Paradox or panacea? — archaeological field trials with the GEM®-300 Multi Frequency Electromagnetic Profiler

Stephen Bullas[1], Glynn Barratt[2] and Roberto Grassi[3]

[1]Strategic Decisions Ltd., Department of Applied Geophysics,
Park House, 158-160 Arthur Rd., Wimbledon Park, LONDON SW19 8AQ, England
[2]University of Birmingham, Dept. of Archaeology & Ancient History,
Edgbaston, BIRMINGHAM, England
[3]GRADAR snc, via E. Zacconi 18, I-20157 MILAN, Italy
stephen.bullas@ecode.org.uk

Abstract. A multiple frequency electromagnetic induction sensor is discussed which can simultaneously collect comparative data from metal detection, electrical conductivity and magnetic susceptibility in a single session and at different stratigraphical depths. Special software was designed and written in the UK to more fully utilize the capabilities of the instrument. Field trials conducted in different countries produced variable results. With some adjustments this instrument has the potential of saving on manpower and survey costs.

Keywords: electromagnetic profiling, simultaneous data collection.

1 Introduction

The GEM–300 is a portable, multiple frequency electromagnetic induction sensor built in the United States[1] and engineered for principal use in environmental geophysics. Its design encompasses a frequency domain, electromagnetic profiling system configured by the operator to simultaneously measure up to sixteen user-defined frequencies between 330 Hz and 20,000 Hz with fixed coil separation. Both in-phase and quadrature measurements are recorded; output is the mutual coupling ratio (Q) in parts/million (ppm) or apparent conductivity in mS/m. Survey acquisition parameters and the recorded data are stored together within internal memory for subsequent download to a PC; separate files are created for each individual survey.

Dependent upon the operating frequencies chosen, simultaneous collection of data from three different physical principals is possible, viz.: metal detection, electrical conductivity and magnetic susceptibility. Since the machine can record at up to sixteen different user-selectable frequencies per station, with the advantage of allowing subsurface anomalies detected by permutations of the three different principals to be mapped at differing depths, the potential of such an instrument within archaeologically geophysics is profound. The capability of producing multiple sets of comparative data in a single session and at different stratigraphic depths could have the ability to completely transform generally accepted field methodologies, to dramatically reduce the costs associated with the survey and to substantially increase client-confidence in the completeness and accuracy of results.

In order to investigate more fully the capabilities of the instrument, extensive field trials at a number of known archaeological sites were carried out during the course of 1998 in England, Italy and Sweden and, in 1999, in Romania. So that the instrument's full potential might be effectively exploited, new software was designed and written in the UK specifically for it; the software was further refined in the field as trials progressed and more experience in the use and characteristics of the machine was gained.

This paper presents a critique of the instrument as used in the field, the results of the trials in England and Sweden, an overview of the functionality behind the new software and a programme for further fieldwork in future years. Additionally, a number of recommendations for further development of both hardware and software — commensurate with the GEM's potential use in archaeological, rather than environmental, geophysics — is outlined.

2 The instrument's physical characteristics and features

Fig. 1. The GEM-300

At 188 cm x 20 cm x 15 cm and with a weight of 8 kg, the GEM-300 (Fig. 1) comes complete with a carrying

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[1] Manufactured by Geophysical Survey Systems, Inc., 13 Klein Drive, P.O. Box 97, North Salem, NH 03073-0097, USA and distributed in the UK, Belgium & Germany by Allied Associates Geophysical Ltd., Concept House, 8 The Townsend Centre, Blackburn Road, DUNSTABLE, Bedfordshire LU5 5BQ, England

strap for bearing on the back or shoulders at about waist height or for dragging along the ground by the operator. The coil separation is 1.67 metres and the electronics are powered by a hefty but compact NiMH rechargeable battery. Onboard memory for 200,000 items is provided and up to 16 user-selectable frequencies between 330 and 20,000 Hz are available.

A comprehensive series of configuration options is available from the menu-driven front panel (Fig. 2).

Fig. 2. Menu-driven front panel

Digital output is available directly to the display or to the built-in data logger. Analogue output is available in real-time to the display panel (Clip 1) in the form of a bar chart, line graph or hi lo graph.

