Assessment of the CMD Mini-Explorer, a New Low-frequency Multi-coil Electromagnetic Device, for Archaeological Investigations

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ABSTRACT
In this article we assess the abilities of a new electromagnetic (EM) system, the CMD Mini-Explorer, for prospecting of archaeological features in Ireland and the UK. The Mini-Explorer is an EM probe which is primarily aimed at the environmental/geological prospecting market for the detection of pipes and geology. It has long been evident from the use of other EM devices that such an instrument might be suitable for shallow soil studies and applicable for archaeological prospecting. Of particular interest for the archaeological surveyor is the fact that the Mini-Explorer simultaneously obtains both quadrature (‘conductivity’) and in-phase (relative to ‘magnetic susceptibility’) data from three depth levels. As the maximum depth range is probably about 1.5 m, a comprehensive analysis of the subsoil within that range is possible. As with all EM devices the measurements require no contact with the ground, thereby negating the problem of high contact resistance that often besets earth resistance data during dry spells. The use of the CMD Mini-Explorer at a number of sites has demonstrated that it has the potential to detect a range of archaeological features and produces high-quality data that are comparable in quality to those obtained from standard earth resistance and magnetometer techniques. In theory the ability to measure two phenomena at three depths suggests that this type of instrument could reduce the number of poor outcomes that are the result of single measurement surveys. The high success rate reported here in the identification of buried archaeology using a multi-depth device that responds to the two most commonly mapped geophysical phenomena has implications for evaluation style surveys. © 2013 The Authors. Archaeological Prospection published by John Wiley & Sons Ltd.

Key words: Electromagnetic induction; Slingram; conductivity; magnetic susceptibility; CMD Mini-Explorer

Introduction
Low-frequency electromagnetic (EM) techniques using Slingram instruments have been used for archaeological prospecting since the 1960s. Traditionally in Europe, EM surveys have not enjoyed widespread use (Gaffney, 2008) for a number of reasons, such as limited data collection ability, inherent issues of instrument drift, a lack of depth analysis and, partly, the community’s over reliance upon magnetometer, earth resistance, and ground-penetrating radar technology. Despite this, EM surveys have previously offered a number of benefits over traditional magnetic and electrical methods, principally the simultaneous acquisition and co-location of quadrature and in-phase data to assess soil properties similar to those identified in earth resistance and magnetometer surveys. The measurement of quadrature and in-phase components allows the calculation of conductivity and magnetic susceptibility, respectively. Under certain practical conditions EM surveys...
provide a very reasonable approximation of these properties and are therefore capable of identifying a broad range of archaeological features, including cut features, masonry and areas of burning. However, previous studies have indicated the values are only estimates as the conductive and magnetic components are not entirely separated (Tite and Mullins, 1973; Tabbagh, 1986a; Linford, 1998) and these relate to all instruments of this type.

Both commercial and academic prospecting strategies have recently been driven by a need to resolve all (or most) archaeological features, rather than those that exhibit exclusively magnetic properties, by the acquisition of high-resolution data in an increasingly efficient manner (Gaffney et al., 2012) and by the investigation of archaeological features at depth using three-dimensional or pseudo-three-dimensional methods. These drivers have previously been met by high-speed multi-method investigations employing magnetometer, earth resistance and/or GPR surveys (Dabas, 2009; Trinks et al., 2010; Campana and Dabas, 2011), however, the development of a new generation of multi-depth instruments suggests that EM prospecting may have a role to play. This article reports the use of a new Slingram instrument, the CMD Mini-Explorer and its applicability to archaeological prospecting.

Electromagnetic surveys

The successful application of earth resistance and magnetometer surveys to archaeological sites since the late 1940s (Clark, 1996) prompted the investigation of EM methods for similar purposes. Electromagnetic prospecting techniques have been used for archaeological purposes since the late 1960s (Colani, 1966; Colani and Aitken, 1966). The soil conductivity meter (Howell, 1966) was the first truly portable Slingram instrument specifically designed for archaeological prospecting. The Slingram design passes an alternating current through a transmitter (Tx) coil, inducing a primary electromagnetic field through the ground. As the primary field passes through the soil, it encounters conducting materials within which eddy currents are induced with a phase shift. Subsequently, the conducting material produces a secondary magnetic field with the phase of the eddy currents and is finally returned to and measured by a receiver (Rx) coil. The phase shift of the secondary field is known as ‘quadrature’ or ‘out-of-phase’ with the primary field and its value is observed as a measure of soil conductivity.

