasibility study
Feasibility Study for the application of new integrated technology to the detection, delineation and characterisation of archaeological sites with potential for mineral development.

GANT chart to emphasise the key milestones numbered (1) to (3) and described in the text below.

1.4.1 Project programme and key milestones
The project programme is set out in the chart below, following a logical progression within the short timespan available. Key milestones are identified by the vertical bars labelled (1) to (3), which are:

1. Mid-October - completion of fieldwork. Especially limited by the daylight and weather opportunities as well as the time constraint on the project, this is a crucial milestone. Attaining this will confirm that the installation and testing of new equipment has run smoothly. As one of the innovations of this project, this is inevitably an area where some new challenges may arise, although our previous experience with the system leads to a high level of confidence.

2. New Year – completion of basic data processing. This must be met to enable sufficient time for interaction with the client members of the consortium on the interpretation of the data.

3. Start February – interpretation completed. This milestone must be met to allow a suitable period for reflection on the project and production of future development plans and final report.
1.5 **Approach and methodology**

1.5.1 **Development of Geophysical Surveying**
As technology advances, particularly digital and communications technology, data collection and processing applications must continuously evolve. Considerable impact on geophysical surveying has come from developments in navigational systems (Differential Global Positioning System, DGPS), geophysical sensor development, rapid wireless data transmission, and the rise in power of field portable computers. The combination of these factors leads to the opportunity to collect more accurate data, better located, and transmit it to field computers for Q/A and processing. All of this can be done more quickly. The overall result is to be able to collect more data and process it more quickly, leading to an increase in quality and a decrease in cost of the survey. Additionally, the prospect lies ahead that the data can be processed and displayed in a geologically meaningful way in near real-time. This not only reduces costs further, but also leads to the possibility of modifying surveys in real-time, to design and conduct follow-up detailed surveys to investigate interesting features. The advantages of seeing an interpretable image in near-real-time, over a written report some weeks later are immense.

1.5.2 **The MSP Concept**
Our approach to harnessing these advances in technology has led to the design of the Multi-Sensor Platform (MSP). The key concepts derive directly from the points above. Firstly, no single geophysical parameter can be uniquely diagnostic of a particular subsurface structure. Measuring multiple physical parameters simultaneously, vastly increases the value of the data for geological interpretation. For instance, Iron and saturated clay are both electrically conducting, but only one is both conducting and strongly magnetic. Combining multiple data sets requires very accurate navigation. This constraint becomes less difficult if the measurements are made simultaneously by sensors in fixed relative positions. Making multiple measurements on one pass over the ground also inevitably speeds up the survey process. This is the first driving logic of building a system that has multiple sensors to record different parameters simultaneously.

This does however lead to two other problems: mutual interference between sensor systems, and the need to monitor data quality as the survey proceeds. We solve both of these problems by minimising the electronic equipment close to the sensors by telemetering the data from the sensors to a fixed ground station where it can be logged and displayed for instant QA. We also appreciate that different surveys will demand different combinations of sensors, so the system must be “open” to accommodate any selection from a wide range of possible geophysical sensors.

Thus the principle features of the MSP system are:
- An accurate and reliable navigation system and adequate power supply
- Simple connection for data input from a variety of sensors (currently up to 6)
- Telemetry to transmit the data to a remote station
- Software to receive the incoming data and display it in real-time for QA and survey management.
- Software to provide an onward data flow to rapid field data processing and display.

1.5.3 **Progress under the FIESTA Project**
Under the FEISTA project (DLI Foresight LINK project) we have developed the system to provide a fieldworthy data acquisition system following the principles outlined above. The current system is illustrated schematically in the block diagram (Figure 1) and as its actual implementation in Figures 2 and 3.
Figure 1  Schematic diagram of the MSP system

Figure 2  The MSP system in the field. The sledge carries the sensors including GPS and compass, and is towed and powered by the small tractor. The data is telemetered to the van where the data is logged on a laptop PC.

Figure 3  The laptop PC displaying the survey track (lower panel) and the various data parameters from sensors either as numeric or waterfall displays.
This system has completed numerous weeks of field survey over different terrains and has been developed to be effective and robust. It collects multiple data streams while travelling at a speed of about 4 mph, and requires no pre-survey to locate marker pegs or grid lines. This saves hugely on time spent in the field. Within the FIESTA project it has successfully contributed to the program of mineral exploration in Derbyshire. This has proved that data are accurately recorded and positioned. Repeat surveys produce duplicate data. The resulting geophysical anomaly maps have provided new interpretations of the geological structure, which can be tested by drilling.

1.5.4 New developments for this project
The main activity of this project is to extend the capability of the system with new combinations of sensors and test the value of the resulting system by conducting a complete data collection and interpretation case study on a well-controlled site.

For the detection of archaeological features in the subsurface, the most versatile and widely used technique is magnetic surveying. The current MSP has the facility to deploy two magnetic sensors simultaneously. A key issue in archaeological surveying is that the targets sought are small, often less than 1m across, and shallow, less than 1m deep. The combination of size and depth means that the anomaly to be detected is small in horizontal dimensions. It is also often very weak in terms of magnetisation. This problem of small, weak targets is best attacked by making measurements at very close spacings, with very accurate instruments. Caesium vapour magnetic sensors are now available which have very high sensitivity (0.01 nanoTesla) combined with a fast rate of reading (0.1 sec.) This combination means that if such a sensor is carried along at walking pace it will take readings every 0.1 to 0.2 m along the survey line. On the MSP, multiple sensors can be attached at constant separations perpendicular to the survey line, so multiple survey lines are recorded at once. We intend to extend the system to 6 sensors for this project. Currently 6 of these sensors are not available for hire in UK, so we include in this proposal the cost of buying two, with four more being hired from Geomatrix.

For surveying mineral deposits, such as aggregates, a very useful subsurface property is the electrical resistivity. While this can be measured by inserting metal electrodes in the ground, this is not easy for mobile methods. We intend to use an electromagnetic technique. The Geonics EM34 is a well-established exploration tool, usually deployed by two men walking along survey lines and stopping at intervals to take readings. It is possible to modify the EM34 instrument to take readings at regular intervals (< 1 sec.) and output the data as a serial data string which can be recorded by the MSP. Deep penetration (>10m in this context), can be by increasing the separation between the electrical coils of the system. Geomatrix can modify their EM34 instrument to produce this output data, and Leicester and Geomatrix will collaborate to build a towing system so the instrument can be deployed with variable coil separation in the range 5-30 metres.

1.5.5 The case studies (1) Mineral extraction.
This case study will be carried out at the Bull’s Lodge aggregate deposit near Chelmsford, Essex, worked by Hanson. This large gravel deposit has been drilled on a regular grid and is now in active production. The main gravel layer lies at depths of 5 to 15 metres and varies substantially in thickness and quality. While the MSP will be making surveys of magnetic, natural gamma radiation and shallow conductivity measurements, the main emphasis will be on assessing the effectiveness of the towed EM34 system, both for collection of data, and then for geological application by correlation to the known control points at the boreholes. The area to be surveyed is in excess of 70 hectares. This will need to be covered several times with different EM34 coil separations to provide a measure of the depth of the deposit.