Three different modes of operation are possible:

- *Anomaly Finder Mode* - simple observation of the front panel response signal amplitude;
- *Continuous or Automatic Mode* - up to 1,000 data points may be observed, but only the data (i.e. with no gridding information) are recorded. An automatic timer, the interval frequency of which may be set from a predetermined range by the user, means that the instrument may be used in a non-stop mode of operation. With a little practice, it becomes a simple matter for readings to be taken at one metre or one half-metre intervals. However, the amount of time that it takes the GEM to record the data will depend upon how many frequencies are currently in use. Out of a maximum of sixteen, five or six will generally give acceptable results in terms of the time necessary to complete a series of 20 x 20 or 30 x 30 squares at single metre station intervals;
- *Station or Manual Mode* - full gridding information is recorded at pre-selected station intervals and traverse distances. The disadvantage, however, is that recording of the data must be manually triggered, and this has significant ergonomic impact on the ease with which the instrument may be carried. A choice of two trigger buttons (each has an identical effect) is available, with the buttons being located at the top of the two fixed carrying handles.

The instrument is portable, robust and waterproof. It has an interchangeable battery pack and, with average use, a life of about four hours between charges. Two batteries are provided as standard, thus providing a full day's survey capability. With the auto-positioning grid correction feature enabled and the instrument carried at waist height, a single person generally best operates the GEM-300. However, if being dragged along the ground, a second operator is needed to activate the trigger at each station.

3 Potential benefits

Predicated on which operating frequencies the user has selected for the survey, simultaneous data collection using 3 different physical principals is possible

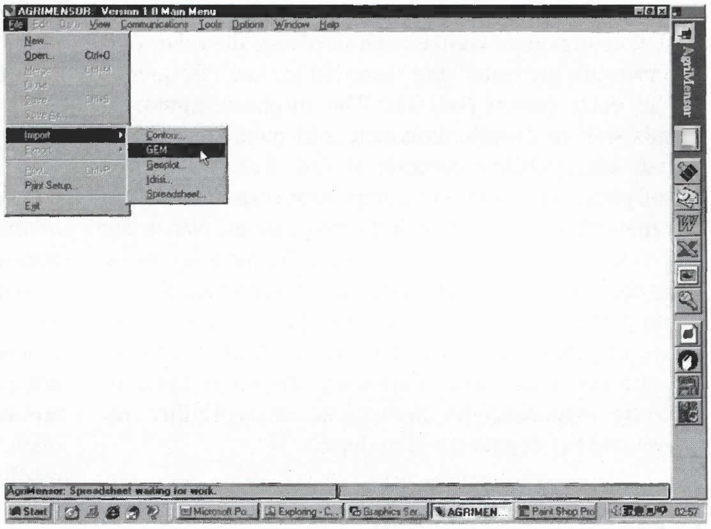
- Electromagnetic Induction;
- Electrical Conductivity;
- Magnetic Susceptibility.

These equate to depths of between 1.2 m and 70 m (!), dependent upon a variety of factors which are discussed more fully below.

Minimum grid layout time is required as, in common with several other modern instruments, an audible beep is sounded when the next station reading is to be taken. Auto-positioning can be enabled to achieve simple grid correction where necessary.

4 Principles of Operation

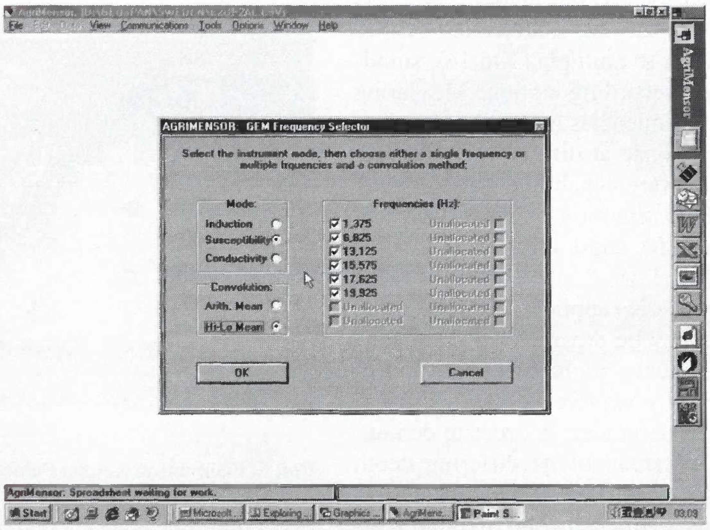
This instrument falls into the so-called 'active' class of operation. An active instrument is one in which there is both a transmitter and a receiver coil. Signals from the sinusoidally varying field in the transmitter coil induce a flow of currents under the ground which are then picked up by the receiver coil; a third, or 'bucking', coil ensures that there is no direct coupling between transmitter and receiver. Active class instruments differ from passive class ones, where a single coil picks up a signal from a third party source such as the remnant magnetism from an artifact or from the magnetic field of the Earth itself. As an active class instrument, the GEM-300 is by definition fully self-contained, but it does suffer from the disadvantage of all instruments in its class in that its sensitivity falls off as the sixth power of the depth, whereas with a passive instrument, the corresponding power is one third. For archaeologically work, the practical skin depth of the GEM-300 is effectively limited to between some 4 to 8 metres (as measured



AGRIMENSOR: Version 1.0 Main Menu

AgriMensor: Spreadsheet waiting for work.