Although the soil conductivity meter was designed to obtain electrical conductivity measurements, Tite and Mullins (1969) demonstrated that it responded more to magnetic properties in the soil. This occurs when the primary field intercepts magnetic material; the secondary field is produced by the magnetic susceptibility of the feature. The received secondary field wave is regarded as ‘in-phase’ with the primary field. In reality the secondary signal is a mixture of both phases and subsequent EM instruments were developed to measure both conductivity and magnetic phase variance. Although this was achieved, research indicated that the most important influences on the ability to detect archaeological features are coil spacing and orientation (Tabbagh, 1986a, 1986b; Won et al., 1996; Benech and Marmet, 1999).

From the above, it can be understood that EM instruments are ‘active’ instruments that induce an electromagnetic field in the ground and measure a response attenuated by the underlying soils. The survey speed of active techniques, such as EM instruments, will never be as quick as passive instruments, such as magnetometers, although this is balanced by the fact that the EM technique is capable of identifying a wider range of features than a single passive instrument. The EM instruments have enjoyed particular success in the Middle East and in parts of North America (Clark, 1996; Witten et al., 2000; Berle Clay, 2006), where earth resistance surveys perform poorly or not at all upon the dry soils. The EM instruments in the USA are often used to replace earth resistance surveys, as they are suitable for dry, hard and arid site conditions (Bevan, 1983). The instrument used in the majority of the published examples for archaeological purposes from the USA is the Geonics EM38. The fundamental technology established by the EM38 instrument is similar to most of the subsequently developed instruments.

Multi-depth EM technology

Low-frequency EM instruments operate at <300 kHz, however, there is no universal ‘ideal’ frequency applicable to all EM instruments as the ability to identify archaeological deposits is primarily determined by physical issues (e.g. coil geometry and sensor height) and the physical attributes of the soil (e.g. permeability, geology, depth of investigation, type of archaeological remains likely to be encountered). Some attempts at building multi-frequency instruments and hence provide variable depth data for pseudo-three-dimensional data cubes have been found to be unreliable for archaeological prospecting (Bonsall, 2001). The fixed distance in a Slingram instrument between the Tx and Rx coils has a greater correlated influence on the depth of...
penetration than differing frequency. The new generation of EM instruments contain multiple Rx coils separated from the Tx coil by differing distances, allowing for an assessment of different depth levels. The known frequency, coil geometry and sensor height allow for the approximate calculation of depths for each Tx/Rx pair. Two examples of the new multi-receiver/depth type EM instrument are the Dualem-21S (Dualem Inc.) and the CMD Mini-Explorer (GF Instruments).

Coil geometry

Coil geometry is an important influence on the success or otherwise of prospecting for a buried feature at depth. In older systems, one response was generated by a single pair of Tx and Rx coils. More recent instruments operate at one frequency over several coil arrangements, which allows for the collection of multiple depth responses. Others have suggested that a frequency of no more than 100 kHz should be used and a coil spacing of less than 2 m for archaeological prospecting (Scollar et al., 1990). The Dualem-21S for example operates at a frequency of 9 kHz, has four Rx coils and two coil arrangements; perpendicular (PERP), spaced 1.1 m and 2.1 m from the Tx coil, and horizontal coplanar, spaced 1.0 m and 2.0 m from the Tx coil (Figure 1). The CMD Mini-Explorer, which has been tested for this investigation, differs from this in frequency, coil geometry, orientation and separations. The Mini-Explorer operates at 30 kHz, has three Rx coils (spaced 0.32 m, 0.71 m and 1.18 m from the Tx coil) and two coil arrangements; a horizontal coplanar (HCP) configuration (in the vertical dipole orientation or the ‘full depth’ range) and, when the instrument is rotated through 90°, a vertical coplanar (VCP) configuration (in the horizontal orientation or the ‘half depth’ range). The HCP/VCP coil arrangement of the Mini-Explorer is identical to that of the popular EM38 and EM38-MK2 sensors, but differs in the geometry of these instruments in relation to the number of coils and their spacing. Although the Mini-Explorer has a higher operating frequency than other instruments, it is comfortably within the (<300 kHz) definition of ‘low frequency’ EM.