Particular questions to be answered concern the mutual interference between the EM34 system and other sensors, and the usefulness of the continuous stream of output data in relation to the widely separated values which would result from conventional surveying.
Hanson will provide access to all the relevant exploration data on their deposit, both borehole and grab sampling on quarry faces and trial pits. They will also provide access to the site and relevant health and safety precautions for surveying on a working quarry site. They will liaise and advise on the details of the location and conduct of the survey, to ensure it ties in well to their geological control. After the survey, they will follow up results as appropriate with drilling/excavation, and collaborate in the geological interpretation of the data.

This site has also recently been found to have archaeological features, including hut-circles. These are not well enough defined to be sure that they would provide a benchmark test of the system, but will provide another aspect of interest to the interpretation of the shallow data.

1.5.6 The case studies (2) Archaeology.
The roman city site of Wroxeter is very well known and has been extensively investigated archaeologically and surveyed geophysically. With a wealth of background information, it provides an excellent test of the precision and accuracy of the system, particularly for magnetic data. Here the major factors which are critical in providing high-quality maps for archaeological interpretation are a high density of accurately positioned data points, and the precision of the individual data values. There is an additional trade-off in the requirement to have high data density, but also to survey large enough areas to reveal large-scale structures such as road and dyke systems. The ideal of high data density, of high precision points over large areas is scientifically attainable, but usually prohibitively expensive.

The MSP system tackles this problem by employing multiple sensors to acquire data rapidly. We are intending to use 6 sensors in this case, but the engineering limit for the system would be in excess of 20. Using DGPS navigation, and having no requirement for pre-location of survey grids, the data collection can be rapid and cover large areas. There may be a trade-off that the additional electronics of the navigation and telemetry systems will produce background magnetic noise on the sensors.

English Heritage are tackling the same problem for magnetic surveying by building a system which is as magnetically quiet as possible, but less capable of autonomous navigation and data handling. At the Wroxeter site we will test both systems over the same well-known test area and gain insights into the development paths for both systems from the comparison of the data.

The MSP system will also be used for resistivity, radiometric and EM surveys at the site. It is quite possible that we will determine that the two systems have complimentary uses: the MSP for large area multi-sensor surveys, and the English Heritage system for detailed localised follow-up.

1.5.7 Analysis and processing of the data
Data analysis for the MSP data is carried out by pre-processing formatting and verification of the data by our own in-house software, followed by input to the Geosoft Oasis data analysis and plotting software. This processing flow is well-established from the previous FIESTA project.

This project will face new challenges in terms of navigational accuracy for the archaeological surveys, data volume for the multiple magnetic sensor surveys, and a totally new data type from the EM34 data.

Navigational accuracy will be upgraded by using the latest DGPS system with satellite derived differential corrections. The multiple magnetic sensors will provide only new technical issues, and the increased data volume is not expected to produce particular problems.
The EM34 data will be a novel data-type in the sense that such a densely-sampled data volume is very unusual. We expect it to produce high-quality, reliable data where noise due to near-surface effects (services, concrete) can be easily identified.

1.5.8 Geological interpretation and assessment
This must necessarily be a product of the combined input from all partners led by Leicester, Geomatrix, and Geosoft on the technical side and Hanson and English Heritage on the geological/archaeological interpretation.

This will require a round of discussion meetings between the partners, probably on a bilateral basis at first, (pre-Christmas) followed by a partner meeting in January, which will move on to outline the main features for the final report.

1.5.9 The final analysis
The final report will provide a documentation of the case studies, critical analysis of achieved data quality and the pathways forward to develop the system and improve its performance.

1.6 Narrative of Project Progress

1.6.1 Timescale
The project period was 1st September 2003 to 29th February 2004. Within this period the field case studies were carried out in four weeks in late September and October. The remaining time was spent in analysing the data. This phase consisted of critically assessing the performance of each individual component of the MSP system, as well as processing the data to a stage where geological interpretation could be carried out.

1.6.2 Personnel
It was planned that a post-doctoral research fellow would be employed to carry out the bulk of the scientific work. In reality, since notification of the award did not come through until shortly before the project start, then there was little time to advertise and recruit a suitable person. Two eligible candidates did not apply because of the short term of the contract. In consultation it was agreed that Ian Hill would carry out the scientific work, and the salary component of the grant would be spent paying others to cover his teaching commitments. Dr Norry and Dr McKenzie, both of the Department of Geology, Leicester did this for the first Semester of the academic year, up to February 2004.

Research Student Tim Grossey was employed to assist with the field work. Tim was ideal in this role since he had been heavily involved in the development of the MSP in the FIESTA project. Tim was employed also for the period of February 2004 to complete the data processing while Ian Hill had to continue his teaching commitments.

1.6.3 Equipment
A requirement for the archaeogeophysical survey was to establish the effectiveness of surveying with multiple magnetic sensors simultaneously. Due to the difficulty of renting enough of these, two sensors were bought for the project. These caesium vapour magnetometers were Geometrics G823B units built to a high specification with a very low heading error. Combined with all available sensors supplied by Geomatrix, this allowed 6 sensors to be deployed simultaneously.

1.6.4 Fieldwork
The data collection component of the feasibility study was carried out over the period 16th September to 17th October, as planned. This incorporated two weeks fieldwork at Bull’s Lodge site in Essex, and one week at Wroxeter roman city in Shropshire. The fieldwork ran
to plan. Several aspects of the geophysical systems were novel, particularly the use of
towed, continuously recording EM34 system (Bull’s Lodge). There were some minor
equipment faults and breakdowns but extensive suites of data were collected at both sites.

The fieldwork period ran entirely to plan and was blessed by four weeks of almost totally dry
weather. It was greatly facilitated by backup support by the relevant project partners,
Hanson, English Heritage and Geomatrix. After two days equipment testing at Leicester, two
weeks were spent at the Bull’s Lodge site in Essex, and one week at Wroxeter in Shropshire.
The detailed schedule was a function of the varying equipment availability throughout the
field period.

1.6.5 Data Processing
The data collected have been archived and have now been processed. The processing has
raised a number of new problems since no data of this type have been processed before.
Particular problems relate to the accuracy of position determination for the MSP, the
calculation of absolute position of each individual sensor on the MSP, and the calibration,
heading error and mutual interference between sensors and the MSP logging systems.

Initial reviews of the data are very encouraging. The gravel deposit at Bull’s lodge is clearly
a resistive target with much variation within it. The MSP is seeing such variations in
resistivity.

The data processing will be described in detail later, but has been a lengthy process. On
each field site particular items of equipment were deployed on the MSP for the first time;
EM34 conductivity system at Bull’s Lodge and 6 magnetic sensors at Wroxeter. Each type of
data threw up new problems, partially a function of the very dense data sampling that
revealed several features of the instrument performance that had not previously been
appreciated.

1.6.6 Presentation of Results
This document is the final report of the project, and as well as satisfying the requirements of
a final report of this project, the separate field studies provide a data report for English
Heritage as a requirement of their survey licence, and a useful survey report for Hanson.

A summary of the project will be presented by Ian Hill at a MIST project meeting at BGS,
Keyworth on March 26th. Tim Grossey will give a paper at the meeting of the European
Geophysical Union meeting in Nice in April 2004 including some of this work, and Ian Hill will
be presenting a paper based on this work at the European Association of Geoscientists and
Engineers (EAGE) in Paris in June 2004. A further presentation of results of the Wroxeter
case study will be given by Ian Hill at the Near Surface Geophysics Meeting in Utrecht in
September.