Fig. 3. Import filters



AGRIMENSOR: GEM Frequency Selector

Select the instrument mode, then choose either a single frequency or multiple frequencies and a convolution method:

Mode:
- Induction ○
- Susceptibility ●
- Conductivity ○

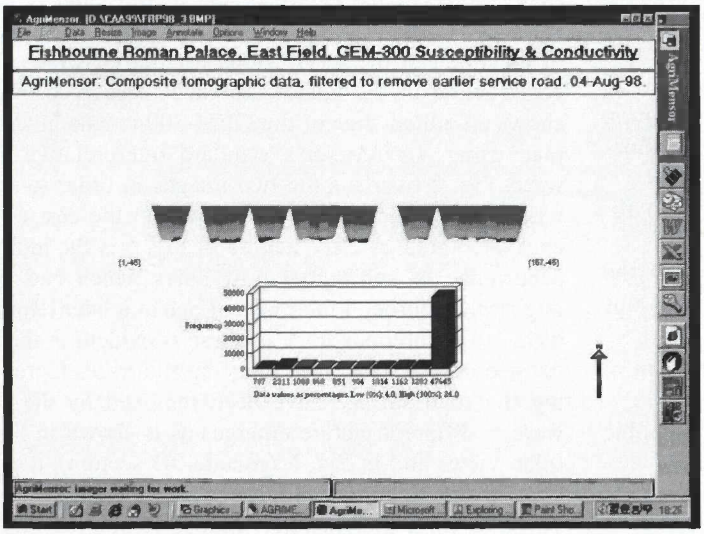
Convolution:
- Arith. Mean ○
- Hi-Lo Mean ●

Frequencies (Hz):

☑ 1,375	Unallocated ☐
☑ 6,825	Unallocated ☐
☑ 13,125	Unallocated ☐
☑ 15,575	Unallocated ☐
☑ 17,625	Unallocated ☐
☑ 19,925	Unallocated ☐
☐ Unallocated	Unallocated ☐
☐ Unallocated	Unallocated ☐

AgriMensor: Spreadsheet waiting for work.

Fig. 4. convolution algorithms



AgriMensor. [D:\CAA99\FRP98_3.BMP]

Fishbourne Roman Palace, East Field, GEM-300 Susceptibility & Conductivity

AgriMensor: Composite tomographic data, filtered to remove earlier service road. 04-Aug-98.

AgriMensor: Imager waiting for work.

Fig. 5. graphical representation for pseudo-3D tomographic sections

from its height above the ground), dependent upon coil orientation.

Two component signals, one in-phase, the other out-of-phase, are generated and recorded for each frequency and at each station position. The in-phase signal responds well to metallic conductors at most frequencies and to susceptibility contrast at low frequencies; the out-of-phase or quadrature component responds well to non-metallic conductors at high frequencies. When the user selects the lowest and highest frequencies to be used, the electronics automatically interpolates the remaining frequencies in a geometric progression. These values may be manually overridden if desired. In general, the lower the signal frequency, the lower the conductivity response, the higher the susceptibility response and the deeper the skin depth.

5 Software functionality

The depth of exploration for a given medium is determined by the GEM-300 operating frequencies. As we have seen, these may be set to multiple (1 to 16), simultaneous readings at each recording station. Measuring the response at different frequencies is therefore equivalent to measuring the response at different depths and, given the appropriate software capability, the data may be used to provide a 3D distribution of subsurface features. We shall review how valid this assumption is later in the paper.

Although basic software is supplied with the instrument and digital output may be downloaded for use by standard spreadsheet products, more imaginative programming is needed to fully exploit the claimed capabilities of the machine. In particular, in order to demonstrate the tomographic potential of its differing depth capabilities through the simultaneous capture of received signals at various frequencies, no suitable software was offered by the manufacturer nor was any immediately available in the countries in which we tested the machine (the U.K., Italy, Sweden and, subsequently, Romania). It was therefore decided to undertake the design and development of specific code extensions to Strategic Decisions' geophysical analysis program, *AgriMensor*™, in order to incorporate additional functionality specific to the GEM-300.

