High-resolution multisensor geophysical surveys for near-surface applications can be rapid and cost-effective

Ian Hill and Tim Grossey, University of Leicester, U.K.
Chris Leech, Geomatrix, Luton, U.K.

Too often geophysical surveys of the near surface are a last resort. Direct sampling by trenching or trial pits is relatively cheap and gives a geologist or engineer a direct view of the target. Boreholes are a natural extension from trial pits since, although they sample in depth at only one point, they may recover physical samples of the material from the units under investigation. Geophysics is frequently regarded as useful in terms of being noninvasive, but lacking in resolution, and incapable of coping with complex near-surface materials. This presents a strange contradiction, since geophysical surveys are accepted as a good tool for archaeological surveys, where the main purpose is to identify inhomogeneity in the near surface with high resolution. Archaeogeophysical surveys are highly detailed, but slow and expensive. Running surveys of the same area with multiple geophysical methods is even more expensive, though this offers the prospect of improved characterization of subsurface materials.

The multisensor platform (MSP) system provides a rapid and cost-effective solution to the above problems by exploiting recent developments in geophysical sensors, navigation, and communications. The logic behind the MSP is very simple—record densely-sampled data as rapidly as possible. Resolution in geophysical data depends on adequate sampling. For surface surveys, spatial sampling is a critical factor. Closely spaced samples allow investigation of signal at a wide range of wavelengths, and objective assessment of the separation of noise and signal. While geophysicists may (or may not) have a clear appreciation of the importance of spatial sampling in determining the minimum wavelength of features they can define with their data, geologists often do not.

Exploration or site investigation with a grid of widely spaced boreholes is rarely supported by a geostatistical analysis of the validity of interpolating between the boreholes. An easy solution to the sampling problem is to oversample. Many geophysical instruments now produce output at constant time intervals, typically between 1 and 10 Hz. Thus, if they are moved steadily over the ground, they can measure densely sampled profiles. The consequent requirements are to establish the position of the instrument with sufficient accuracy at the time of each reading, and to be able to store the data produced, perform quality checks in real time, and pass the data rapidly onwards in a convenient format for processing and display. If multiple measurements with different sensor types can be made simultaneously, the efficiency of the system improves. A further time advantage is gained if the system is completely self-locating and needs no prior surveying of reference grids. Yet another advantage of a self-locating system, coupled with real-time quality control, is that areas of poor or unusual data can be resurveyed, or the survey plan modified in response to the incoming data.

The MSP system. MSP (Figure 1) allows a field crew of two people to operate autonomously and produce geophysical data in one day, which would take a crew of 4-5 several days to collect using conventional methods. Any instrument can be accommodated provided only that it produces a serial output data string, and that it does not mutually interfere with other instruments on the platform. The target time from end of data

***Figure 1.** The Leicester MSP system comprising towing tractor (right), MSP sledge (center), in this case with six Cs vapor magnetometers, and the hired van (left) which transports all the equipment and acts as office and workshop on site.*

