Comparison of magnetic, electrical and GPR surveys to detect buried forensic objects in semi-urban and domestic patio environments

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Abstract

Near-surface geophysical techniques should be routinely utilised by law enforcement agencies to locate shallowly buried forensic objects, saving manpower and resources. However, there has been little published research on optimum geophysical detection method(s) and configurations beyond metal detectors. This paper details multi-technique geophysical surveys to detect simulated unmarked illegal weapons, explosive devices and arms caches that were shallowly buried within a semi-urban environment test site. A concrete patio was then overlaid to represent a common household garden environment before re-surveying. Results showed the easily-utilised magnetic susceptibility probe was optimal for target detection in both semi-urban and patio environments, whilst basic metal detector surveys had a lower target detection rate in the patio scenario with some targets remaining undetected. High-frequency (900 MHz) GPR antennae were optimum for target detection in the semi-urban environment whilst 450 and 900 MHz frequencies had similar detection rates in the patio scenario. Resistivity surveys at 0.25 m probe and sampling spacing were good for target detection in the semi-urban environment. 2D profiles were sufficient for target detection but resistivity datasets required site detrending to resolve targets in map view. Forensic geophysical techniques are rapidly evolving to assist search investigators to detect hitherto difficult-to-locate buried forensic targets.

5,832 words, 16 Figures and 2 Tables

Running title: Semi-urban and patio geophysical surveys

Introduction

Geo-scientific methods are being increasingly utilised and reported upon by forensic search teams for the detection and location of clandestinely buried material in terrestrial environments. Parker *et al.* (2010) provides a comprehensive review of forensic geophysical searches within freshwater bodies. In a law enforcement context, forensic burials are at a maximum of 10 m below ground level (bgl) and usually much shallower (Fenning & Donnelly 2004). Forensic objects needing to be located vary from illegally buried weapons and explosives, landmines and improvised explosive devices (IEDs), drugs and weapons caches to clandestine graves of murder victims and mass genocide graves (see Pringle *et al.* 2012a). In the U.S.A., neighbourhood criminal gangs often hide used illegal weapons for later recovery (Dionne *et al.* 2011).

Recovery of buried forensic material often results in successful criminal convictions and it is thus critical for them to be located (Harrison & Donnelly 2009). Law enforcement agencies need to have prioritised locations to physically excavate due to shortages in manpower and resources, especially if the search area is large. Specialist trained search dogs have been widely used to identify different buried objects, commonly IEDs (see Curran *et al.* 2010), drugs and human remains, the latter teams sometimes referred to as cadaver dogs (see Rebmann *et al.* 2000) but are less successful with buried inorganic objects. Metal detector search teams are used during forensic investigations when deemed appropriate, especially when there is a high contrast between the target and local background environment (see Nobes 2000).

Geotechnical investigations routinely use near-surface geophysical methods to identify buried locations of, for example, cleared building foundations and underground services (see Reynolds, 2011), as well as environmental forensic objects such as illegally buried waste (see Bavusi *et al.* 2006; Ruffell & Kulessa 2009). Magnetic detection methods are commonly used in geotechnical (e.g. Marchetti *et al.* 2002; Reynolds, 2004; Reynolds 2011) and forensic archaeological investigations (see Linford 2004; Hunter &

Cox 2005). Acheroy (2007) provides a useful review of field detection of anti-personnel mines using ground penetrating radar (GPR).

However, little control study research has been published in which buried forensic objects are detected using a variety of geophysical methods, other than to confirm metal detection team results (e.g. Davenport 2001; Rezos et al. 2010) and for human remains (e.g. Miller 1996; Davenport 2001; Schultz *et al.* 2006, Schultz 2008; Pringle *et al.* 2008; Pringle *et al.* 2012b). Dionne *et al.* (2011) did conduct a control study with buried weapons and found electro-magnetic equipment could detect metallic objects buried in a grid distribution in a rural environment but this study did not have access to a Geonics™ EM38 instrument. The Murphy & Cheetham (2008) control study found that magnetic techniques proved difficult to differentiate between target buried weapons and background materials, even when surface metallic items were cleared from the survey site prior to geophysical data collection. Murphy & Cheetham (2008) also found GPR methods could locate buried forensic targets but were difficult to locate in certain orientations so GPR was an obvious technique to trial.

This case study therefore intended to utilise a variety of current commercial, shallow near-surface geophysical equipment to locate hard-to-detect, small-scale buried forensic metallic objects in a semi-urban environment, using survey procedures commonly used in geotechnical and archaeological investigations. The study site was also re-surveyed once a concrete slab patio was laid to also simulate a common domestic property garden forensic scenario (see Toms *et al.* 2008; Congram 2008; Billinger 2009). To give the study more of a sense of realism, the survey is that of a heterogeneous soil content, representative of a U.K. garden, and both target objects and non-target objects (brick, metallic screw and iron plate) were also buried. The locations and orientations of objects were recorded.