Substantive published papers will be submitted on the same timescales.
2 Multi-Sensor Platform (MSP) System Development

The MSP system allows a field crew of 2 people to operate autonomously and produce geophysical data in one day, which would take a crew of four or five over a week to collect using conventional methods. Any instrument can be accommodated provided only that it produces a serial output string, and that it does not mutually interfere with other instruments on the platform. The target time from end of data acquisition to production of first draft survey data plots is 30 minutes.

The main component of the system is the MSP itself. This is a lightweight sledge with mounting brackets for a wide range of geophysical sensors. The sledge is geophysically undetectable being made from a variety of plastic components and plywood. Essential permanent components of the sledge are a DGPS antenna and a three-component fluxgate compass. Both of these produce digital output as serial data strings that allow the determination of the position of each individual geophysical sensor on the platform. The serial data from these two navigation systems, and from up to 6 geophysical sensors, is multiplexed together into an Ethernet signal and broadcast by Wireless LAN (WLAN) technology to a recording station where the data are viewed in real-time and logged on a laptop computer.

The towing vehicle is a small tractor. This was chosen as providing the necessary motive power, with the minimum geophysical signature. When towing the MSP with an 8 m towing cable, it is invisible to EM systems, and produces a magnetic heading error of less than 1 nT. The tractor is necessary since in routine surveying the system can survey at 7 line km per hour. Using instruments with a sampling cycle of 0.1 Hz, such as the EM38, EM31 or Cs Vapour magnetometers, this gives a sample interval of about 0.15 m along track. The tractor carries an LCD display for the driver showing his survey track plot so that he can check his line positioning and modify it as necessary when he encounters physical obstructions such as trees and field boundaries. The tractor also supplies power to the sledge at 12 and 24 Volts DC. With multiple geophysical instruments operating continuously, changing separate battery packs in each instrument would be highly inefficient.
The data logging base station consists of a WLAN base station linked to a Laptop computer. Geometrics’ Maglog software is used to display the incoming data and to write the serial data strings to text files. Separate data files for each instrument are merged together with the position information in a single database file in CSV format. This can then be directly input to a commercial processing package (e.g. Geosoft Oasis Montage) or subject to further pre-processing in alternative commercial software or user-generated applications. While it is convenient to run the base station inside a vehicle, on sites with particular access problems all the base station equipment can be placed in a wheelbarrow and moved as necessary manually. It is possible to run the system with two laptops at the base station linked by an Ethernet hub. In this case the survey observer can be processing data on the second one, while monitoring the current survey on the first.

2.1 Physical structure

The MSP is built of a frame of plastic pipes with a deck of plywood to give a firm mounting position for instrumentation. The fluxgate compass unit and DGPS antenna have fixed permanent positions. The signal multiplexer electronics are also mounted on the platform at the front end. All these components are essential to system operation and are always present. The base of the tubular frame is supported on Nylon “skis” which provide a durable low-friction running surface for the sledge. Wheels were rejected for a variety of practical reasons, including complexity, geophysical noise, and sledge stability. The sledge is towed by a Kevlar strain member that is encased with electrical cables in a tough outer sheath.

![Figure 2-2 Scale drawing of the MSP with the usual location of geophysical sensors annotated.](image-url)
2.2 Power supply
The MSP is designed to run for 6 to 8 hours per day collecting data. During that time the geophysical sensors will be running continuously. Such usage makes heavy demands on battery packs, and the design of the MSP has always incorporated the ability to power the on-board instruments from the towing vehicle, such that system failure due to individual batteries losing power would not occur. Generally this requirement is not difficult since most geophysical systems are designed to use minimum power to conserve battery life. During the surveys at Wroxeter 6 Caesium vapour magnetometer sensors were used simultaneously. Each requires a nominal current of about 0.5 Amps at 24 V for normal running, and more during switch-on and initial heating. This continuous drain of 3 Amps at 24 V required an upgrade to the power supply system such that additional 12V batteries were carried on the tractor, and the DC converter producing the 24V output was upgraded.

In normal use the power supply box on the tractor contains DC-DC converters to provide 24V, 12V and 5V outputs that are available both on the tractor, and on the MSP.

2.3 System transport
In Figure 2.1 the full system is shown with a long-wheelbase panel van as the transport. The MSP is carried into the van and supported on slings from the roof. The tractor is then driven in on ramps and parks under the MSP. The dry relatively clean space provided by the van makes a convenient office and repair shop. As a simpler transport option, both tractor and MSP can be accommodated on a small two-wheel trailer that can be towed by any car. The disadvantage of this system is that there is no security for the contents of the open trailer, nor protection from weather conditions. Additionally there is no convenient “dry” space for the base station.

2.4 DGPS system.
The system was initially designed with the basis of the navigation being a differential GPS system. For the mineral surveys which were the original objective, positioning to an accuracy of about 2 m was considered adequate. Since that original design the accuracy of DGPS fixes has been increased by several unrelated changes. Selective Availability, the degradation of the GPS signal by the US military was abandoned. The Ordnance Survey have constructed additional DGPS beacons in the UK. The EGNOS European geostationary satellite system giving differential corrections is on trials prior to formal commissioning during 2004. All survey locations for the MSP used during this project were obtained using EGNOS differential DGPS. Informal tests show that the accuracy of fixes is sub-metre. A difficulty is that since the system is not formally commissioned, the satellite signals are not totally stable, and portions of the survey were conducted with no differential correction being available. This is mentioned where relevant in the case studies.

For the Bulls Lodge surveys using EM34, a second DGPS was mounted with the second coil on the second sledge. This was a conventional ground-station corrected DGPS system. There is some evidence of sudden offsets in the relative positions provided by these systems, but this has not been investigated in detail.

DGPS navigation was chosen since it is simple to operate, readily available, and sufficiently accurate for most applications. In principle any other navigation system could be used if more appropriate. Both RTK GPS and tracking total station EMD are viable alternatives, as long as they can output a continuous serial data string which can be merged with data from the MSP itself. Neither of these possibilities has yet been explored.

2.5 Data Capture and Telemetry
The telemetry system on the MSP can accept up to eight separate serial data channels, normally running at 9600 baud, though lower speeds are acceptable. Two of these channels are taken by the DGPS signal and the compass, leaving 6 channels for geophysical sensors.
The serial signals are multiplexed together and broadcast by 802.11b Wireless LAN technology. The bandwidth of this wireless system is sufficiently large that there is no constraint on the length of serial data strings produced on the MSP, or their frequency. In fact, the wireless communication seems to maintain signal lock better at extreme ranges when there are larger volumes of data being transferred.

The maximum range for the WLAN link has not yet been determined. Provided line of sight exists, the range is at least 1 km. Tests at greater ranges have not been carried out since they are largely irrelevant. With 1km range, the MSP could survey over 3 km² without the base station moving, and this is more area than can realistically be surveyed in one day. In any case, the base station may be repositioned with relative ease. For the efficient function of the system, the tractor driver and the observer at the base station stay in speech radio contact. The range of this radio system is also relevant, and is untested beyond 1 km.

When making magnetic surveys a magnetometer base station is routinely established some distance from the MSP base station. The magnetometer signal is broadcast over a separate serial VHF radio link to the MSP base station where it is logged with the other sensor data.