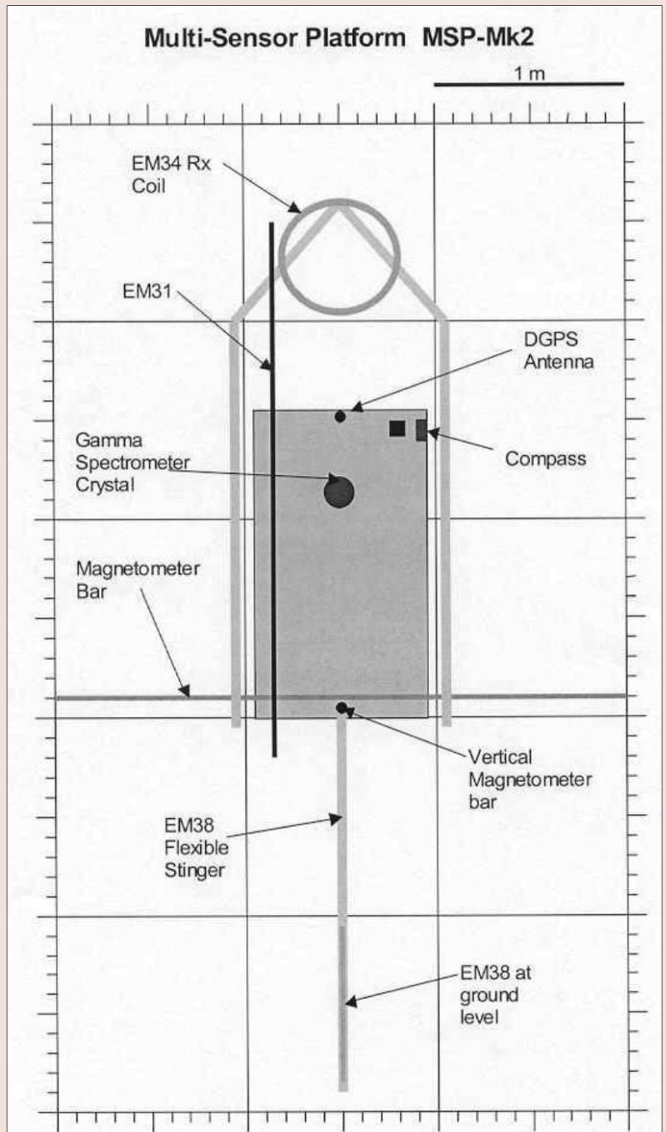

***Figure 2.** Scale drawing of the MSP with the usual location of geophysical sensors annotated.*

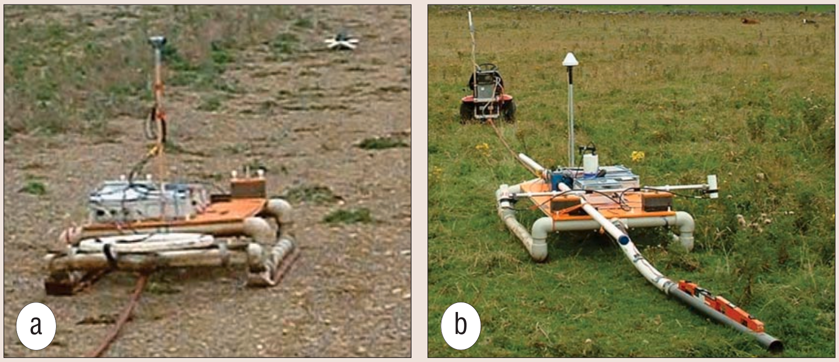

Figure 3. *(a) MSP equipped with EM34 system with a 20 m separation. The second coil is carried on a separate towed sledge located by its own DGPS system. (b) MSP in the Tearsall survey equipped with two cesium magnetometers, EM31, EM38, and gamma-ray spectrometer.*

acquisition to production of first draft survey data plots is 30 minutes.

The main component of the system is the MSP itself (Figure 2). This is a lightweight sledge with mounting brackets for a wide range of geophysical sensors. The sledge, made from a variety of plastic components and plywood, is geophysically undetectable. Essential permanent components of the sledge are a DGPS antenna and a three-component fluxgate compass. Both 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 six 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, chosen because it provides the necessary motive power with the minimum geophysical signature. When towing the MSP with an 8-m 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/hour. Using instruments with a sampling cycle of 0.1 Hz (such as the EM38, EM31 or Cs vapor magnetometers), this gives a sample interval of about 0.15 m along the track. The tractor carries an LCD display for the driver that plots the survey track plot so that line positioning can be checked and modified as necessary when physical obstructions such as trees and field boundaries are encountered. 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.

DGPS navigation was chosen since it is simple to operate, readily available, cheap, 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 EDM are viable alternatives, as long as they can output a continuous serial data string which can be merged with data from the MSP itself.

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 channels are taken by the DGPS signal and the compass, leaving six channels for geophysical sensors. The serial signals are multiplexed together and broadcast by 802.11b WLAN. The bandwidth of this wireless system is sufficiently large so 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 a range of 1 km, the MSP could survey over 3 km^2 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 irrelevant, 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 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 write the serial data strings to text files. With a fairly full instrument load, the MSP records megabytes of data per hour. Efficient handling of these data through postprocessing is essential to the practicality of the system. Separate data files for each instrument are merged with the position information in a single database file in CSV format. This can then be directly imported into a commercial processing package or be subject to further preprocessing. While it is convenient to run the MSP base station inside a vehicle, on sites with particular access problems, all base station equipment can be placed in a wheelbarrow and moved manually as necessary. It is possible to run the system with two laptops at the base station linked by an Ethernet hub. In this case the observer can process data on the second while monitoring the current survey on the first.