Study objectives for both semi-urban and patio environments were to: 1) evaluate and find optimum magnetic detection technique(s) of the target buried forensic material; 2) compare with electrical and GPR detection methods; 3) determine optimum GPR detection frequencies; 4) determine optimum respective equipment configuration(s) / survey specifications / optimum processing steps; 5) determine which technique(s) could determine target depth below ground and 6) determine if different buried metal types could be distinguished. It was also instructive to decide if certain detection techniques could be relatively easily utilised by forensic investigators to acquire, process and interpret forensic geophysical datasets.

Methodology

Test site

The forensic test site was situated on Keele University campus situated near Stoke-on-Trent, in England, U.K. It was chosen as a representative of a semi-urban U.K. environment as the site history indicated the presence of greenhouses with remnant cleared foundations still present (Fig. 1). Previous site studies also confirmed this, indicating that the local mixed sand and clay soil was predominantly 'made ground' with Triassic Butterton Sandstone Formation bedrock present at a shallow level, only ~2.6 m below ground level (or bgl) (see Jervis *et al.* 2009). The local climate is temperate, which is typical for the U.K.

A five metre by five metre survey area was selected as this was deemed small enough to keep the multi-geophysical techniques data acquisition time feasible, but sufficiently large enough to allow several targets to be buried and be separately resolvable in the resulting datasets. Permanently marked by plastic tent pegs, survey lines were laid 0.25 m apart (Fig. 1a). Multi-technique geophysical datasets were acquired prior to object burial to give control datasets for comparison purposes (see Table 1). A variety of forensic and mostly metallic objects (see Fig. 2 & Table 2 for details) were then buried ~15 cm bgl in a non-ordered configuration within the survey area and their locations recorded (Fig. 3). Note the ammunition box (Fig. 2f) had to be dug well below this depth to ensure the top was consistent with other target depths. In addition to these 8 target objects, 3 non-target, non-forensic objects were buried, including a domestic house brick, a steel plate and a metallic bolt for control and comparison purposes (see Fig. 2 & Table 2). This approach therefore significantly differed from the single technique and more ordered target control studies undertaken by Rezos *et al.* (2010) and Dionne *et al.* (2011). The survey area was then geophysically re-surveyed at least two weeks after the forensic objects were buried to ensure some settlement of replaced topsoil. Finally a 6 cm thick layer of concrete paving slabs (~0.5 m by ~0.5 m) was laid over the grid (Fig. 1b) and the area then geophysically re-surveyed for the last time, with the exception of a resistivity survey due to the inability to insert resistivity probes into the patio slabs.

Metal detector surveys

Standard metal detectors produce an alternating magnetic field which may induce nearby conductive material to produce a secondary field. When the equipment detects a magnetic field which is in-phase with the transmitted field, it produces an audible (but not usually measured) response (see Milsom & Eriksen, 2011 and Dupras *et al.* 2006 for theoretical background). The Bloodhound Tracker™ IV all-metal detector was used on the survey site before objects were buried (to act as control), after objects were buried and finally after the concrete patio was laid (Fig. 4a) using a sweep method in parallel transects 0.5 m apart at a constant height of ~5 cm (see Dupras, 2006; Rezos *et al.* 2010). Any areas where the detector produced an audible signal were then marked on a map of the survey area. These surveys were repeated by three different operators in an attempt to account for any operator technique variations. The survey area was then re-surveyed after forensic objects were buried, and again after the patio was laid (Table 1) with audio target locations again noted each time.

Magnetic susceptibility surveys

Magnetic susceptibility meters generates a low intensity AC magnetic field and measures the resulting change in positive or negative susceptibilities in S.I. (dimensionless) units of the sampled medium. This bulk reading is usually due to a combination of highly magnetic minerals (e.g. magnetite), man-made ferro-magnetic material (if present), other materials and background magnetism (see Milsom & Eriksen, 2011 and Reynolds, 2011 for further information). Magnetic susceptibility data were collected using a Bartington™ MS.1 susceptibility instrument with a 0.3 m diameter probe placed on the ground surface at each sampling point (Fig. 4b). Data samples were collected on a 0.25 m grid over the survey area before forensic object burial to act as control, then resurveyed after burial and finally again after the patio was laid (Table 1). This was a smaller data point sample spacing than typically utilised for clandestine grave surveys (see, e.g. Pringle *et al.* 2008).

Basic data processing was initially undertaken which involved de-spiking to remove anomalously large isolated data points caused by operator/equipment error. Data were then processed using the Generic Mapping Tools (GMT) software (Wessel & Smith 1998). To aid visual interpretation of the data, a minimum curvature gridding algorithm was used to interpolate each dataset to a cell size of 0.0125 m by 0.0125 m. In addition, 'detrending' of the data was conducted to remove long-wavelength site trends to allow smaller, target-sized features to be more easily identified. This was achieved by fitting a cubic surface to the gridded data and then subtracting this surface from the data, as this surface gridding method was found to produce the best results.