The extensions provided the following new facilities:

- import filters to read ASCII files created by the standard LCU.EXE and GEM300.EXE programs (Fig. 3)
- convolution algorithms to deal with multiple in- & out-of-phase responses (Fig. 4)
- graphical representation for pseudo-3D tomographic sections (Fig. 5).

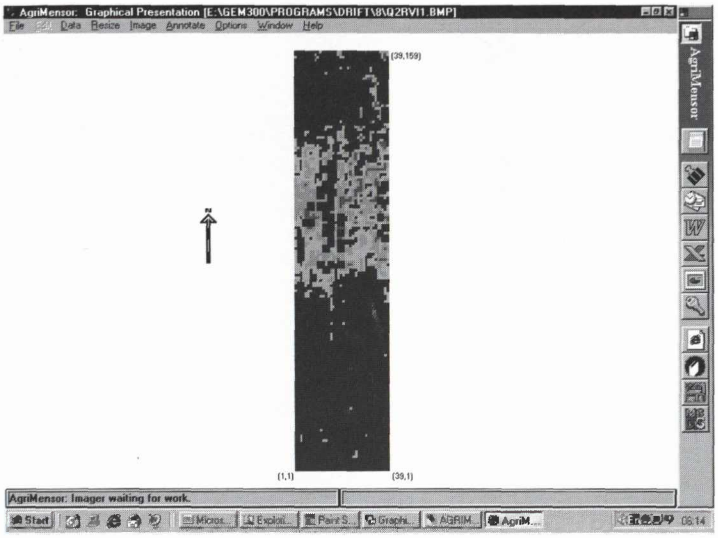
6 Results and interpretation

Field trials have demonstrated that the GEM-300 is capable of producing both spectacularly good results under some conditions and absolutely none at all (good or bad) under others. A large part of our research has attempted to categorise which conditions give rise to the former and which to the latter, but we have been unable to discover any consistency in this regard. We had initially assumed that a combination of differences in weather conditions (and, therefore, in the dryness and compactness of the soil), anomalies in the homogeneity of the subsoil and any structural remains therein contained, and the underlying geology would lead to some amount of variance in results, but these reasons alone would not lead to the total disparity often encountered. Indeed, the trials at Fishbourne Roman Palace in southern England provided the opportunity for us to repeat our surveys in two consecutive years under similar climatic conditions, one year of which yielded excellent results, the other very poor ones. In the second year, we were fortunate enough to have access to two identical (as far as we know) instruments, neither of which gave results comparable with the preceding year.

Fig. 6. Fishbourne Roman Palace

The following example is indicative of the good results. Fig. 6 is a photograph showing part of the site during excavations. In the centre of the picture, and running from east to west (north is towards the top), the remains of metalling of the service road used at the time of the construction of the Palace are easily discerned. Fig. 7 shows an edited slice of the GEM-300 results in simple plan using *AgriMensor*'s standard interpretative software. Fig. 8 overlays the two images in order to show where the readings were taken, just to the east of the excavated area. A clear feature of Fig. 6 is the multiple occurrence of substantial post holes which had been dug straight through the road surface at a later (Roman) date, but no obvious trace of these is evident in the initial geophysics. However, once the anomalies representing the road surface have been removed by the software, a different picture emerges as is shown in Fig. 9 (plan view) and in Fig. 5 (pseudo-3D section), demonstrating very clearly just how easy it can be for a surveyor to miss the, literally, hidden depths of this instrument.

Figs. 10, 11 & 12 from Uppåkra in Sweden again demonstrate this quite clearly. The first image shows an anomaly arising from part of a wall of a buried Viking



AgriMensor: Imager waiting for work.