An assessment of various EM coil arrangements (Tabbagh, 1986b) found that the PERP was the most appropriate for the detection of archaeological features, followed by the VCP, which is best suited to the measurement of more centred and symmetric anomalies that are very important for an accurate representation of the underlying archaeological features. The HCP was considered as the best for detecting a deep conducting layer, but the worst for detecting a magnetic layer; the HCP also gave changes in polarity of the measured response, although this is a common occurrence in EM instruments (Linford, 1998; McNeil and Bosnar, 1999; Dalan, 2008). The expected polarity change for the HCP configuration (as recorded for other EM instruments that use HCP) can be used to aid relative and even absolute depth estimates (as seen in Figure 2).

The presence of both PERP and HCP coil arrangements in the Dualem-21S allows it to simultaneously record eight output signals, creating a large EM dataset.
that has proved useful for the analysis, reconstruction and modelling of soil profiles for complex multi-layered Holocene deposits at variable depth, particularly when supplemented by augering (Simpson et al., 2009). From an archaeological-feature perspective the instrument has produced promising apparent magnetic susceptibility results comparable to magnetometer data (De Smedt et al., 2011, 2013) and apparent electrical conductivity data that correspond well with excavation data (Saey et al., 2012). Recent work has shown that the Dualem surveys were able to identify a variety of archaeological features, including 2m-wide ring ditches (Simpson et al., 2010), a large (12 m wide) moat (Saey et al., 2012) and brick block foundations ca. 1 m² (De Smedt et al., 2013). The large Tx/Rx coil separation strongly influences the depth penetration and response pattern, currently suggesting that the towed Dualem system is very well suited to large landscape studies analysing soil components; the relatively large volumes of soil investigated, however, suggests that smaller scale features are less likely to be mapped. As a result we have focused our investigations on the capabilities of the CMD Mini-Explorer with shorter distances between coils and with reference to the soils and archaeological site types found in the British Isles.

Technical capabilities of the CMD Mini-Explorer

The CMD Mini-Explorer (Figure 3) probe is 1.275 m long, 0.05 m in diameter and weighs 1.8 kg. The manufacturer indicates that the instrument has an effective depth range of 0.25 m, 0.5 m and 0.9 m for VCP in the horizontal coil dipole orientation; this is extended to 0.5 m, 1.0 m and 1.8 m by rotating the orientation of the Tx/Rx coils by 90° to use HCP in the vertical coil dipole orientation. If the survey is repeated using both coil orientations a total of six levels of depth data can be obtained from the combined vertical and horizontal configuration, ranging between 0.25 and 1.8 m (Table 1). Responses from 0.5 m occur in both the VCP and HCP data; each coil orientation measures a different volume of earth and these should not be expected to produce identical data at this depth level. The depth of investigation of the CMD Mini-Explorer, as determined by the manufacturers, is indicative only and they suggest that it is equal for both quadrature and in-phase responses; however, others (Tabbagh, 1986b; Scollar et al., 1990) have shown that this is not the case for most EM instruments investigating archaeological soils. The accuracy of depth levels is beyond the scope of this paper, which focuses instead upon the use and application of the instrument for the identification of archaeological features.

As with other modern EM devices, the Mini-Explorer measures apparent conductivity (quadrature) in mS m⁻¹ and the in-phase ratio in parts per thousand, which is largely determined by the magnetic susceptibility contribution of the soil. The in-phase response is a relative value and is not calibrated to measure magnetic susceptibility directly. It is understood that the complexity of the EM response in relation to quadrature and inphase (and its relative contribution from magnetic susceptibility) is not resolved, however, this is inherent
in this class of instrument and is not specific to the CMD Mini-Explorer alone.