Fluxgate gradiometry surveys

Fluxgate gradiometry equipment records only the vertical (Z) component of the Earth's magnetic field that will be affected by proximal ferro-magnetic materials, their orientation, depth bgl etc. (see Milsom & Eriksen, 2011 and Reynolds, 2011 for more information). Due to the short data acquisition time (see Table 1) it was deemed not necessary to undertake diurnal correction of the datasets (see Milsom & Eriksen, 2011 for further information). Fluxgate gradiometry data were collected using a Geoscan™ FM18 gradiometer held at a constant height (Fig. 4c). For all three surveys (Table 1) the meter was first carefully zeroed over a magnetically 'quiet' area out of the survey area to remove any potential reading differences that may result from positional variation in instrument orientation relative to magnetic North when acquiring data (see Milsom & Eriksen, 2011). Survey lines were also orientated to magnetic north to avoid any potential profile line orientation issues (Fig. 1). Basic data processing was again undertaken which involved de-spiking and detrending as previously discussed.

Magnetic (potassium-vapour) gradiometry surveys

Magnetic gradiometry data were collected using a GSMP-40 potassium vapour magnetic gradiometer using 1 m vertically separated total field sensors (Fig. 4d & Table 1). As with the fluxgate gradiometry equipment, the potassium vapour gradiometer is another method of measuring the vertical component of the Earth's magnetic field which will be affected by proximal ferro-magnetic materials. The advantages of this equipment was that it collects both upper/lower sensor total magnetic vertical (Z) field readings as well as gradient measurements between the two sensors and is industry standard for geotechnical investigations (see Reynolds, 2004; Reynolds 2011). Due to the short data acquisition time (see Table 1) it was again deemed not necessary to undertake diurnal correction of the datasets. Data was acquired over the 0.25 m spaced survey lines obtaining readings every 0.2 s which roughly equated to a sample spacing of ~0.01 m. The equipment was maintained at a constant height above the ground surface for all surveys (to reduce any data variation due to variable instrument height) by use of a temporary non-magnetic stick attached to the bottom sensor (Fig. 4d). Minimal data processing was undertaken which involved data despiking and detrending as previously discussed.

Fixed-offset resistivity surveys

The inverse of conductivity, electrical resistivity is measured by applying a constant current through a sample (here: soil) of known size and measuring the resulting drop in voltage (see Milsom & Eriksen, 2011; Reynolds, 2011). Bulk-ground resistivity data were collected using a Geoscan™ RM15-D resistance meter mounted on a custom-built frame which allowed the almost simultaneous acquisition of both 0.25 m and 0.5 m spaced, pole-pole probe array measurements using four 0.1 m long stainless steel electrodes (Fig. 4e). The pole-pole probe array was used as it is rapid, the most popular configuration used and deemed most sensitive to near-surface lateral variations (see Eriksen & Milsom, 2011). Remote probes were placed 1 m apart at a distance of 15 m from the survey area to ensure probe placements do not affect the resulting data (see Milsom & Eriksen, 2011). For the control and semi-urban surveys (Table 1), resistivity measurements were made at 0.25 m intervals along survey lines that were spaced 0.25 m apart (Table 1). This sample spacing was smaller than the more typically used 0.5 m spaced resistivity datasets (see, e.g. Pringle & Jervis 2010) but high resolution datasets were deemed important to acquire for comparison purposes to the magnetic surveys. A post-burial survey was not possible to be acquired over the patio due to a requirement for probes to be inserted into the ground using the utilised equipment. Minimal data processing was undertaken which involved data despiking and detrending as previously discussed.

Ground penetrating radar surveys

Ground penetrating radar (or GPR) is a well documented technique, using an antenna to transmit an electro-magnetic pulse into the ground, which reflects at boundaries of contrasting di-electric permittivity, and is captured by a receiver antenna, subsequently being converted to digital image and stored (see Milsom & Eriksen, 2011, Reynolds, 2011). The signals stored in time formats can be converted to depth if the local site velocity is known. GPR signal penetration depth and resolution are a function of antennae set frequencies; high frequency (450+ MHz) gives relatively high resolution but poor penetration whilst low frequency gives low resolution but good penetration (see Jol 2009 for background theory and operational detail). GPR datasets were collected using pulseEKKO™ 1000 equipment using both 450 MHz (Fig. 4f) and 900 MHz dominant frequency bi-static, fixed-offset (0.34 and 0.17 m respectively) antennae along 0.25 m spaced lines and having trace sample intervals of 0.05 m and 0.025 m respectively (Table 1). The survey area was surveyed three times; one to provide a control dataset, the second over the buried forensic objects and the third over the buried forensic objects in the patio scenario.