Survey methods. It is conventional to collect geophysical data along regular straight lines of a presurveyed grid. There is a 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 agricultural field systems, 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 presurvey is required. The MSP can move around 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 on tight corners will approach the MSP. This leads to increased error levels in data from EM or magnetic sensors. To minimize this, 180° turns are avoided where possible. The usual track plan is thus to start by making circuits round the outside of a survey area spiraling in towards the center 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 realign 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.

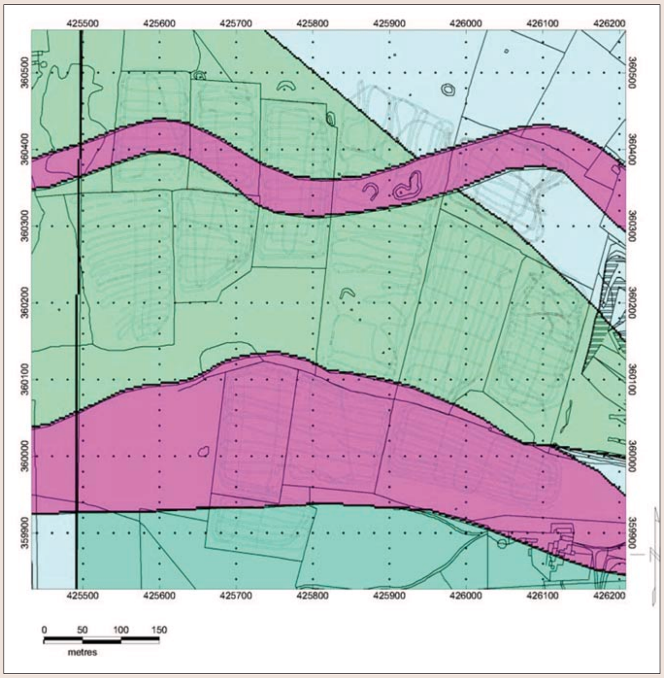

Figure 4. Geologic map of the Tearsall area, showing limestone country rock (blue) with interbedded basic lavas (purple). The topography slopes about 12° downwards to the north, and the beds dip northwards at about 17°. Gray lines show the MSP survey tracks. (Grid squares 100 m)

All accessible area is covered by data tracks efficiently. The disadvantage is that established software for analyzing 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.

The physical structure of the MSP easily accommodates a large range of geophysical sensors (Figure 3). 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 minimize this, the magnetic sensors are always mounted to the rear of the MSP, away from the electronics modules. Interestingly, the control electronics for the magnetometers causes as much magnetic interference as does the MSP itself. Both effects are down at the 1 nT range.

Deciding which sensors to use in combination is a compromise between ultimate data quality and time in the field. If a heading error of a few nT 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 optimize field efficiency 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.

Mineral exploration case history. The MSP system was first developed for mineral exploration surveys in the U.K.'s South Pennine ore field. A thick Carboniferous limestone succession contains interbedded basic lavas. The lavas have been heavily altered and are clay-rich, making them electrically conductive as well as magnetic relative to the limestones.

The location of the lavas is critical with respect to mineralization. An example test site surveyed is at Tearsall, near Matlock, Derbyshire. Figure 4 shows a geologic map of the area with field boundaries and topographic features superimposed. The limestones and lavas dip to the north at about 17° below a hillside also sloping down to the north at a lower angle, about 12°. The area is agricultural land with little geologic exposure. A quarry at the extreme eastern edge of the map provides access to detailed control for the geologic structure of the site.

The total area of about 20 hectares is divided into many small fields, with trees, bushes, spoil dumps, and capped mineshafts from historical mineral workings at the site. For logistical reasons, the survey was conducted in a number of separate work periods spread over a week, but the total time spent in the fieldwork was less than two days for a crew of two people. The gray lines on Figure 4 show the track lines of the MSP system over the area. The track lines in some areas appear random, and were dictated by access around obstructions such as those listed above. The combination of tractor, flexible towline, and sledge makes the system maneuverable and agile, which is important in coping with rough ground, steep slopes, and confined areas.

Magnetic data were collected using two cesium vapor sensors separated perpendicularly to the MSP track by 2 m (Figure 3b). Data from each sensor were corrected for drift, using a remote base station, and for heading error before the data were merged to produce the plot in Figure 5. The magnetic data highlight the location of the two lava beds in the north and south of the area. It is clear that the inferred outcrop pattern of the lava on the geologic map is not correct in detail. The high positive amplitudes of the magnetic field show that the northern (upper lava) outcrop is displaced by a fault, and the southern (lower lava) is much thinner than mapped.