The simultaneous acquisition and co-location of quadrature and in-phase data means that the same volume of earth is investigated for any given sample point, something which magnetometer and earth resistance surveys are unable to do, no matter how accurately the data are collected. This gives the Mini-Explorer a significant advantage over conventional magnetometer and earth resistance surveys in terms of analysing the geometry and geophysical magnitude of responses from subsurface archaeological features.

Given the short baseline and coil orientation options, the acquisition of variable levels of depth penetration and the co-location ability to simultaneously measure two soil properties, the Mini-Explorer might represent a suitable instrument for the assessment of discrete archaeological features and has therefore been tested to assess this proposition.

Practical survey considerations

As the CMD Mini-Explorer must be used in either the full depth (HCP, vertical dipole orientation) or the half depth (VCP, horizontal dipole orientation) mode (Figure 4), two survey ‘sweeps’ are required over a given area if depth data from both dipole orientations are desired.

Table 1. Coil configuration, orientation, separation and effective depth of investigation for electromagnetic measurements collected with the CMD Mini-Explorer. The depth of investigation has been determined by the manufacturer (GF Instruments) and should be regarded as indicative only.

| Configuration | Coil orientation | Electromagnetic measurement | Coil separation (m) | Depth of investigation (m) |
|---------------|------------------|-----------------------------|---------------------|---------------------------|
| 1-HCP-Q       | Horizontal coplanar | Quadrature                  | 0.32                | 0.5                       |
| 1-HCP-I       | Horizontal coplanar | In-phase                    | 0.32                | 0.5                       |
| 2-HCP-Q       | Horizontal coplanar | Quadrature                  | 0.71                | 1.0                       |
| 2-HCP-I       | Horizontal coplanar | In-phase                    | 0.71                | 1.0                       |
| 3-HCP-Q       | Horizontal coplanar | Quadrature                  | 1.18                | 1.8                       |
| 3-HCP-I       | Horizontal coplanar | In-phase                    | 1.18                | 1.8                       |
| 1-VCP-Q       | Vertical coplanar  | Quadrature                  | 0.32                | 0.25                      |
| 1-VCP-I       | Vertical coplanar  | In-phase                    | 0.32                | 0.25                      |
| 2-VCP-Q       | Vertical coplanar  | Quadrature                  | 0.71                | 0.5                       |
| 2-VCP-I       | Vertical coplanar  | In-phase                    | 0.71                | 0.5                       |
| 3-VCP-Q       | Vertical coplanar  | Quadrature                  | 1.18                | 0.9                       |
| 3-VCP-I       | Vertical coplanar  | In-phase                    | 1.18                | 0.9                       |
The probe is used in conjunction with a control unit, which are usually connected via Bluetooth (which operates in the GHz band and does not impact upon the 30 kHz operating frequency of the EM sensor). The Bluetooth connection allows for either a pedestrian hand-held survey or a GPS-enabled sledge/cart mounted survey, if required. The instrument can be set up efficiently within 3 minutes. An internal temperature compensation automatically provides absolute calibration of apparent conductivity data prior to each line or profile of data collected, which limits drift across the dataset. Surveys occurring over several days may require preliminary data treatment to compensate for temporal influences on soil moisture/temperature. The sensor can be held comfortably in one hand at the optimum probe height of approximately 0.05 m above the ground in order to ensure maximum depth of penetration. The probe height can be adjusted using a telescopic handle when encountering sites of variable terrain or vegetation cover.

The geometry of a given survey area is user-defined in terms of grid and sample resolution. Rectangular grids comprised of individual lines or profiles are collected – if the instrument is used in GPS-enabled mode the survey can be carried out in a ‘gridless’ fashion. If using GPS, a non-drifted calibration mode, as reported by Simpson et al. (2009) can be used. Data are collected along each profile at a user-defined sample rate of up to 10 Hz (timed intervals from 0.1 to 1 s) or at manually logged positions.