Fig. 7. Edited slice of the GEM-300 results

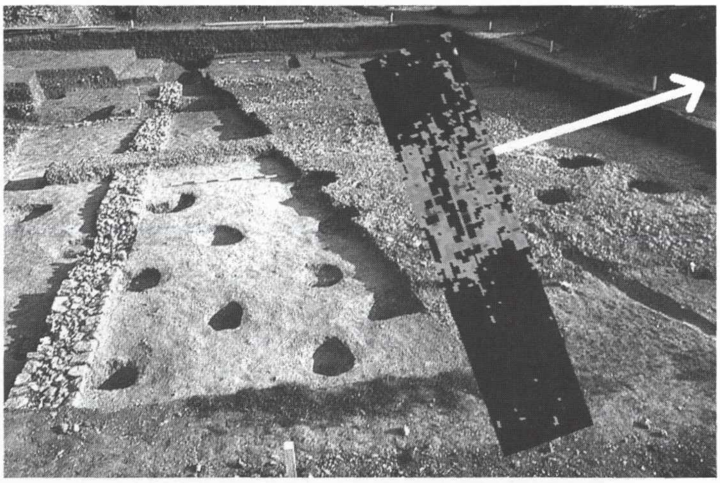
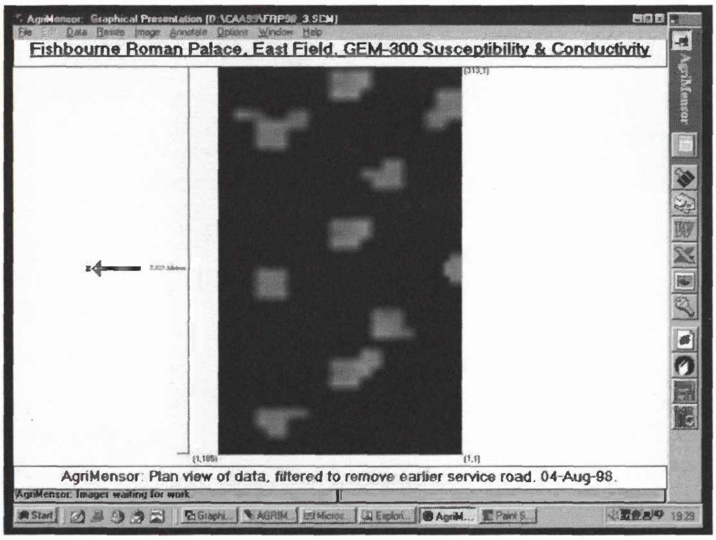


Fig. 8. Overlay of figs 6 and 7



Fishbourne Roman Palace, East Field, GEM-300 Susceptibility & Conductivity

AgriMensor: Plan view of data, filtered to remove earlier service road. 04-Aug-98.

AgriMensor: Imager waiting for work.