During this survey, the MSP system also carried EM31 and EM38 sensors. The data from the EM38 are plotted in Figure 6. In this plot, the conductivity data output by the EM38 have been converted to resistivity values to simplify a later comparison with resistivity imaging data. The most noticeable feature is the contrast between the resistivity over the lava units in the north and south of the area with that of the interstratified limestones. The lavas show a much lower resistivity than the limestone in the center of the image. The resistivities for the limestone may appear low, but due to the limited depth of penetration of the EM38, the value returned is that of weathered rock. The lava units give a low resistivity due to their extensive alteration. The resistivity plot shows the same offset of the northern lava outcrop, and the relatively narrow southern lava outcrop as was inferred from the magnetic data.

A more subtle feature is the trough of low-resistivity values running approximately east-west, cutting through the limestone sequence in the center of the image. This correlates with a clay way-board outcropping at the surface. The high clay content of the altered tuff that constitutes the way-board produces the conductivity contrast with the limestone. The reality of this correlation can be tested with independent geophysical and geologic evidence. Figure 7a shows a photograph of the western wall of the quarry on the eastern edge of the survey area, taken looking west. The dip of the limestone beds, as can be clearly seen, is steeper than the surface topography. The resistivity imaging profile (Figure 7b) shows that the thin (~0.2m) clay way-board produces a clear effect on the imaging profile.

This example shows that it is possible to collect usefully detailed geophysical survey data at this scale of survey, covering some 20 hectares of ground in less than two days. The survey also recorded EM31 and gamma-ray spectrometer

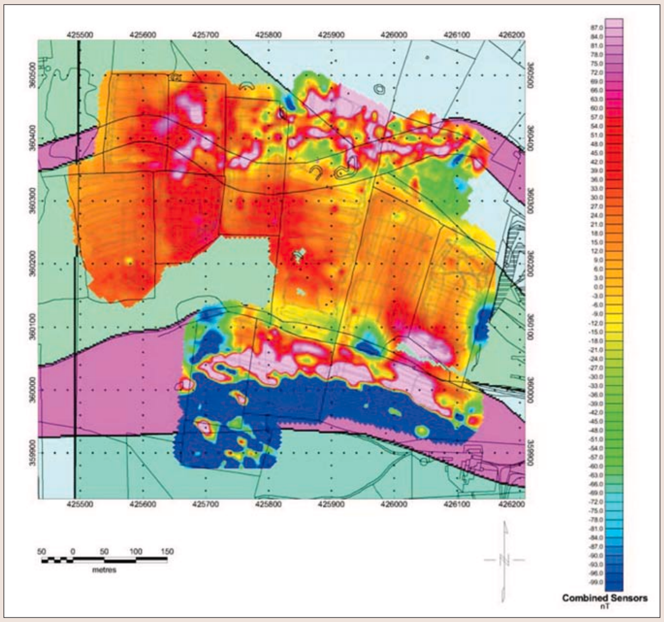

Figure 5. Magnetic map for the Tearsall area formed by combining data from two sensors in the configuration shown in Figure 3b. (Grid squares 100 m)

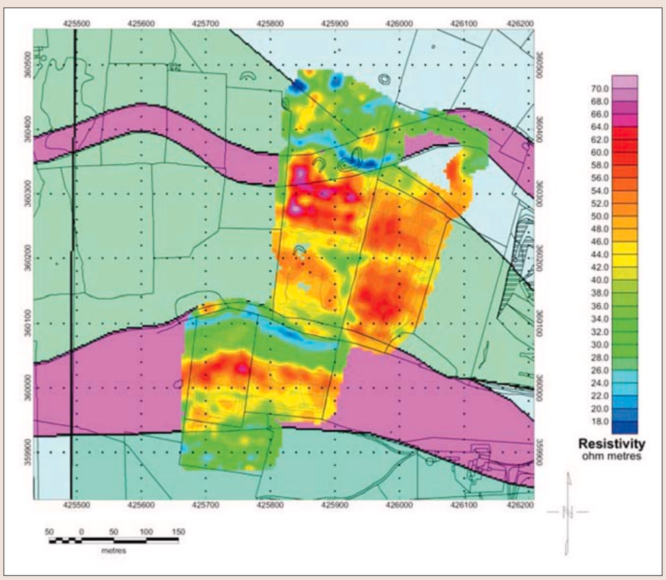

Figure 6. EM38 data mapped as resistivity values for the Tearsall area. These data were collected simultaneously with the magnetic data of Figure 5. (Grid squares 100 m)

datasets which are not reported here.