Assessment of the Mini-Explorer for archaeological prospecting

In the period of May 2011 to May 2012 we have undertaken 22 EM surveys across the Republic of Ireland and the UK. The Mini-Explorer has been used on a variety of site types and compared with earth resistance, electrical resistivity tomography, magnetometer and excavation data where possible. The surveys were designed to:

(i) assess the ability of the Mini-Explorer to detect archaeological features;
(ii) assess the reliability of the apparent conductivity and in-phase data.

Four case studies are presented from a nineteenth–twentieth century graveyard in Yorkshire, a hengiform monument at Stonehenge, England, an embanked enclosure from Co. Kilkenny in Ireland and a time-lapse study comparing the quadrature response to earth resistance-derived conductivity data.

Case study 1: The Asylum Cemetery at High Royds, Menston, West Yorkshire (UK)

A survey with the CMD Mini-Explorer was undertaken at the asylum cemetery for High Royds Chapel, Menston, West Yorkshire (UK). The cemetery contains 2,861 known (but unmarked) paupers’ graves, which were interred between 1890 and 1969. An archive plan for the cemetery shows around 1,000 plots (approximately 2 m × 1 m), but from previous geophysical surveys conducted with an earth resistance meter, ground-penetrating radar and magnetometer (Gaffney and Gaffney, 2011) it became apparent that the burial plots contained multiple burials. It is likely that a number (if not all) of the plots were originally marked by a simple cast-iron cross, and some have been recovered in the recent regeneration of the site by the ‘Friends of High Royds Memorial Garden’ charitable company. The survey performed using the CMD Mini-Explorer over the area provided a useful comparison to the 0.5 m probe separation earth resistance (0.5 m × 1 m) and the fluxgate magnetometer (0.5 m × 0.125 m) data.
The survey was conducted using both the HCP and VCP coil orientations to enable analysis of six depth levels over an area of 60 m × 40 m. Both the HCP and VCP surveys were conducted at a spatial resolution of 0.5 m × 0.2 s (gridded to 0.5 m × 0.25 m and interpolated to 0.25 m × 0.25 m using the sin(x)/x method). The data were collected at right angles to the known orientation of the grave plots. The EM plots (Figure 5) show data collected at four of the depth levels for both quadrature and in-phase measurements. The data underwent basic processing, including de-spiking and drift correction as appropriate.

An interpretation of archaeological features from the HCP conductivity and in-phase data is slightly complicated by a change in the polarity of the signal. Data from the VCP configuration are not affected by polarity changes and are slightly easier to interpret. The HCP polarity shift occurs at depths greater than 1 m, that is, HCP Level 1 data are consistent with the VCP responses, whereas data from HCP Levels 2 and 3 have ‘flipped’ polarity. The polarity change is an inherent characteristic for HCP coils and although this may seem confusing, the phenomenon has been well documented and understood over the past 25 years (Tabbagh, 1986b; Linford, 1998; Simpson et al., 2009). The polarity shift does not, however, affect the ability to distinguish between anomalous contrasts and the background responses; archaeological features are still clearly visible in all of the datasets presented. Although the general appearance of data may be inconsistent between all six depth levels, the individual conductivity and in-phase responses – the relative values – are valid indicators of...
discrete archaeological features that allow for the identification of small-scale components and large landscape complexes.

The results from the data collected at Menston help to reveal further information regarding the depth and nature of a number of the burial plots on the site compared with the magnetometer and earth resistance surveys conducted previously. The in-phase responses are able to delimit depths for a number of the single burials, indicating also where multiple burials have been interred in the same plots. To the south of the survey area, a large area of increased magnetic noise is visible in the data. This area exists between two extant paths in the cemetery and may indicate a more recent levelling deposit, possibly masking the in-phase response of the deeper burials and therefore may be inherent in this particular situation. The quadrature plots are, however, rather complementary to the in-phase datasets and are not affected by this increased magnetic noise.