Fig. 9. Plan view with anomalies removed

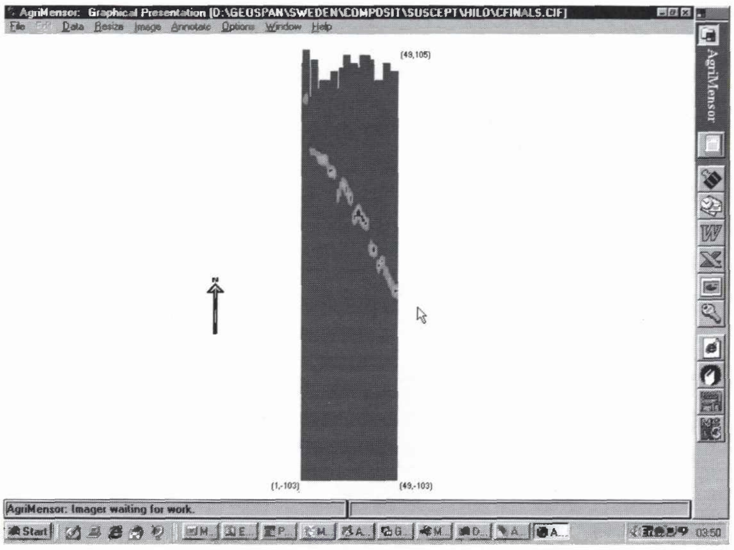


Fig. 10. Anomaly in buried Viking long house from Uppåkra, Sweden

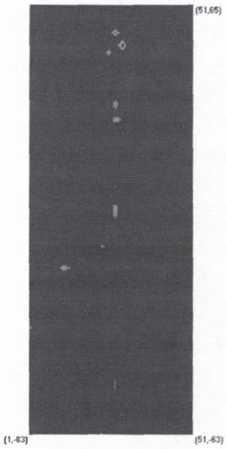


Fig. 11. Results of survey to the east of the Viking long house

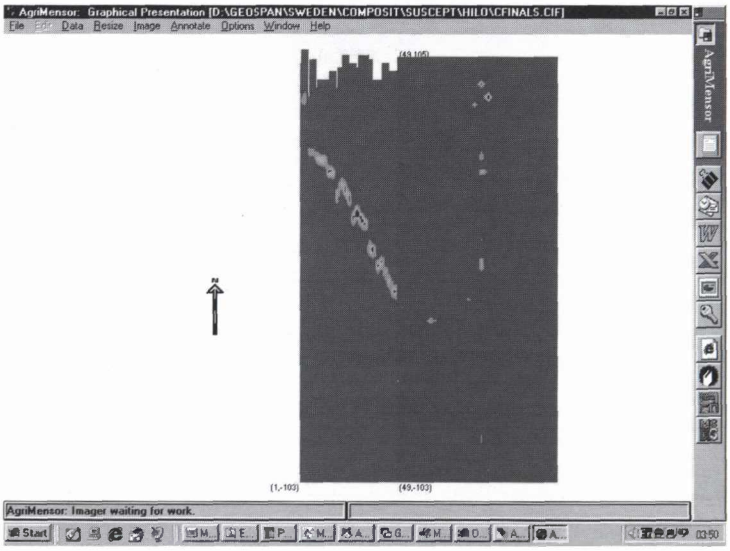


Fig. 12. Combination of plots from figs 10 and 11

long house. It was decided to survey a larger area immediately to the east in an attempt to determine the extent of the building. The results shown in Fig. 11 were extremely disappointing, and although taken with the same range of user-selected frequencies, there seemed to be no trace of the building at all. Could it be that we had by coincidence met the end of the building at the very edge of the first survey area? If so, then this raised more questions than it answered, as where, then, was the end-return?

Only when placing the two plots together, Fig. 12, was the answer apparent. The wall does, in fact, continue in a more-or-less straight line. But when seen without its companion piece, the anomalies of Fig. 12 simply get lost in the general scatter. Indeed, it is tempting to suggest that the wall turns just past the edge of the initial survey area, travels northeast for a while, and than proceeds due North. Several unsystematic changes of frequency later enabled a more substantial projection of the wall to be seen, but why were these changes in frequency necessary after just a few days and with no discernible change in either the terrain or the weather conditions? And how is the surveyor to know exactly which frequencies should be chosen, and when? Unfortunately, these are just some of the questions relating to this enigmatic instrument that still remain unanswered.

Our attention thus turned to the method of use of the instrument. Reviews of the then very limited literature (Won *et al.* 1996; Keiswetter and Won 1997; Pellerin and Alumbaugh 1997; Witten 1997; Won and Keiswetter 1997) produced no consistent methodology on how to hold and handle the GEM-300 whilst conducting an archaeologically survey. Should the instrument be carried at waist height as in an environmental or a magnetometer survey? Alternatively, should it be suspended high above the ground (unlikely), as in a geological survey, or near to the ground as in a susceptibility survey? Or, finally, should it be placed directly on the ground so as to loose as little as possible of the returned signal, at the same time substantially reducing operator fatigue?

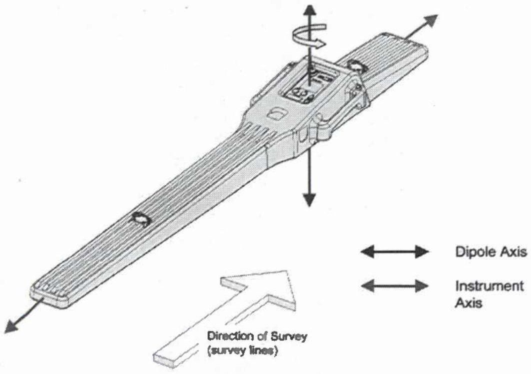


Fig. 13. Vertical coplanar

In each of these cases, which of the 2 possible coil alignment axes (vertical coplanar, Fig. 13, or horizontal coplanar, Fig. 14) would yield the better (or any) results? Would parallel alignment (Fig. 15) of the instrument with respect to the direction of survey, perpendicular alignment (Fig. 16), both or neither produce constant results across all 3 types of physical response?