Archaeogeophysics case history. A good test of the resolution attainable with the system would be to perform a survey which requires high levels of accuracy, both in spatial positioning and geophysical parameters. For this purpose the site of the Roman city of Wroxeter, Shropshire was selected. This site has the benefit of having already been subject to a complete and detailed archaeogeophysical survey with magnetic gradient data maps published. In addition it was also used by English Heritage geophysicists for their own independent tests of their cesium magnetometer survey system. 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 allow determination of the MSP system's effectiveness.

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 published surveys as field 4 (Figure 8).

This field was surveyed with three main magnetometer configurations, and some minor variations on each. For every survey, a separate cesium vapor 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 MSP base logging computer. The magnetometer configuration used for the data shown in Figure 8a comprised six sensors distributed at 0.5 m intervals along a transverse bar towed at constant height (0.4 m) above the ground. The photograph in Figure 1 was taken at the start of this particular survey. To produce the plot in Figure 8a, the data from each of the six magnetometers were corrected for diurnal variation and individual sensor heading error. The corrected data values were assigned positions determined by adding the offset of the sensor to the DGPS antenna position. The sensor offset was calculated using the orientation of the MSP determined from the onboard compass, and the known offset distances of the sensor from the DGPS antenna. Depending on the actual tracks of the MSP, the six sensors follow parallel lines defining one data swath, but there may be a data gap of variable width between adjacent swaths recorded on consecutive tracks.

Since the MSP and tractor leave almost no physical mark on pasture fields, it can be difficult for the tractor driver to ensure that each following track is correctly positioned to the nearest 0.5 m. A consequence of this is that unsampled gaps can be left between swaths. All data points were then interpolated to a 0.5 m grid, and presented as a monochrome plot. Large data gaps caused by over-wide track spacing have not been interpolated, producing white gaps in the data coverage. The data collection took less than two hours.

The plot in Figure 8b has been produced from data collected by English Heritage using their cesium vapor magnetometer system. Their data collection period was completely independent, and occurred about four weeks after that for the data in 8a.

These latter data have magnetometer instrumentation directly comparable with that used on the MSP, but the data were collected along a regular presurveyed grid with a line spacing of 0.5 m. Location of their data grid was using RTK DGPS surveying. The total survey time taken to produce the data used in this figure was between 1 and 2 days, for a team of three people. The data were processed by Neil Linford of English Heritage using an in-house software system developed specifically for archaeogeophysical surveys.

Both parts of Figure 8 show a section of the Roman city of Wroxeter near the eastern city gate. The main blocks of the city plan, about 100 m across, are clearly visible. Within these the outline of building walls and smaller isolated features can be correlated between the plots. The magnetic anomaly amplitude range is from +15 to -10 nT. Here, discussion will concentrate on the quality of the data, rather than the archaeological interpretation. The comparison of the two parts of Figure 8 is interesting, viewed from different perspectives. Firstly, the objective of demonstrating the resolution fairly easily attainable with the MSP system has been achieved. While it is clear that the image of Figure 8a is less sharp than that of 8b, the main features with areal extent of greater than 1 m are defined on both images. There is an apparent tradeoff between the higher level of resolution, against reducing the survey time by a factor of 10 or greater.

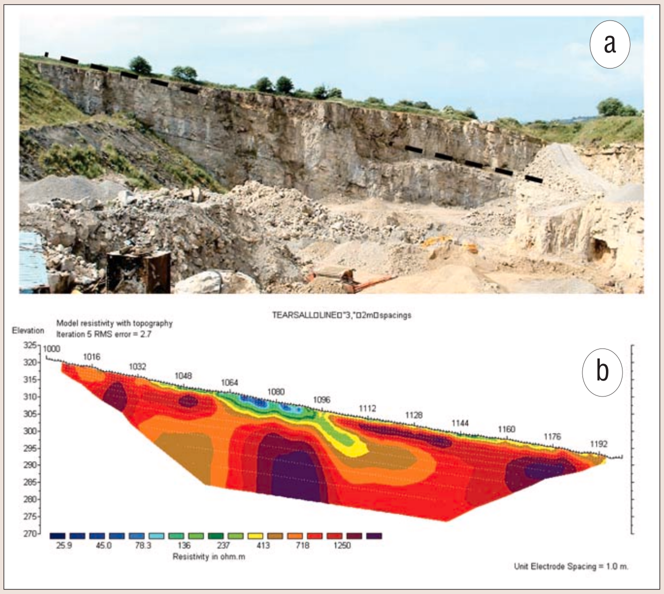

Figure 7. *North-south sections across the Tearsall area. (a) Photo of the western wall of the quarry as seen on the eastern edge of the survey area in Figures 4-7. (b) Resistivity imaging section parallel to the quarry face but displaced to the west (along strike). The low-resistivity layer corresponds to the way-board layer (an altered clay-rich tuff) visible in the quarry face.*