The resulting GPR datasets were sequentially processed using Reflex-Win™ Version 3.0 (Sandmeier) software using the following steps: 1) 'Dewow' (low-cut filter) to remove nonlinear effetcs associated with the antennae; 2) Move to constant start-time; 3) 1D bandpass filter (Butterworth) to remove high frequency noise; 4) 2D filter to make anomalous features more prominent; 5) Stolt migration to collapse hyperbolae to point sources (only used for time-slices) and finally; 6) horizontal time-slice generation of each dataset to produce plan-view, relative amplitude images of the test site.

Results

Metal detector

For the post-burial semi-urban environment survey, all 8 target objects and 1 non-target object were detected. The two undetected objects were; the (1) brick (as might be expected) and, (2) the metallic bolt (*cf.* Fig. 3 and Table 2). For the post-burial patio survey, the brick and metallic bolt non-target objects remained undetected and of the target objects, the (5) entrenching tool and both the (7) WWII and (8) WWI hand grenades were also not detected. Therefore 100% (semi-urban) and 63% (patio) total target detection success rates are calculated for the respective metal detector surveys. For both surveys, six additional anomalies were noted.

Magnetic susceptibility

Magnetic susceptibility datasets (441 data points for each survey) for the control, post-burial semi-urban and patio environment scenarios were highly variable between surveys, having respective median and 2σ values of 55.0 S.I. and 214.8 2σ (control), 93.0 S.I. and 412.2 2σ (semi-urban) and 42.0 S.I. and 110.8 2σ (patio) respectively. The 2σ (two standard deviations) given here and throughout represents a 95% confidence limit and gives the variance of each respective dataset. The control and semi-urban survey results indicated significant heterogeneous ground conditions as would be expected as the test site was a semi-urban environment.

Magnetic susceptibility data for the post-burial, semi-urban environment also showed significant site variations, with the same magnitude of high and low susceptibility readings as obtained in the control dataset. In addition to the control isolated high anomalies again being present, several other isolated high anomalies were present that could be correlated with 2 non-target object locations; (2) the bolt and (3) the steel plate, and 4 target object locations; (4) the two breadknives, (5) the entrenching tool, (6) the single breadknife, and (7) WWII hand grenade . Low isolated anomalies, with respect to background values, could also be correlated with the remaining 4 target object locations; (9) the handgun, (10) the ammunition box and (11) the spent mortar shell (Figs. 5 & 6). Magnetic susceptibility data for the post-burial patio environment had significantly less site variations, ranging from -242 to 496 S.I. units. In addition to the control isolated high anomalies again being present, several other isolated high anomalies were present that could be again correlated with 2 non-target object locations; (2) the bolt, (3) the steel plate, and now 3 target object locations; (4) the two breadknives, (5) the entrenching tool and (7) the WWII hand grenade (Figs. 5 & 6). Low isolated anomalies, with respect to background values, could also be correlated with (9) the handgun, (10) the ammunition box and (11) the spent mortar shell locations (Figs. 5 & 6). Selected 2D profiles are shown in Figure 6. Target detection rates with magnetic susceptibility are therefore 100% (semi-urban) and 88% (patio) respectively.

Fluxgate gradiometry

Fluxgate gradiometry datasets (441 data points in each survey) for the control, post-burial semi-urban and patio environment scenarios were very variable and geophysically ‘noisy’, having respective survey median and 2σ values of -56.6 nT and 145 2σ (control), -3.1 nT and 157 2σ (semi-urban) and -45.8 nT and 144 2σ (patio) surveys respectively. This would be expected in such heterogeneous ground conditions, with a significant proportion of the datasets (32%, 31% and 30% respectively) not recording data at sampling positions. However these non-sample areas were consistent which suggested the instrument was not faulty nor calibrated incorrectly. With such a high proportion of the survey area not recording values, the resulting gridded and contoured map view plots of the control, post-burial semi-urban and patio environment scenarios were not that useful, having significant large areas of high and low magnetic gradiometry areas with respect to background values. However, 2D data profiles acquired over the forensic objects did allow estimation of target detection to be undertaken, and some selected 2D survey profiles are shown in Figure 7.

Within the post-burial semi-urban environment, high magnetic anomalies, with respect to background values, could be correlated with 1 non-target object location; (3) the steel plate and 3 target object locations; (4) two breadknives, (5) the entrenchment tool, (8) the WWI grenade and (10) the ammunition box (Fig. 7). Within the post-burial domestic patio environment, high magnetic anomalies, with respect to background values, could again be correlated with (3) the steel plate, and the same 4 target object locations; (4) two breadknives, (6) the single breadknife, (8) the WWI hand grenade and (10) the ammunition box (Fig. 7).

Fluxgate gradiometry survey results therefore gave a 50% (semi-urban) and 50% (patio) total target detection success rate respectively.