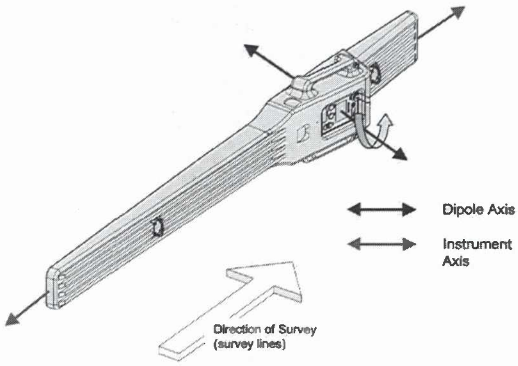


Fig. 14. Horizontal coplanar

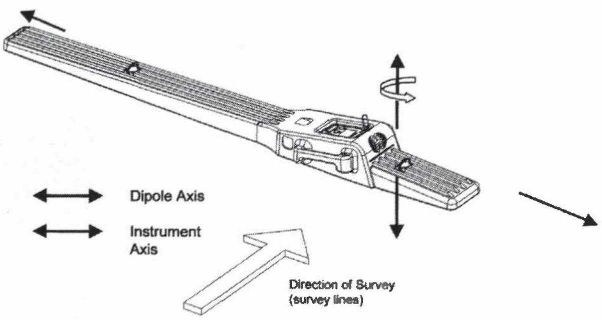


Fig. 15. Parallel alignment

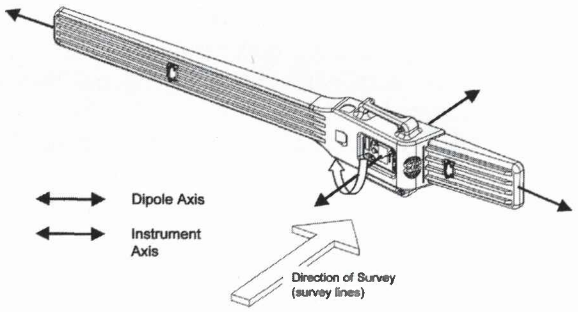


Fig. 16. Perpendicular alignment

The suspension method was considered to be impractical in terms of necessary equipment, time and cost; it was also felt that although the underlying geology might respond well (as had been the case in the manufacturer's own field trials with a predecessor instrument, the GEM-2), anomalies arising from archaeological near-surface activities almost certainly would not. Future field trials might revisit this decision with possible assistance from TimeTeam$^{©}$, a UK Channel 4 television programme in which a helicopter is regularly used for the purposes of air survey and related activities and which might be used to tow the instrument in its so-called “continuous operation” mode.

Numerous tests using all combinations and permutations of machine and coil orientation both on and near to the ground, at waist height and at a selection of operating frequencies were attempted — Clip 2 shows a number of different methods in action. The tests were initially concentrated at or close to ground level, since it was assumed that the strength of the received signal would be insufficient at waist height owing to the sixth-power falloff in an active instrument such as the GEM. The first tests involved placing the GEM-300 at fixed intervals of one metre in Station mode using the adjustable carrying strap; the second tests were similar, but the instrument was dragged to the station instead of carried. As may be seen from the accompanying video clip, both methods required the use of two operatives and were slow and inefficient; however it was the least tiring mode of operation. Unfortunately, it produced indeterminate results.

The next series of tests firstly involved carrying the instrument at about 15 cm above the ground using the carrying strap clasped in one hand. This proved comfortable to use in Continuous Operation mode but, unfortunately, the beep was only just audible in a rural context. Had the trials been carried out in an urban area, traffic noise would have undoubtedly ruled out this mode of operation and a second operator would have again been needed just to press the button. Results were on a par with those obtained by the earlier methods of positioning and dragging directly on or over the ground.

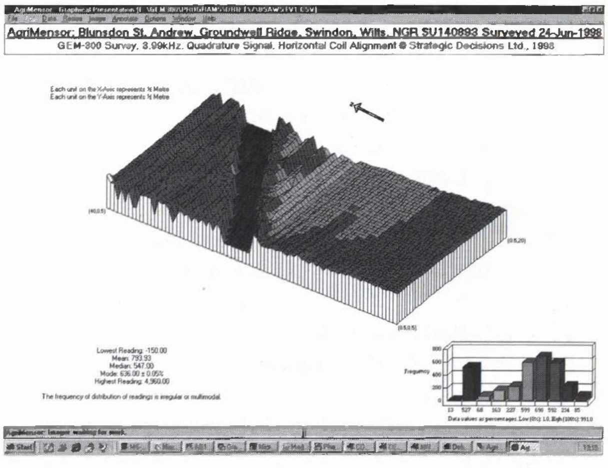
Tests were then repeated at waist height, in vertical coplanar orientation with parallel alignment using the carrying strap diagonally across one shoulder. This was followed by perpendicular alignment using the carrying strap around the back of the neck and across both shoulders. Whilst producing, somewhat surprisingly, better results than at ground level, both methods proved to be extremely tiring with noticeable strain to the human atlas and axis vertebrae.

The final method used was that of waist height, horizontal coplanar orientation with parallel alignment, again using the carrying strap diagonally across one shoulder. It was not possible to use perpendicular alignment in Station Mode since the body of the operator inhibits the view of the screen; however, in Continuous Operation, the method works well apart from the strain to the shoulder muscles.

As may be seen at the end of the video (Clip 2), differing heights and builds of various operators mean that either the carrying strap needs to be adjusted to retain consistent instrument height above the ground or that in a multi-person team, it is not advisable to swap operators between sessions.

The authors' findings were that horizontal coplanar orientation with parallel alignment at waist height (Fig. 14) was the preferred method of operation from the viewpoints of both results and human physiology. That is not to say that consistent results were always obtained using this method but, rather, that when good results were obtained, it was invariably when this method had been used.