The MSP base station runs using Geometrics Maglog software. This system was originally intended for airborne applications where serial data from sensors in the aircraft are gathered and logged on a PC computer. While it performs the basic logging function well, the software has some disadvantages. When the WLAN link loses signal, the Maglog software issues warning messages, but rapidly gets into a closed loop and locks the computer. The logging computer has to reset, which initiates a scandisc check, and this means it takes roughly 20 minutes to reset the system. Since this may be caused by loss of signal for only a few seconds while the MSP passes behind a tree, this can cause lengthy and repeated delays of data acquisition. It would be preferable to have a logging system which records continuously, flags the absence of valid data, but just continues to log, eventually recognising the re-establishment of radio linkage with valid data.

### 2.6 Post-processing Software

Two software units have been written to speed the post-processing of the data. The first “Interpol”, takes the separate ASCII data files produced by the Maglog software and combines them into a single uniform flat database structure, also as an ASCII file. This database file can be used as input directly to Excel, Geosoft Oasis, or any other preferred package. The second, “MSPDP” reads the flat database file and can extract particular data types, calculate the corrected position of that geophysical sensor at the time of the measurement, and outputs another standardised ASCII file. This again can be easily read into other software.

While these programs do not carry out any fundamental processes that could not be carried out in other packages, their importance is in speeding the dataflow from initial logging, to meaningful data imaging. With a fairly full instrument load, the MSP records megabytes of data per hour. Efficient handling of this data through the post-processing stage is essential to the usefulness of the system.

#### 2.6.1 The Interpol program

This is written in Visual Basic and provides a graphical user interface that allows the user to select the files to be merged for any one survey. Each file is initially read to detect data format errors or other inconsistencies. These can be automatically edited out of the data file before the data merging operation is attempted. While parts of this editing operation are trivial, having to carry out this operation by hand is extremely time-consuming and prone to error. For example the DGPS signal file for one hour of surveying will have 18000 lines of GGA data strings.

Edited data files are then merged, using the time from the DGPS signal as the master signal. All data channels are interpolated or decimated as required to a constant master sample...
interval. Where the real data are more widely spaced than 2 data sample intervals, interpolation is not carried out, and the unfilled data fields are filled with asterisks, as a standard null character. Where appropriate data fields are created to give indication of the quality of the geophysical data being interpolated.

Using the data from the compass unit, the data is allocated sequential line numbers, where the end of a straight section of track is automatically detected, and the line number incremented when another section of straight track is being created. On the intervening turn, the data may be prone to additional errors due to proximity of the towing tractor to geophysical sensors. Such sections of track on turns are given a separate series of line numbers so that the turning tracks can be easily isolated. Such turns are normally excluded from geophysical data analysis.

The merged file can then be used to produce a simple track plot diagram that shows the quality of the DGPS signal along the track, changing the display colour depending on the number of satellites, or the latency of the differential correction.

2.6.2 The MSPDP program

This program reads a standard file output from the Interpol program. The user is presented with a graphical display of the MSP and can interactively specify the location of each of the geophysical sensors relative to the DGPS antenna. A particular geophysical sensor is then selected and the program uses the combination of DGPS location, sensor position on the MSP and orientation of the MSP from the three axis compass unit, to calculate the precise position of that sensor for each sample interval of the input file. The output data are written to another ASCII file. Such positional corrections can be performed in other software packages, but not so simply and quickly as in this manner.

2.7 System Operation and Reliability

As detailed in the case histories, the MSP system performed up to expectations and produced high quality data. This is an excellent result. However, the current system is a prototype, and is not a fully developed operational system. An essential aspect of the feasibility study is to examine what went wrong with the system.

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Power supply connectors: Tractor seat
Equinox Overheating
Wlan power supply connectors
GR256 vibration, Maglog shutdown
Temporarily lost 3rd gear
Power supply voltage
Puncture -2 hours lost
Physical damage to one sensor cable

Figure 2.3 shows an analysis of the system breakdowns. The rows represent individual days of the survey period, with the numbers being the date in September or October 2003. The columns indicate the type of system failure. An immediate conclusion is that the geophysical
sensors, which are represented in most of right-most nine columns, are robust and reliable. The motion and/or vibration on the MSP does not appear to cause particular problems. A possible exception to this is the Gamma Ray Spectrometer (GR256) at the Bull’s Lodge site where certain parts of the survey area were very hard and rough, causing serious vibration of the MSP.

For the MSP itself, the story is not so good. The vast majority of the breakdowns involved failure of the WLAN system. In the design of the electronics of the MSP, commercially available WLAN components were bought and mounted on the MSP, with shock-padding as appropriate. Nearly all of the WLAN failures involved temporary loss of electrical contact at an external connector, for power or signal. Such events are not serious in themselves, but they invariably triggered the Maglog logging software to crash. This combination of events results in each of these temporary failures, of perhaps one second duration, taking down the system for about 20 minutes. This is clearly unacceptable. In the light of this analysis the WLAN system has been redesigned and repackaged to remove what are essentially “office” environment connectors. It is expected that this will improve the reliability of the system considerably.

The tractor itself had several failures. These were mainly connected with the severe vibration at the Bull’s Lodge site. The system was repaired and strengthened as the work progressed. There were no such breakdowns at Wroxeter. Loss of time due to punctures has been minimised by carrying a spare wheel.

### 2.8 Survey methods

#### 2.8.1 Planning of survey tracks

It is conventional to collect geophysical data along regular straight lines of a pre-surveyed grid. There is considerable body of logic behind this in terms of uniformity of sampling, and subsequent processing of the data. The MSP concept was however born from the need to cope with surveying in small, complex field shapes in Derbyshire, where any attempt to maintain a regularly spaced rectangular grid would be either very time-consuming or impossible. The positional autonomy of the MSP system is one of its great advantages. No pre-survey is required. The MSP can move round obstacles, collecting data where possible, and adapting the survey track plan to the natural barriers present.

A survey plan gradually evolved from field experience. The major influence on this is that the MSP has degraded data quality when turning corners. Here, the tractor position is indeterminate relative to the MSP, and it will often approach the MSP. This leads to erroneous readings on EM or magnetic sensors. To minimise this, 180-degree turns are avoided where possible. The usual track plan is thus to start by make circuits round the outside of a survey area spiralling in towards the centre at the required track spacing. When such outer tracks have covered sufficient ground all around the periphery of the area for the MSP to turn and re-align itself, the remainder of the area is infilled with a grid of parallel lines, ending with perpendicular tie-lines. Such track plans have been used in both the case studies reported here.

The advantage of the above system is speed and efficiency. All the accessible area is covered by data tracks efficiently. The disadvantage is that established software for analysing data errors such as magnetic heading error relies on regular grid patterns of data. There is a need here for a more detailed analysis of the essential qualities required of a field track plan such that the competing demands of logistical convenience, and data processing integrity, can be reconciled.
2.8.2 Instrument packages

The physical structure of the MSP easily accommodates a large range of geophysical sensors. The essential limiting factor to what may be accommodated simultaneously is the issue of mutual interference between sensors. Most obviously, high accuracy magnetic sensors will be degraded if virtually any other system is added to the MSP. Even the MSP’s own electronics may cause a small effect. To minimise this, the magnetic sensors are always mounted to the rear of the MSP, away from the electronics modules. Interestingly, the control electronics for the Geometrics G858 magnetometers causes as much magnetic interference as does the MSP itself. Both these effects are down at the 1nT range.