Magnetic (potassium-vapour) gradiometry

Magnetic (potassium-vapour) gradiometry data for the three surveys (total data points of 5,437 (control), 3,729 (semi-urban) and 4,050 (patio) respectively) were also geophysically 'noisy'. Respective survey medians and 2σ of lower sensor total field data were 49,172.7 nT and 450 2σ (control), 49,182.4 nT and 1,112 2σ (semi-urban) and 49,184.5 nT and 1106 2σ (patio). Survey medians and 2σ of gradiometry data were 81.7 nT and 860 2σ (control), 88.5 nT and 742 2σ (semi-urban) and 94.8 nT and 708 2σ (patio) indicating a generally good survey repeatability. Magnetic gradiometry map view plots of the control, post-burial semi-urban and patio environment scenarios are shown in Figure 8, and detrended datasets displayed in Figure 9 for comparison. It was found considerably easier to use the 2D profiles for estimation of target detection (selected examples shown in Fig. 10) due to the high variability of gradiometry measurements within the survey area, which made subtle anomalies difficult to identify in plan-view plots (Fig. 8) even after detrending (Fig. 9).

Within the post-burial semi-urban environment magnetic dataset, high magnetic anomalies, with respect to background values, could be correlated with, of the non-target object locations; (3) the steel plate, and of the target object locations; (6) the single breadknife, (7) the WWII hand grenade, (8) the WWI hand grenade, (9) the handgun and (10) the ammunition box positions (Figs. 8, 9 & 10). Within the patio scenario magnetic dataset, high magnetic anomalies, with respect to background values, could be correlated with, of the non-target object locations; (2) the bolt and (3) the steel plate, and of the target object locations; (4) the two breadknives, (6) the single breadknife, (7) the WWII hand grenade, (8) the WWI hand grenade, (9) the handgun and (10) the ammunition box locations (Figs. 8, 9 & 10). Selected 2D survey profiles are shown in Figure 10. Potassium vapour gradiometry survey results therefore gave a 63% (semi-urban) and 75% (patio) total target detection success rate respectively.

Resistivity

Fixed-offset (0.5 m) resistivity data for the control dataset (441 data points) had resistance maximum / minimum values of 111.7 Ω / 47.3 Ω with median of 75.0 Ω and 25.4 2σ value, therefore confirming that the site was relatively electrically heterogeneous. The post-burial (semi-urban) 0.25 m and 0.50 m fixed-offset repeat surveys had resistance maximum / minimum values of 194.5 Ω / 76.0 Ω (25 cm) and 129.5 Ω / 51.5 Ω (50 cm), with median values of 121.6 Ω (25 cm) / 78.8 Ω (50 cm) and 37.2 2σ (25 cm) / 27.2 2σ (50cm) respectively. Data repeatability for the 0.5 m fixed-offset surveys was therefore generally good, and can presumably be said for 0.25 m surveys despite the lack of a control dataset.

Within the post-burial semi-urban environment, high resistance anomalies in the 0.25 m fixed offset survey, with respect to background values, could be correlated with target object locations of the (5) entrenching tool, (6) the single knife, (7) the WWII hand grenade, (9) the handgun, (10) the ammunition box and (11) the spent shell (Figs. 11 & 12). Low resistance anomalies, with respect to background value, could be correlated with non-target object locations; (1) the brick and (3) the steel plate.

Within the semi-urban environment resistivity (0.5 m fixed-offset) survey, only high resistance anomalies, with respect to background values, could be correlated with (10) the ammunition box and (11) the spent shell locations (Figs. 11 & 12). Selected 2D profiles are shown in Figure 12. This therefore gave a 63 % (25 cm) and 25 % (50 cm) total target detection success rate respectively.

Ground penetrating radar

Both the 450 MHz and 900 MHz dominant frequency GPR control datasets showed a number of non-target objects were located within the survey area; this therefore provides confirmation that the study site is representative of a semi-urban, hetereogeneous site. Within the post-burial semi-urban environment dataset, ½ parabolae isolated anomalies in the 450 MHz frequency dataset could be correlated with (3) the steel plate, (7) WWII hand grenade, (9) the handgun, (10) the ammunition box and (11) the spent mortar shell locations (Figs. 13 & 14). Within the 900 MHz frequency dataset, ½ parabolae isolated anomalies could be correlated with (3) the steel plate, (4) the two breadknives, (6) the single breadknife, (7) WWII hand grenade, (9) the handgun, (10) the ammunition box and (11) the spent mortar shell locations (Figs. 13 & 15). Selected 2D profiles are shown in Figures 14 and 15. This therefore gave a 50 % (450 MHz) and 75 % (900 MHz) total target detection success rate respectively.

Within the post-burial patio environment dataset, ½ parabolae isolated anomalies in the 450 MHz frequency dataset could be correlated with (3) the steel plate, (6) the single breadknife, (8) the WWI hand grenade, (9) the handgun, (10) the ammunition box and (11) the spent mortar shell locations (Figs. 13 & 14). Within the 900 MHz frequency dataset, ½ parabolae isolated anomalies could be correlated with (3) the steel plate, (4) the breadknives, (5) the entrenching tool, (6) the single breadknife, (9) the handgun (10) the ammunition box and (11) the spent mortar shell locations (Figs. 13 & 15). Selected 2D profiles are again shown in Figures 14 and 15. This therefore gave a 63 % (450 MHz) and 75% (900 MHz) total target detection success rate s.