A notable exception to all the above consistency considerations is the case where anomalies arise from large buried trenches and are surveyed in almost any terrain and weather conditions. Given the underlying physical principles of the instrument's operation, this is perhaps not surprising, but a good example of what we mean is given in Fig. 17, where one of the channels feeding a series of Roman water temples may be clearly seen to the north of the ancient terracing. Rain or shine, in Spring, Summer and Autumn (tests in winter were not carried out), virtually identical results were obtained.



AgriMensor: Blunsdon St. Andrew, Groundwell Ridge, Swindon, Wilts. NGR SU140893 Surveyed 24-Jun-1998

GEM-300 Survey, 3.99kHz, Quadrature Signal, Horizontal Coil Alignment © Strategic Decisions Ltd., 1998

Each unit on the X-Axis represents ½ Metre
Each unit on the Y-Axis represents ½ Metre

Lowest Reading: -150.00
Mean: 793.93
Median: 547.00
Mode: 636.00 ± 0.05%
Highest Reading: 4,960.00

The frequency of distribution of readings is irregular or multimodal.

Data values as percentages. Low (0%): 1.0, High (100%): 991.0

Fig. 17. Feeding channel of Roman water temple

7 Strengths and weaknesses

The GEM-300 potentially combines several complementary physical methods into a single machine and, therefore, in a single survey. This renders site surveys more complete and, after allowing for initial purchase, may produce a very cost-effective solution for those organisations that are carrying out archaeological surveys on a regular basis. Additionally, the ability to simultaneously record data at different depths adds much to the information that can be built up in a single survey. However, there appears to be no simple way of deciding which or how many frequencies should be allocated.

It has been discussed earlier in this paper how conductivity, susceptibility and penetration vary with the selected signal frequencies. However, it is not yet fully understood exactly how this crossover varies with frequency, geology, topography, climate and other potential environmental and human factors. As may be seen from the field trials and test results from Sweden, frequency gaps may lead to missing anomalies, thereby rendering features invisible to the user or, at a minimum, make them appear much smaller or less significant than they actually are (Fig. 12). It is as yet unclear which frequency ranges should best be used over differing types of terrain. Since the software algorithms are predicated upon frequency convolution for each individual *modus operandi* of the machine, it is difficult to see how computer programs can at this stage be accurately calibrated to plot depth against either frequency or these environmental parameters.

On the operational front, the instrument is extremely tiring on the neck and shoulders and is unwieldy for near-surface operation. The front panel and its controls are poorly positioned for archaeological survey, although it must be said that the instrument was not initially conceived for use in this discipline and the rather ambiguous documentation reflects this. A lack of headphones makes surveys very difficult in urban or heavy traffic / flight path contexts.

Although the internal flash memory has capacity for c. 256K words, about 16K of this is taken up by the instrument's menu-driven firmware, leaving 240K for user data. At each station, 1 word is used for each of the in- & out-of-phase measurements at each frequency together with 1 word for the station time stamp. So, if all frequency allocations were to be used, there would be room to record data at

$$240 * 1024 \ / (16 * 2 + 1) * S$$

or 7,447 stations.

In practice, both battery capacity and physical weariness would limit the number of stations visited to about half this value, especially as the time spent at each station is proportional to the number of frequency selections in use.

8 Future work programmes

Comparative surveys between the GEM and more conventional instruments such as magnetometers, resistivity equipment and GPR are planned for Fishbourne and West Heslerton (England), Uppåkra (Sweden) and Alba Iulia (Romania). In addition, plans are being laid to conduct field trials over known objects in order to further research frequency-dependent functional crossover.

9 Recommendations

- For archaeological fieldwork, the instrument should be made more ergonomic and less cumbersome;
- Audio facilities should be upgraded for use in non-rural environments;
- Documentation should be reoriented to address discreet target audiences (archaeologists, geologists, environmentalists);
- The sale price (currently believed to be around £15,000) needs to better reflect its target audiences (military, civic, commercial, archaeological).

10 Summary and conclusions

- Huge savings potential for manpower and survey costs once initial capital has been expended;
- More complete survey interpretation resulting from multi-sourced data;
- Multi-frequency operations allows graphical depth representation using pseudo-3D tomographic sections;
- Unanswered questions concerning consistency and completeness of results require further research;
- Merits serious consideration as a complementary tool until such time as the underlying physical principals are fully understood.

Acknowledgments

Thanks are due to Norman Bell of Allied Associates Geophysical Ltd., without whose generous loan of the instruments over a number of seasons, none of the field trials would have been possible. Thanks are also due to Dave Smale and Matt Stairs who bore much of the heavy weight of the instrument during the field trials in England.

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