Deciding which sensors to use together is a compromise between ultimate data quality and time in the field. If a heading error of a few nanoteslas is acceptable on magnetic data, then the MSP can be used with multiple magnetometers, EM31, EM38 and Gamma ray spectrometer simultaneously. The situation is analogous to that of borehole logging, where for any specific application it is possible to devise packages of instruments that can run together to optimise file deficiency without unacceptable compromises on data quality. While there can be general guidelines, the detailed solution will be specific to the requirements for any individual site.
3 Case Study 1: Sand and Gravel Mineral extraction at Bull’s Lodge, Chelmsford.

3.1 Introduction and Objectives

The data collection component of the feasibility study was carried out over the period 16th September to 17th October, as planned. This incorporated two weeks fieldwork at the Bull’s Lodge site in Essex. The fieldwork ran to plan. Several aspects of the geophysical systems were novel, particularly the use of towed, continuously recording EM34 system. There were some minor equipment faults and breakdowns but extensive suites of data were collected at both sites. The weather throughout the period was excellent.

The Bull’s Lodge site lies a few kilometres to the North of the centre of Chelmsford, and is the location of a former WW2 airfield. The airfield has since been used as a test track for the Ford motor company, and the north-eastern corner is the base of the Essex police helicopter and the Essex air ambulance unit. The current workings by Hanson are based at the southern extremity of the airfield runways. The Runway system lies on the summit of a low hill at about 50 metres elevation.

The data collected have been archived and have now been processed. The processing has raised a number of new problems since no data of this type have been processed before. Particular problems relate to the accuracy of position determination for the MSP, the calculation of absolute position of each individual sensor on the MSP, and the calibration, heading error and mutual interference between sensors and the MSP logging systems.

Initial reviews of the data are very encouraging. The gravel deposit at Bull’s lodge is clearly a resistive target with much variation within it. The MSP is seeing such variations in resistivity.

Figure 3-1 location map of survey area(shaded) at Bull's Lodge
3.2 Geology of the Site

Extensive drilling by Hanson and former operators of the quarry have defined the extent of a large sand and gravel deposit. This deposit is overlain by Boulder Clay, and lies unconformably on the London Clay. The sand and gravel deposit varies from 5 to 10 metres in thickness and the overlying Boulder Clay varies from 0 to 15 metres in thickness. The sand and gravel is an electrically resistive layer lying between two conductive horizons.

3.3 Data Acquisition

![Diagram](image)

Figure 3-2 The main survey area, and a smaller survey to the SW of the main hangar. Grey Line is one resistivity imaging profile, Line D. Black line is the EM34 calibration line.

From the initial planning of this survey it was expected that electromagnetic (EM) surveying would provide an effective tool for detecting the sand and gravel layer. The survey was planned to investigate what degree of detail could be determined in such a circumstance,
and whether the EM systems could detect the base of the unit. Using the MSP would allow efficient data acquisition over a large, open site. The multi-sensor capability also allowed magnetic and radiometric sensors to be carried for additional detail. The site does have surface archaeology, but the extent of this is unknown, so it cannot be used effectively as a test of the ability of the MSP system to detect archaeological structures.

The main site, referred to as area 1, was surveyed several times with different EM systems. Additionally a smaller area to the southwest of area 1 was also surveyed with one EM system. All surveys were primarily designed to optimise the data collection of the EM systems. EM systems selected for the survey were those manufactured by Geonics, the EM38, 31 and 34, which have increasing depths of sub-surface penetration. The survey tracks were arranged to cover the whole of the survey area, but the spacing between tracks varied according to the sampling volume energised by each type of EM system. Figure 3.2 shows the borehole control over the survey area, and the tracks used for survey with the EM34 system with 20 m coil spacing. Figure 3.3 shows the tracks for area 1 using the EM31 and EM38 systems. Since these latter systems have a much smaller penetration depth (<6m) and also horizontal sampling extent, the tracks were at a nominal 5 m spacing, while track lines for the EM34 varied from 10 to 40 m, depending on inter-coil spacing.

![Figure 3-3 Track lines for EM38 and EM31 survey in Area 1. Red lines show the resistivity imaging profiles, north-eastern line, Line C; south-western line, Line D.](image)

As a control on the effectiveness of the EM systems, and a calibration of their data values, a Lund resistivity imaging system was used to collect detailed profiles along two sections chosen to run across the area and intersect the location of boreholes. These are shown on Figure 3.3.

The main purpose of this survey period was to assess the ability of the MSP system to use relatively deep penetration EM survey techniques. For the EM34 system, one survey coil was attached to the main MSP unit, and the second was towed behind on a separate sledge system. A second DGPS system was placed with the second coil so that each coil was
independently located, and when coil separation was not held constant, such as when the system turned at the end of a survey line, this could be detected. The location of all EM measurements has been taken to be midway between the two coils. The appearance of the system while making this type of survey is shown in Figure 3.4.

Figure 3-4 MSP system surveying using the EM34 instrument with 10m coil separation. The two DGPS systems are visible as the black circular, and white conical antennae by the leading and trailing coils respectively.

All the EM systems produce digital output of their measured parameters at 10 Hz, so with the system moving at maximum speed, the sample interval along profile is about 0.2 m. This dense data sampling along profiles contrasts with the sampling that might be made using the systems in conventional man-portable mode, where data might typically be taken at intervals of 25% of the coil spacing, for these surveys this would be 5-10 m. The statistics for the sets of EM data are shown in Figure 3.5. The major benefit of this dense sampling is to provide great redundancy in the data such that very small-scale variation in the resistivity values can be monitored, and tested to distinguish between random system noise, and real geological signal. In this survey, the control lines provided by the Lund resistivity imaging system also verify the quality of the resistivity values. Each of the EM systems routinely outputs values of electrical conductivity in millimho per metre. Since the data are being compared with the resistivity data, all values given in this report have been converted to resistivity in Ohm.metres. The resistivity imaging profiles in turn tie to the borehole control, so the complete data set is very well controlled.

<table>
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Figure 3-5 Table showing the statistics of data collected with various electromagnetic systems.

Subsidiary datasets of magnetic and radiometric data were also collected, but are not reported in detail here.
3.4 Data Processing

![Four profiles of EM34 Resistivity values along the same line as Imaging profile C. The profiles were recorded with the same equipment configuration, but gradually increasing vehicle speed (downwards from the top).](image)

To determine the quality of the EM data recorded with the EM34 system, repeated surveys were made along a single survey line, with the system moving in opposite directions, and at various speeds. The data plots in Figure 3.6 show this data and allow assessment of the repeatability of the data. The horizontal scale is in metres along profile, and the vertical scale is in Ohm m. Some data at the ends of the lines show considerable differences, but this is due to the system turning at the ends of the profile. The top profile was recorded with the
system moving at about 2 km per hour, while the lowest one was at a speed of about 7 km per hour, the maximum speed of the system. Comparison of the profiles reveals that with increasing speed, the data are progressively smoothed, but the data is quite repeatable within very narrow limits. Following this initial test, the whole area was surveyed.