Discussion

This section has been deliberately organised to answer and discuss the study objectives.

(1) Evaluate and find optimum magnetic detection technique(s) of the target buried material

The metal detector survey results for post-burial, semi-urban surveys of the forensic targets were very successful, with a target detection success rate of 100%. However, the addition of the patio material over the survey area significantly reduced the success of target detection to 63% . The success rate reduction over the patio was presumably due to the difficulty of the electro-magnetic waves penetrating the concrete paving slabs. These results would be a cause for concern if metal detectors were the sole magnetic detection method in a forensic search within a semi-urban or patio environment as this study simulated. These results also provide a contrasting metal detector study to Rezos *et al.* (2010) within a rural environment which gained a 100% target detection success rate (Fig. 16).

The magnetic susceptibility survey results after burial of forensic targets proved very good, with target detection success rates of 100% (semi-urban) and 88% (patio) respectively (Fig. 16). In fact all the forensic buried target objects were found in the semi-urban environment scenario; it was just the two control buried objects, (1) the brick and (2) the bolt and screw, that were not detected.

Both magnetic gradiometry methods compared poorly against the metal detector and magnetic susceptibility equipment. The fluxgate gradiometry survey results after burial of forensic targets were generally poor, with target detection success rates of 50% for both semi-urban and patio surveys (Fig. 16). The grouped breadknives, the entrenching tool,, the ammunition box and one hand grenade were successfully located, although a key target, the handgun, was not detected. This technique may also be problematic to utilise in urban environments due to the high percentage of the survey area area (averaging

31% over the three surveys) having out-of-range data recorded, as other authors have discussed (Reynolds, 2011).

The magnetic (potassium vapour) gradiometry survey results after burial of forensic targets were relatively good, with considerably better target detection success rates than the fluxgate gradiometry equipment, of 63% (semi-urban) and 75% (patio) respectively (Fig. 16). Interestingly, the target detection success rates increased over the patio versus the semi-urban environment – perhaps due to less geophysical 'noise' as the patio had a damping effect on low-intensity, background anomalies. A small sampling increment spacing suggests data had good resolution but target detection success rates were not higher than the magnetic susceptibility surveys which had a much wider sampling point separation. Data repeatability was reasonable with similar 2σ values for both post-burial surveys. The instrument utilised was, however, often difficult to obtain a 'lock' between sensors to gain usable data which may prove problematic in forensic surveys where limited survey time may be a significant issue. One suggestion may be for equipment to be cart-mounted to improve data quality (see Reynolds 2004).

Considering that the magnetic methods measure related properties; it would not have been surprising if the techniques had yielded similar results. However, the success of the techniques is quite variable, which can be attributed to the differences in ways each piece of equipment acquires data; for example, each at different heights above ground level from the target objects.

(2) Compare magnetic methods with electrical and GPR detection methods

The variability in the control resistivity dataset confirmed the heterogeneous ground conditions of the survey site. The post-burial dataset target location success rates for the 0.25 m and 0.5 m fixed-offset probe spacings were very different; 63% and 25% respectively (Fig. 16). The 0.25 m spaced probe survey data is therefore less favourable to the magnetic survey techniques, although both the handgun and single knife were detected. However this technique could not be utilised over the patio due to the inability of the steel probes to be inserted into the ground. Other equipment manufacturers do have the ability to record data from hard ground by having a flat probe end which may be worth exploring in future research.

The GPR survey results were mixed, with only 50% and 63% of targets found using 450 MHz dominant frequency antennae over the urban and patio environments respectively. This contrasted with 75% of targets found using 900 MHz dominant frequency antennae over both the semi-urban and patio environments. .

(3) *Determine optimum GPR detection frequencies*

From the detail shown in this study, it was suggested that 900 MHz dominant frequency antennae was the optimal set frequency. Murphy & Cheetham (2008) also found that higher frequency (800 MHz versus 400 MHz) GPR antennae were optimal in buried handgun detection in rural environments.

(4) Determine optimum respective equipment configuration(s) / survey specifications / optimum processing steps

Magnetic susceptibility datasets showed 0.25 m spaced gridded sampling points proved sufficient to resolve even the smallest objects with little data processing required and thus was deemed optimal in this study – simply creating 2D graphical summaries of survey lines was sufficient to gain a high target detection success rate. Fluxgate gradiometry datasets were geophysically 'noisy' and required significant time removing erroneous data points and detrending data to gain usable data to interpret from. Magnetic (potassium-vapour) gradiometry equipment proved useful at 1 m sensor separations orientated vertically in order to obtain gradient data. There were, however, significant amounts of data generated that needed to be processed and detrended before being usable. However, even after detrending of the datasets, fluxgate gradiometry and magnetic (potassium vapour) gradiometry results were difficult to interpret in plan-view plots due to the subtle anomalies caused by the target objects. In fact, it could be argued that many of the target locations would not have been identifiable at all in these scenarios, had the control data not been collected for comparison. Equipment operators also needed to be careful that a constant height was maintained between the sensors and the ground surface to improve data quality which may be problematic in forensic search scenarios on uneven ground.