The CMD Mini-Explorer datasets offer more interpretative information than the previous surveys conducted with magnetometer and earth resistance techniques alone, providing a better assessment of individual position and depth of burials over the survey area. The in-phase datasets are very similar to the magnetometer response, especially at a depth range of 1 m; however, the increased magnetic noise in the south of the survey area seems to affect the in-phase results much more than the magnetometer, masking the weaker burial response at depth. The quadrature datasets complement the in-phase response over this area and are not affected by the increased magnetic noise. The quadrature survey was also able to add much more information to the site than the previous earth resistance area dataset.

Case study 2: Hengiform Monument Amesbury 50, Stonehenge, Wiltshire (UK)

A new ‘hengiform’ monument was identified by magnetometer and GPR data in 2010 at the site of what was previously recorded as a barrow, known as ‘Amesbury 50’, located 800 m to the northwest of Stonehenge. The ‘barrow’ monument is now known to comprise of two opposed arcs of large pits surrounding a pit circle (Gaffney et al., 2012, figure 3), located beneath a mound.

The CMD Mini-Explorer was used at the hengiform site to collect quadrature and in-phase data at a spatial resolution of 0.5 m × 0.1 s (gridded to 0.5 m × 0.25 m, interpolated to 0.25 m × 0.25 m, using the sin(λ)/λ method). The instrument was used in HCP vertical dipole orientation, at a height of 0.05 m above the ground, obtaining three levels of data within a suggested depth range (Table 1) of 0.5 m (Level 1), 1.0 m (Level 2) and 1.8 m (Level 3). As the survey was carried out in the HCP configuration, the responses undergo the expected polarity change at depths greater than 1 m.

The Level 1 conductivity and in-phase data contain soil noise (Figure 6). This has been noted as a common occurrence throughout our tests when using the HCP orientation; however, work at other sites has shown that noise is not always apparent when using the VCP orientation. The HCP noise reflects topographic changes (magnifying the periodicity of walker ‘bounce’) and magnetic variations in the topsoil. Although it may look erroneous, soil noise can be an important indicator of archaeological deposits – the effect of the noise due to the underlying archaeology at the hengiform monument is particularly noticeable upon the uneven surface of the mound and all but ceases in areas of flat and level ground. Soil and operator noise can generally be removed via processing software but it has been left in to illustrate these factors. The noise decreases in Level 2 and is mostly absent in Level 3.

The conductivity data from Level 1 indicate an approximate outline of the hengiform monument, comprised of soil noise on the edges of the earthwork and a circular patch of low conductivity representing the mound. The conductivity data from Level 2 identifies the two opposed arcs of large pits as a ring of irregular shaped high conductivity anomalies, surrounding an internal ring of equally irregular shaped low conductivity anomalies that may represent upcast material from the two arcs of pits. The Level 3 conductivity data clearly defines the two arcs of large pits and also suggests the presence of an internal pit circle.

The in-phase data from Level 1 have clearly identified the two arcs of large pits. The Level 2 in-phase data give a greater definition to the pits and indicate the presence of a low in-phase anomaly in the centre, representing the upcast chalky soil of the mound. The Level 3 in-phase data give the best resolution of the two arcs of large pits, further indications of the chalky mound soil and a slight suggestion of a narrow linear pit near the centre of the hengiform monument. The internal pit circle identified in the Level 3 conductivity data also appears in the in-phase data at the same depth, although less clearly defined.

The EM survey of Amesbury 50 has demonstrated that the complex site components of the hengiform monument can be identified. The mound earthwork, two opposing arcs of pits and an internal pit circle
were apparent as clear and coherent anomalies. The in-phase and conductivity data from Level 3 gave the clearest indications of the smallest cut features; however, important archaeological information was obtained from all three depth levels.

**Case study 3: Davidstown, Co. Kilkenny (Republic of Ireland)**

During prolonged periods of hot weather and low rainfall, dry conditions caused by evapotranspiration can either prevent the identification of earth-cut features in earth resistance data and/or hinder the insertion of probes within the compacted soil (Clark, 1996; Fry *et al*., 2011; Parkyn *et al*., 2011). An earth resistance survey of an enclosure ditch on sandstone geology at Davidstown was abandoned, having failed to obtain satisfactory probe contact owing to seasonally dry soils at the surface.