Data were recorded using the standard MSP logging system. The digital output from the various EM systems were in a coded form with data values multiplied by scaling factors that depended on the scale settings on the instrument. The relevant scaling factors were obtained from Geonics in Canada, and the algorithms to convert the output to standard conductivity values were written into the Leicester data processing software. With this in place the data were then merged with the DGPS positions of each coil. These merged data were then input to Geosoft Oasis for further processing. The DGPS positions were combined to give a continuous record of the inter-coil spacing, and the position of the centre of the coil pair, the position allocated to the EM value. The conductivity values and the in-phase response of the system are then monitored. The in-phase response should be almost constant during normal operation. Marked variations in the in-phase response are mainly indicators of a change in the inter-coil spacing, almost entirely due to the system turning at the end of survey lines. The data were edited to exclude any conductivity values where the corresponding in-phase value indicated incorrect coil spacing due to the system turning.

The edited data were converted from conductivity values to resistivity, and these data used to produce the plots in Figures 3.7 to 3.11. These plots each contain the data from EM systems with successively deeper depths of penetration. In each case the colour scaling has been made uniform so that the succession of plots can be viewed as a succession of depth slices through the sub-surface across Area 1.

Figure 3.7 shows the data from the EM38 system with nominal depth of penetration of 1 m. Since the near surface is relatively dry, the resistivity of the surface boulder clay is relatively high for clay, about 18 Ohm m. but relatively uniform. In the south of the area values rise to around 45 Ohm m indicating a more resistive formation in the near-surface. Visual inspection of the ground shows outcropping gravel in this area.

Figure 3.8 shows the equivalent data from the EM31 system with a nominal depth of penetration of 5m. This system can be operated on the MSP simultaneously with the EM38 and both these data sets were collected simultaneously, in about 5 hours of surveying. This Figure shows that the resistive layer is more extensive in the southern part of the area at depths of a few metres. Over the majority of the area however, a fairly uniform value of some 18 Ohm m indicates Boulder Clay continuously to that depth. At the edges of the area surveyed, low values of resistivity indicate not geological structure, but the effect of metal reinforcing in concrete runways, cable conduits, and steel bands in tyres in tyre-walls built along the edge of the runways.

Figure 3.9 shows the first data from the EM34 system, here with 10 m inter-coil spacing giving a depth of penetration of about 7 m. Here the average values over most of the area have risen to about 35 Ohm m, indicating a layer of increasing resistivity with depth. This layer is however non-uniform, resulting in systematic variations in resistivity across the area. These could be caused by either changes in the depth to the top surface of the resistive layer, internal variations in resistivity of that layer, or a combination of both these factors.

Figure 3.10 shows the data from the EM34 system, here with 20 m inter-coil spacing giving a depth of penetration of about 15 m. Here the average values have decreased again to about 18 Ohm m. In the southern part of the area the system is detecting the lower resistivity of the London Clay underlying the sand and gravel. In the northern part of the area however, the average resistivity remains higher, since here the sand and gravel layer is deeper and the system is not penetrating completely through the more resistive sand and gravel. Both Figures 3.9 and 3.10 show an east-west trending feature running across the area, and affecting the base of the sand and gravel layer.
Figure 3-7  Survey of Area 1 with the EM38 system, nominal penetration 1 metre.

Figure 3-8  Survey of Area 1 with the EM31 system, nominal penetration 5 metres.
Figure 3-9  Survey of Area 1 with the EM34 system, nominal penetration 7 metre.

Figure 3-10  Survey of Area 1 with the EM34 system, nominal penetration 15 metre.
Figure 3.11 shows the data from the EM34 system, here with 40 m inter-coil spacing giving a depth of penetration of about 30 m. Here the average values have decreased again to about 14 Ohm m in the south of the area, and 18 Ohm m in the northern part. In this case the system is clearly penetrating completely through the sand and gravel and showing the low resistivity of the underlying London Clay. The values plotted in each of the Figures 3.7 to 3.11 are the apparent resistivity values measured directly by the instruments. These values represent an average value of the resistivity of all the material within the depth of penetration of that system. Thus the values of about 14 Ohm m in Figure 3.11 are averages of the values for Boulder Clay, sand and gravel, and London Clay. In this situation the true resistivity of the London Clay must be much less than the apparent resistivity of 14 Ohm m.

Given enough information about the variation of apparent resistivity with depth over the whole area, it would be possible to interpret the apparent resistivity values in terms of the variation in true formation resistivity with depth. Since this dataset is unique in the density and extent of the available data, there is no readily available software to provide such an interpretation. Such an interpretation does however offer considerable possibilities for revealing further geological information. Both variations in the bounding surfaces of the sand and gravel layer, and variations in the material properties within it, are potentially extractable. Such information would provide a tool for detailed modelling of the shape and internal structure of such a deposit.

Resistivity imaging profiles were recorded across the area, both to calibrate the EM results already described, and also to show the type of information which can be gained by a full inversion interpretation of a collection of densely sampled resistivity values. Figure 3.12 shows stages in the interpretation of Line C, located in Figure 3.2. The Figure shows three separate frames of data. The top frame shows the observed data values. Each pale dot on the section shows the location of each single data value. The data are produced by direct-
current resistivity surveying, and have been processed using RES2DINV software (Loke, 1998). The processing and colour display are different from those used for the EM survey, but are broadly equivalent.

![Data from resistivity imaging Line D](image)

**Figure 3-12** Data from resistivity imaging Line D. For detailed explanation see the text.

The values in the upper frame of Figure 3.12 are thus apparent resistivities, representing averaging of the formation resistivities down to the depth of penetration of each particular measurement. The second panel is computed by the RES2DINV software to model the apparent resistivities in the upper panel. This is a very good match to the observed data. The lower panel shows the actual formation resistivity variation with lateral position and depth used by the RES2DINV software to compute the data in the centre panel. This lower panel thus represents a 2D model of the subsurface structure under this survey line. The sand and gravel layer is clearly defined as a resistive layer lying between the low resistivity overlying Boulder Clay, and the underlying London Clay. The detail of the layer shows complex lower and upper boundaries, and also significant variations in properties within the layer.

### 3.5 Interpretation

The response of the EM34 system appears to be detecting significant variations in subsurface electrical resistivity. As this is the first data which has been collected with this survey method, it is essential to have some form of independent check on both the calibration of the values being measured, and their relationship to known geology. To provide such a check, a Lund resistivity imaging system was taken to the site and used to record two long profiles across the test area. The profiles were located so that their south-eastern ends were as close as possible to the working quarry face, while their orientation to the north-west passed through, or close to as many boreholes as possible. In this way the resistivity images produced can be correlated with the borehole records, and the variation of resistivity on the images can be directly compared with the EM34 data.

The resistivity images produced are shown in Figures 3.4 and 3.5. In each case a high-resistivity layer is seen sandwiched between two very low resistivity layers. On comparison
with the borehole records, the high resistivity layer compares very well with the known extent of the gravel layer, enclosed between the underlying London Clay and the overlying Boulder Clay.

While the mapping of the variations in thickness of the gravel with the resistivity imaging are most impressive, the variations of resistivity shown within the gravel layer are of equal interest. It is highly likely that these reflect lithological changes within the sand and gravel components of the layer and could be of great significance in terms of resource assessment.