The electrical resistivity 0.25 m fixed-offset probe spacing data was vastly superior to the 0.5 m offset probe spaced datasets even when using the same sampling spacings; making the closer probe spacing the more obvious one to utilise for such small and high resolution surveys. However, the amount of ground covered in larger forensic search surveys using this configuration and 0.25 m grid sample spacings may make this technique more problematic.

As mentioned, 900 MHz dominant frequency GPR antennae proved optimal, with a 0.025 m trace sampling interval on 0.25 m spaced survey lines. Basic 2D profile data processing of gain filters and background removal would prove sufficient for target detection although it would be deemed worthwhile to generate horizontal 'time-slices' if targets were more subtle in comparison to heterogeneous ground, and if processing time is allowed.

(5) Determine which technique(s) could determine target depth below ground level

Only GPR data could definitively determine depth of buried forensic target below ground level. Total field magnetic data such as from the potassium vapour gradiometer and the bulk electrical resistivity data could both be forward modelled to gain simple estimations of target depths if sufficient time and specialist resources were available (see Juerges *et al.* 2010; Reynolds 2011 for examples).

(6) Determine if different metal types could be distinguished.

Distinguishing between different buried metallic object types was difficult using the equipment utilised; Rezos *et al*. (2010), for example, used a higher specification metal detector which did allow some metal differentiation to be determined. The resistivity survey results did differentiate between conductive (the metal plate) and non-conductive (the brick) buried forensic targets which may be useful information for forensic search investigators. 2D magnetic forward modelling of total field magnetic data would allow the relative magnetic susceptibility contrast between the target object and the background material to be assessed, (see, for example, Scott & Hunter 2004), but these would not be definitive values.

Finally it was determined that the metal detector, magnetic susceptibility meter, resistivity meter (if in semi-urban environments) and a commercial GPR unit would be relatively easy for forensic search investigators to acquire, process and interpret for buried forensic targets. Metal detector equipment is relatively cheap but also arguably the simplest to use and to generate data from that forensic search teams could interpret buried target locations. When considering both the semi-urban and patio scenarios, however, the magnetic susceptibility equipment provided the best target detection rates, with relatively few additional non-target anomalies. The equipment was also relatively cheap and easy to process into a visual data-plot. The magnetic susceptibility dataset from the patio scenario showed very low variability at points other than at target and non-target object locations, so would be optimal in this environment considering the low number of false positives. GPR data could be viewed in real-time and suspected burial positions marked during the field work. Resistivity data would need to be downloaded and line profiles generated in any data graphical packages of which there are many. The fluxgate gradiometer and magnetic (potassium-vapour) gradiometer are only recommended to be utilised by experienced operators due to the difficulty of calibration, operation and data processing.

It should, however, be noted that the success rates from these surveys are alone not enough to determine optimum techniques and equipment configurations for detection of buried metallic objects. One must also consider that a technique which is capable of detecting all target objects may also be overly sensitive to background anomalies. For example, the metal detector, though capable of detecting all 8 target objects, also detected an additional 6 background anomalies. This means that only 57% of the anomalies can be attributed to buried targets.

Conclusions

From the results of this study, usable geophysical techniques gaining the highest buried forensic object target success rates in semi-urban environments were (in descending order); magnetic susceptibility, metal detection, 900 MHz GPR and electrical resistivity (0.25 m fixed-offset probes), magnetic (potassium vapour) gradiometry, 450 MHz GPR, fluxgate gradiometry and electrical resistivity (0.5 m fixed-offset probes) (Fig. 16). Usable geophysical techniques gaining the highest buried forensic object target success rates in patio environments (in descending order) were; magnetic susceptibility, magnetic (potassium vapour) gradiometry, 900 MHz GPR, metal detection, 450 MHz GPR, and fluxgate gradiometry (Fig. 16). Note resistivity surveys were not utilised in the patio environment. It was worth noting that the magnetic susceptibility had a considerably higher success rate than the other magnetic equipment utilised, i.e. compared to the metal detector and the gradiometers, despite them measuring similar properties and the potassium vapour gradiometer having a closer sample point spacing.