An EM survey (attempted over the same area on the same day as the resistance survey), which does not require ground contact, obtained high-quality conductivity data. The survey was conducted using the HCP coil orientation to enable analysis of three depth levels over an area of 30 m × 40 m. The HCP survey was conducted at a spatial resolution of 0.5 m × 0.2 s (gridded to 0.25 m × 0.25 m and interpolated to 0.25 m × 0.25 m, using the sin(x)/x method). The EM plots (Figure 7)
show Level 3 data for both quadrature and in-phase measurements. The data underwent basic processing, including de-spiking and drift correction as appropriate.

Both the in-phase and conductivity data successfully identified the enclosure ditch and the presence of a bank; this validated the choice of an EM technique as banks are an archaeological feature type that usually fail to appear in magnetometer data due to weak magnetic contrasts and they are also notable by their rarity in earth resistance surveys.

Case study 4: time-lapse comparison with electrical resistance survey

A pilot time-lapse study was undertaken to compare the apparent conductivity response from the CMD Mini-Explorer to a typical twin-probe earth resistance response over the same archaeological ditch feature, situated at Harnhill, Cirencester (Fry et al., 2011). The ditch is a former field boundary cut into limestone geology (at a shallow depth of ca. 0.2 m) of the Cornbrash Formation, infilled with sandy-clay and loam deposits to a depth of around 1 m. Twin-probe measurements, recorded with an RM15 resistance meter with a mobile probe separation of 0.5 m were converted into apparent conductivity to be directly comparable to the converted quadrature measurements.

To provide a cross-section response over the ditch, three adjacent transects were extracted from the dataset and normalized to the average background value. The twin-probe conductivity response over the ditch is then compared with the two Mini-Explorer responses with a supposed depth of investigation of 0.5 m (2-VCP-Q and 1-HCP-Q). The resultant plots (Figure 8) show the comparison between the two methods, over four months of survey.

The conductivity response between the techniques produced very similar curves each month throughout the pilot study. This is especially true over the month of April 2012, where the responses are almost identical. The twin-probe technique seems to be the most stable over the changes in seasonal variation, producing very similar response curves each month. The EM response is variable, and produces more complex curves over the archaeological feature, which may indicate a higher sensitivity to moisture changes over this period or differing variations within the soil volume. The difference in magnitude of response between 2-VCP-Q and 1-HCP-Q each month will be a product of the different volumes of soil sampled with the respective coil orientation (Tabbagh, 1986b). The apparent conductivity response from the quadrature measurements is, however, similar to the earth resistance, and could potentially validate the use of this instrument in places where the earth resistance technique is impractical for use.

Discussion and conclusions

The case studies have highlighted the benefits of a multi-depth EM instrument capable of measuring simultaneously magnetic susceptibility and conductivity properties for the same volume of earth – measurements that cannot be assessed by non-EM techniques, as shown by the assessment of the Amesbury 50 barrow at Stonehenge. These complementary properties offer a significant benefit for the assessment of known

Figure 7. Ditched enclosure at Davidstown, County Kilkenny, Ireland. The CMD Mini-Explorer collected high-quality conductivity data over very dry soils (a comparative earth resistance survey failed to obtain satisfactory probe contact at this site). Both the in-phase and conductivity data identified an enclosure ditch and an internal bank. The bank is noteworthy as it is a feature type that typically fails to appear in magnetometer data due to weak magnetic contrasts; banks are also notable by their rarity in earth resistance surveys. This figure is available in colour online at wileyonlinelibrary.com/journal/arp
archaeological sites and for prospection of unknown architectural features. For the former, an enhanced interpretation may be obtained due to the benefits of co-located data; for the latter, EM instruments reduce the likelihood of selecting an inappropriate instrument (e.g. magnetometry or earth resistance or GPR) for the investigation of large areas, as two complementary soil properties are obtained rather than one, and a minimum of three depth levels are examined for each property.