![Resistivity image interpreted from data recorded along Line C shown in Figure 3.2](image1)

**Figure 3-13** Resistivity image interpreted from data recorded along Line C shown in Figure 3.2

![Resistivity image recorded along the line D shown in bold grey on the plan in Figure 3.1.](image2)

**Figure 3-14** A resistivity image recorded along the line D shown in bold grey on the plan in Figure 3.1.

In Figure 3-14, the resistivity imaging profile was recorded starting (0 m) close to the active face of the quarry to the SE, and ending at the northern end of the survey area, by the cross-runway. The blue (low resistivity) areas neatly define the overlying boulder clay and the underlying London Clay that bracket the gravel. The limits of the higher resistivity layer neatly fit the 5 boreholes that are close to this line. Boreholes miss the region from 250 to 350 along this line so cannot confirm the detailed structure shown by the resistivity.

### 3.6 Conclusions

- Densely sampled EM data have been collected at the Bull’s Lodge site across an area of over 10 hectares, with 5 different depths of penetration

- The EM data clearly detect the sand and gravel layer, as confirmed by independent resistivity imaging profiles.

- There is great potential for further processing of the EM data to provide a more precise 3D location of the sand and gravel, and lateral variations within it.
4 Case Study 1: Archaeological site at Wroxeter roman city, Shropshire.

4.1 Introduction and Objectives
The roman city site at Wroxeter is a classic location in the UK for archaeogeophysics. The roman city was abandoned by 700 A.D., and the site has never been redeveloped. The site lies on the north bank of the river Severn, about 10 km south-east of the present city of Shrewsbury. The area of the city is now protected as a national monument, and farming is restricted to pasturage within the city boundaries so that any underlying archaeology will not be disturbed by ploughing. The site covers an area of about 78 hectares and the bounding outer earthwork makes it very obvious on aerial photography (Figure 4.1).

Figure 4-1 Aerial view of the southern part of the Wroxeter city site. The English Heritage visitor centre and the excavated bath-house can be clearly seen in the south-east angle of the road intersection in the top centre of the image.

4.2 Geology and archaeology of the Site
The site has been subject to extensive investigation in the Wroxeter Hinterland Project (). Over a period of about four years the whole area within the boundary of the city area was systematically surveyed with magnetic gradiometers to produce a complete map of the city (Figure 4.2). With the detailed archaeological control, a detailed interpretation of the magnetic map has been made. While the initial view of the magnetic data clearly shows the street plan of the roman city, and the location of major buildings within each city block, there is much more detail which can be extracted from this data. With the additional constraint supplied by archaeological excavations, even though only a very small percentage of the site has been studied in this way, the evolution of the city over the 600 years of its occupation has been interpreted. This exercise however is not directly concerned with the archaeological interpretation. The main objective is to determine how data collected with the MSP system compares with that from the conventional surveys, and to document the time taken for the MSP surveys, as a measure of the suitability of the MSP system for rapid screening of large areas of land.
Figure 4.2 The published magnetic gradiometer map for the whole of the Wroxeter city area. Our surveys were conducted in the two large fields on the eastern side of the city, known as fields 4 and 5. (See also Figure 4.3)

4.3 Data Acquisition
While it was expected that a large proportion of the site could be surveyed in reconnaissance mode in the time available for this project, this has not been done. The primary objective was to determine the quality of the data that can be collected with the MSP system. To test
this, a small area of the total site was chosen and surveyed multiple times with differing configurations of instruments. Comparisons between the different data sets recorded with different instrument configurations on different days would test the internal consistency of the data. Comparison of the differing data with pre-existing surveys would then allow determination of the effectiveness of the MSP system.

Thus a small area at the eastern side of the city site was selected for repeated survey. Most of this was in a triangular field referred to in previous surveys as field 4 (Figure 4.3).

![Figure 4-3 Total survey lines for the Wroxeter site. Field 4 (the lower triangular field) was surveyed 4 times with different sensor configurations. Thus there are about 60 line km of data from the one field.](image)

This field was surveyed over the week of field activity with three main magnetometer configurations, and some minor variations on each. For every survey, a separate Caesium vapour magnetometer was set up as a base station to record diurnal variation of the earth’s magnetic field. These data were logged via a serial radio-link on the base logging computer. The three different magnetometer configurations were:

- Six sensors distributed at three vertical gradient pairs with 0.5 m vertical separation within each pair, and 0.5 m horizontal separation transverse to the towing direction (Figure 4.4a).
- Five sensors distributed along a transverse bar, and one sensor elevated approx 2m above them to act as a “local” base station(Figure 4.4b).
- Six sensors distributed at 0.5 m intervals along a transverse bar towed at constant height (0.4 m) above the ground(Figure 4.4c).

These configurations are shown in Figure 4.4. The Gradient configuration should give data broadly equivalent to that from more conventional archaeogeophysical magnetometry equipment. The five sensors with a “local” base provide a greater density of horizontal data sampling, and still have the advantage of a reference close to the sampling sensors to
remove local magnetic variations such as those due to nearby passing traffic. The six sensor configuration gives maximum density of spatial sampling.

4.3.1 Data logging
Data transmitted over the wireless LAN system were logged using the Geometrics Maglog software, which saved the data from each instrument as a separate ASCII file, with each data record time-stamped with the time from the logging computer internal clock.

4.4 Data Processing
Processing of the data started with the individual ASCII files recorded from each instrument, and the notes recorded by the geophysical observer operating the logging system. The computer mounted on the towing tractor also held an independent record of the track positions, saved from the Fugawi software package used to display the tracks. In addition to the ASCII files from the geophysical sensors, there are also three additional files, from the DGPS system, the fluxgate compass unit, and the base station magnetometer.

4.4.1 Data merging
The first stage of the data processing is to merge the different data files to provide one “flat” database file of all the data for an individual survey. This is accomplished by a purpose-written program that takes all available data files and merges and interpolates them to a standard record format at a chosen time interval. Through the Wroxeter surveys the time interval was taken as 0.1 seconds, as this is the sampling interval of most of the equipment used (magnetometers, EM38 and compass). The Seres DGPS system could only log positions at a maximum frequency of 5 Hz, so positions are not determined at alternate
sample times. Interpolation is not carried out at this stage. Gaps in the data records are filled with asterisks. Since the maximum survey speed of the system is 7 km/hour, the maximum distance covered in 0.2 seconds is 0.4 m. Errors in linear interpolation of positions for the additional 0.1 second data were not considered serious. The interpolation software was adapted from an earlier version. Principle changes for this work involved accommodating many more sensors, and adding the facility to convert DGPS WGS84 positions into Ordnance Survey Grid References. This was accomplished using library routines provided by Grid Inquest, downloaded from the OS website.

The interpolation software automatically detects major turns in the survey tracks (over 60 degrees) and gives the data incrementing line numbers for each near-linear section of data. In the same process it identifies the period during which the MSP system was turning, and gives this a separate identifier. During such turns the towing tractor position is indeterminate, and may become much closer to the MSP than normal, causing additional noise on magnetic or electromagnetic systems.

The process of merging data also uncovers any errors in the data format caused by either instrument faults, or faults in the data transmission and logging. Thus preliminary editing of the data is combined into this process.

4.4.2 Positional corrections

This was the first time that large volumes of data had been collected with multiple sensors where the position of each sensor was critical to an accuracy of better than 1m. Another software program was written which allows the user to describe the instrument configuration of the MSP system for each survey. The program will then calculate the actual positions for each of the sensors in OS grid coordinates and the height OD. Since a separate set of coordinates (Easting, Northing, Height) is generated for each sensor, the program allows the user to specify which sensor he wishes to use and generates a standard format file for that sensor.

These files may be easily imported to a suitable geophysical analysis programme. In this study Geosoft Oasis Montaj was used.