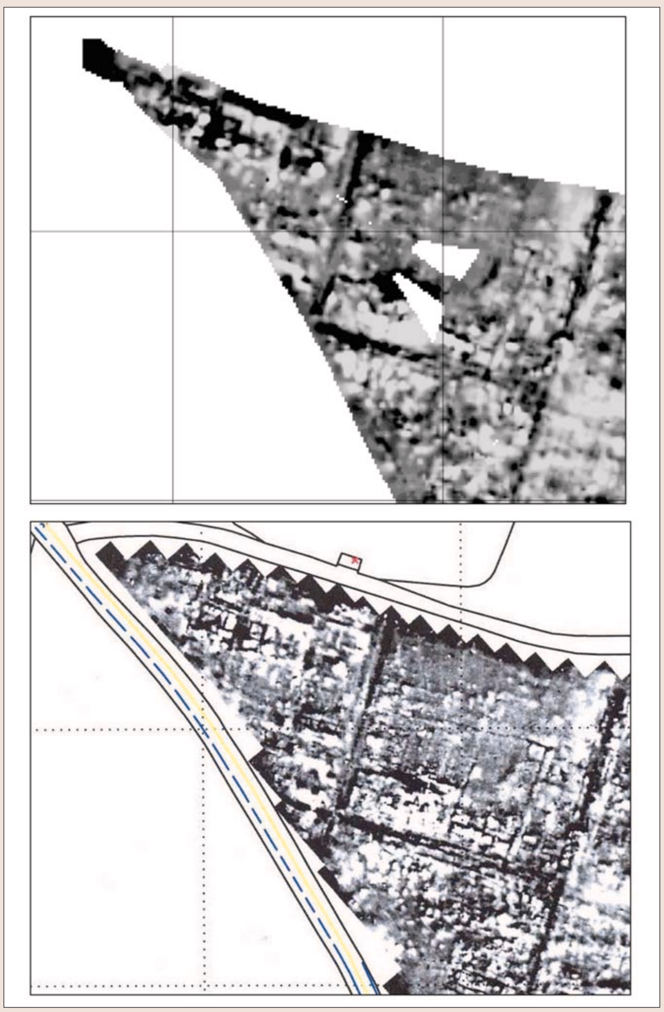

Figure 8. *Magnetic total field data from an archaeological survey of part of Roman city at Wroxeter, Shropshire. (a) Data from the MSP system configured as shown in Figure 1, with 4-m track spacing; (b) data collected by English Heritage with a data line spacing of 0.5 m.*

At a second level of comparison, it would be interesting to identify the detailed causes of the differences between the two images. There are numerous factors to be considered. The navigation by DGPS used for the MSP is inherently less accurate than that for the RTK DGPS system used by English Heritage to position their survey lines. The survey pattern of the MSP is liable to data gaps where adjacent survey tracks are not sufficiently close together. The interpolation of these slightly more sparse and less well-located data to a regular grid then inevitably leads to some high-cut filtering of the data. The processing schemes for the data were different. These issues are currently under investigation. Further analysis of these data may allow us to develop the MSP system and its data processing so that it can produce data very closely equivalent to that from best quality archaeological systems. If this is so, it will not only provide more-than-adequate survey quality for most geologic and environmental applications, but offer a new tool to archaeological investigations, making surveys of large areas not only feasible, but cost-effective. TLE

Acknowledgments: The MSP system has been developed over a number of years through collaborative projects with a range of partners and sponsors. Contributions from the British Geological Survey, English Heritage, Geomatrix, Geometrics, Geosoft Europe, Glebe Mines, Hanson plc, Mineral Industry Research Organisation (MIRO), and financial support from the UK Government through DTI-LINK and DEFRA-MIST funding are gratefully acknowledged. Particular thanks are due to Neil Linford for access to the English Heritage data.

Corresponding author: iah@le.ac.uk