The capability of multi-depth EM to measure the in-phase response – and its change with depth – may have significant contributions to recent magnetic susceptibility research for soundings (Dalan, 2006, 2008; Dalan et al., 2011), as these responses are particularly useful for estimating broad magnetic stratigraphy without excavation, as well as the detection of discrete archaeological features. The efficacy of such soundings might be considered for future research with comparisons to down-hole assessments, where magnetic susceptibility may be taken as indicators of anthropogenic zones. The measurement of magnetic susceptibility directly, rather than the magnetic field, is also a significant advantage over magnetometry; multi-depth responses increase the application of investigating layered or laminar structures in detail.

The depth of investigation for the Mini-Explorer (0.25–1.8 m) is also suitable for the detection of metal objects, which is of particular archaeological use, and others (Tabbagh, 1986b; Scollar et al., 1990) have suggested it offers a significant advantage over the shallow depth penetration of conventional metal detectors. Further, the EM response to ferrous material is much less prone to the wide disturbance associated with bipolar magnetometer anomalies of the same material, which is amply illustrated by the data from Menston.

The CMD Mini-Explorer has demonstrated an ability to detect a wide range of archaeological features. Excavations and two-dimensional geophysical data have confirmed that the conductivity and in-phase responses have identified ditches (including significant enclosed settlements and mounds), pits (including post-pit circles), inhumations and an embanked earthwork. The instrument performed well within the variables assessed, such as geology, soils, vegetation cover and, crucially for international applications, the ability to detect and locate archaeological features efficiently and accurately.

Figure 8. Time-lapse study of responses from apparent conductivity data derived from a twin-probe earth resistance array and the CMD Mini-Explorer over a former field boundary ditch at Harnhill, Cirencester. The ditch is cut into limestone geology (at a shallow depth of ca. 0.2 m), infilled with sandy-clay and loam deposits to a depth of around 1 m. The depth of investigation for the EM survey is claimed to be 0.5 m for the configuration displayed (2-VCP-Q and 1-HCP-Q). This figure is available in colour online at wileyonlinelibrary.com/journal/arp.
applications in areas of dry soils and climate, as demonstrated at Davidstown. The absolute calibration of apparent conductivity per line of data collected is achieved by temperature compensation and also offers a significant advantage over other EM instruments that have historically required substantial drift correction.

The instrument offers a rapid investigation of archaeological soils and is capable of returning six datasets (three of each for quadrature and in-phase) for a 1 ha area in 2 h 40 min (pedestrian acquired gridded data collected at 1 m × 0.1 s resolution, using 50 m × 50 m grids), which is significantly faster than pedestrian acquired earth resistance and GPR surveys and is broadly comparable to the speed offered by handheld magnetometer surveys.

Multi-depth EM research for archaeological evaluation still has a great deal to achieve. It is quite evident that there are practical issues with the CMD Mini-Explorer that need to be resolved, particularly in relation to the sensitivity of the instrument with depth and the accuracy of the depth of investigation for archaeological targets as determined by the manufacturer. However, we do believe that the multi-depth capability is imperative for the future of EM use as it offers greater benefits than single parameter investigation tools. Although the separation width between Tx and Rx coils in this instrument may not be ideal, they offer an alternative to others and one that appears suited for near-surface investigation.

It has been shown that the CMD Mini-Explorer has the ability to determine the presence of a variety of discrete archaeological features across a range of site types and locations. The depth range suggested by the manufacturers is suited to shallow soils and has been found to be particularly useful for the investigation of complex stratigraphy, such as those found on archaeological sites. The instrument is suitable for prospecting surveys of areas of unknown archaeological potential – if archaeological features are present we have found that at least one of the datasets would indicate a measurable and understandable signal. This last point is very important if one considers the use of a multi-depth EM system in commercial or evaluation surveys. The use of a multi-depth EM sensor appears to reduce the chances of incorrect technique choice, especially in areas of difficult geology or variable soil depth.

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