4.4.3 Magnetic data corrections

For each magnetic sensor, a heading error was determined by observing the data values recorded in a cloverleaf survey routinely carried out before each survey. This revealed some interesting variations between the different sensors used. The G858 sensors had heading errors in some cases up to 5 nT. The G823 sensors never showed a heading error larger than 2 nT. These stated values are the heading error observed with the sensor mounted on the MSP, and are thus a combination of the sensor’s own intrinsic heading error, and the effect of the MSP and towing tractor. It is clear that the heading error caused by the towing tractor and MSP is considerably lower than the intrinsic heading error of the worst of the G858 sensors. The determined heading error was applied to the data from each sensor.

After this, there was still found to be an offset between the average anomaly values recorded by each individual sensor during any one survey. This is a data offset inherent in the operation of each individual sensor. For the sensors used on this survey, the maximum offset was 6 nT. These values were determined by examining the mean values of the readings for each sensor for each survey. These offsets were removed from the data from each sensor individually.

Sections of the data previously identified by the merging software as being recorded while the MSP was turning can now be identified and rejected to avoid an additional source of system noise. Unless the turn is very tight, the tractor does not approach the MSP appreciably, and any additional system noise is rarely identifiable.
Figure 4-5 Vertical magnetic gradient data from the western part of field 4.

Figure 4-6 Magnetic gradiometer data for Wroxeter roman city, field 4, collected using caesium vapour magnetic gradiometer and conventional surveying (data kindly supplied by Neil Linford, English Heritage). Dotted lines are 100m grid.
Magnetic data are then checked for the presence of noise spikes. The origin of these spikes is unclear. They seem to be individual to particular sensors and may be a function of ageing of the specific sensors or their connecting cabling. Manual inspection of the data and despiking is a time consuming process, which could be usefully automated. In this survey all editing has been done by hand.

With all the above corrections made to the data from each individual sensor, then these data may then be merged into one dataset, or used to compute gradient data, before being gridded and plotted.

Three pairs of caesium vapour sensors were fixed as vertical gradiometers on the MSP system and towed around the field. The towing speed of about 7 km per hour, with magnetometer reading at 10Hz, gives a spatial sample interval of about 0.15m along track, and 1m cross-track. The MSP is located with DGPS, in this case using the EGNOS system. The MSP system has a magnetic heading error of 1 nT, which is similar to the design specification of the magnetic sensors themselves. One of the lessons learnt in this survey was that each sensor has an individual heading error and zero offset, relative to the others. All these were determined by cloverleaf calibration surveys, and data suitably corrected. At the spatial accuracy required for this survey, the DGPS location was expected to be at its limit. To view this, individual magnetic survey profiles are shown in Figure 4.

Looking at the linear correlation of the anomaly of the roman street that passes NNE through the centre of the Figure, slight miss-alignments of successive sets of 3 profiles can be seen, and these are probably the result of positional error in the EGNOS DGPS system. They are however not a great deal larger than the variations seen within each set of 3, where the variation must be due to the real magnetic source in the ground.

![Figure 4-7 An enlarged section of the survey area shown in Figure 2 and 3. Grid lines are at 10 m separation. Each individual track of the MSP produces 3 parallel gradiometer profiles.](image-url)
Figure 4-8 The total survey track lines for the Wroxeter survey. Multiple surveys of field 4 were followed by a more reconnaissance style survey of the larger field to the north.
4.5 Conclusions
The MSP system has produced data of useful accuracy, but not as clear a final image as conventional surveying by English Heritage. Part of this may be due to positional errors caused by the DGPS navigation of the MSP. The final image quality is also a function of different display parameters. In compensation for its slightly lower resolution, the MSP system did complete the survey of about 2 hectares in one hour, with no previous time spent in establishing survey grids. As a survey system for large areas, it has great potential. For surveys with less exacting positional requirements than archaeogeophysics, the accuracy will be at least equivalent to any other survey technique, with the capacity to collect data at 7 km of line coverage per hour.
5 Conclusions

The details of the project are included in the preceding chapters. Here the main points will be briefly summarised.

5.1 Realisation of Project Objectives

- All the main objectives of the project have been realised.
- The geological interpretation of the data has not been carried out in detail, largely due to time constraints.
- MIRO will establish a website for the project, based on the content of this report. Ian Hill will send to Gordon Riddler a CD containing the material following the format adopted successfully for establishing the FIESTA web-site.

5.1.1 Application of MSP for mineral assessment

- The MSP has shown it can be used to collect electromagnetic data with depths of penetration of the order of 30 metres.
- The repeatable fine-scale detail shown in these data is taken as a justification for the philosophy underlying the MSP, of collecting densely sampled data. Much geological signal may have been missed in the past by poorly designed data sampling.
- In the particular application at Bull’s Lodge, a detailed comparison to the borehole logs has yet to be carried out, but the consistency of the geophysical datasets, and their resolution of the sand and gravel boundaries suggests that internal detail of the deposit is also extractable.

5.1.2 Application of MSP for archaeogeophysical surveys

- The Wroxeter site with its numerous available datasets was an excellent choice for testing the MSP system. The comparison with the English Heritage data is very informative.
- It is clear that there is a trade off between gaining excellent data at a slow pace, and gaining data with lower resolution using the MSP, but being able to cover an order of magnitude more survey area.
- There are three main areas that degrade the MSP data relative to that from English Heritage. The first is navigation. The DGPS used on the MSP was inherently less accurate than the positioning grids used by English Heritage. Secondly, the magnetic data collection process was less refined for the MSP, largely due to inexperience of the field crew, (Ian Hill) in this type of survey. Thirdly the data processing and display used in this project was created during the project, while English Heritage have considerable experience of these aspects and their own software system. All of these three areas could be improved with further work and are not inherent problems with the MSP system.

5.1.3 Data processing problems and issues

- The major problem with data from the MSP is the sheer volume of data, which is of course also its strength. This volume necessitates a smooth automated data flow from acquisition to final plotting. Since both primary data sets produced in this project are entirely new, the dat processing was developed as the project unfolded.
- A particular problem is merging datasets from separate surveys, and filtering out system noise spikes. Both these issues were more prevalent than would be desirable due to the number of failures of the field system, as analysed in Chapter two.
Improved reliability in the field system is an essential prerequisite to ease of data processing.

- There is considerable scope for improving the data flow with more complex and intelligent software during the initial data processing.
- The final reduced data plots are very interesting, but there is a paucity of modelling software that is appropriate to this data. Again this is an area for future development.

5.2 Evaluation of the MSP concept

- The MSP system has demonstrated its ability to collect data quickly and efficiently.
- The system has succeeded in conducting surveys with very different objectives, data types and scales of operation.
- The data quality is high, and its repeatability and correlation with independent control data is very good.
- The intensive use of the system revealed some lack of robustness in some of its components.

5.3 Potential future developments

- The MSP must be made more reliable.
- There is considerable scope for improving the data flow with more complex and intelligent software during the initial data processing.
- The final reduced data plots are very interesting, but there is a paucity of modelling software that is appropriate to this data. Again this is an area for future development.
6 Acknowledgements

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Lastly we owe some thanks to Essex police. Their helicopter unit based on the Bull’s Lodge site allowed us a pass key for their security gate to give us easy access to the site, and more importantly allowed us to use their workshop on one occasion for electrical repairs.
7 References