Concerns were raised in this study over the use of metal detectors and GPR detection equipment solely for detection of buried forensic targets, as important objects such as knives and hand grenades were not detected by even the higher frequency GPR configuration, particularly beneath the patio. It is therefore recommended that the easy to utilise and high target success rates of the magnetic susceptibility equipment should be used as a complementary tool for forensic search investigators in the search for buried objects such as those used in this study. The bulk electrical resistivity technique also showed potential due to its relatively quick collection time and reasonably high detection rate. Unlike GPR data processing, resistivity data processing is relatively straightforward (given available software and operator experience) and can produce either 2D profiles or a single mapview image which can then be interpreted.

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FIGURE CAPTIONS

Fig. 1. Photographs of the 5 m by 5 m forensic test site on campus showing (a) semi-urban environment and (b) simulated domestic concrete patio scenario on the same area with location map (inset). Survey tapes on survey lines are shown. 0,0 position for all surveys is SW corner.

Fig. 2. Selected photographs of forensic buried test objects. (A) Colt Government Cup Replica .45 calibre automatic handgun with solid brass ammunition; (B) Three domestic stainless steel kitchen bread knives; (C) 1943 75 mm M18 shell and two WWII smaller diameter spent shells; (D) (left) WWII allied hand grenade and (right) WWI allied Mk.1 No.5 decommissioned hand grenade; (E) 1943 allied wooden-handled entrenchment tool and; (F) UK mortar ammunition box (containing 2 shell casings shown in C). See Table 2 for details.

Fig. 3. Sitemap showing location of buried forensic objects (see key for details) for both semi-urban environment and patio scenarios (Fig. 2 for selected object photographs).

Fig. 4. Photographs of geophysical equipment used in this study. (A) Bloodhound Tracker™ IV metal detector; (B) Bartington™ magnetic susceptibility probe MS.1 with 0.3 m diameter probe; (C) Geoscan™ FM-15 fluxgate gradiometer; (D) GSMP-40™ potassium vapour magnetic gradiometer with sensors 1 m vertically separated; (E) Geoscan™ RM15-D mobile probe resistivity meter and; (F) pulseEKKO™ 1000 Ground Penetrating Radar equipment showing 450 MHz dominant frequency, bistatic fixed-offset antennae.

Fig. 5. Magnetic susceptibility selected 2D profiles for control, semi-urban and patio surveys with respective target positions marked. (A) Profile 9 (X=2 m) over target (6) single knife; (B) profile 12 (X=2.75 m) over target (8) WWI hand grenade; (C) profile 15 (X=3.5 m) over target (9) handgun and;

(D) profile 18 (X=4.25 m) over target (10) ammunition box (all marked). See key for survey type and Table 1 for details.

Fig. 6. Magnetic susceptibility processed, gridded and contoured map view data plots of (A) pre-burial control with interpreted isolated anomalies, with respect to background values, marked (see text); (B) post-burial semi-urban environment and; (C) post-burial patio garden environment respectively. Scale for (A) and (B) are the same. S.I. (dimensionless) units are used (see text). See Table 2 for target descriptions.

Fig. 7. Fluxgate gradiometry selected 2D surveys profiles for control, semi-urban and patio surveys with respective target positions marked. (A) Profile 9 (X=2 m) over target (6) single knife; (B) profile 12 (X=2.75 m) over target (8) WWI hand grenade; (C) profile 15 (X=3.5 m) over target (9) handgun and; (D) profile 18 (X=4.25 m) over target (10) ammunition box (all marked). See key for survey type and Table 1 for details.

Fig. 8. Magnetic (potassium vapour) gradiometry processed, gridded and contoured map-view plots using upper sensor, lower sensor and gradient for pre-burial, post-burial semi-urban and patio environments (A-I, respectively) Units in 1000nT. See Table 2 for target descriptions.

Fig. 9. Magnetic (potassium vapour) gradiometry processed, detrended, gridded and contoured map view plots using upper sensor, lower sensor and gradient for pre-burial, post-burial semi-urban and pre-burial patio environments (A-I, respectively). Units in 1000nT. See Table 2 for target descriptions.

Fig. 10. Magnetic (potassium vapour) gradiometry with total magnetic (left) and gradient (right) selected 2D survey profiles for control, semi-urban and patio surveys with respective target positions marked. (A/B) Profile 9 (X=2 m) over target (6) single knife; (C/D) profile 12 (X=2.75 m) over target (8) WWI

hand grenade; (E/F) profile 15 (X=3.5 m) over target (9) handgun and; (G/H) profile 18 (X=4.25 m) over target (10) ammunition box (all marked). See key for sensors, survey type and Table 1 for details.

Fig. 11. Post-burial, semi-urban, bulk ground-resistivity contour plots using raw and detrended datasets with 0.25 (A and B respectively) m and 0.5 m (C and D respectively) probe spacings. Note the relatively high anomalies corresponding to the knife (6), handgun (9) and mortar shell (11). See Table 2 for target descriptions.

Fig. 12. Bulk-ground resistivity 2D profiles for selected targets using 0.25 m and 0.5 m probe separations with units in Ohms (Ω). Note generally high resistivity anomalies associated with targets with the exception of 0.5 m probe separation survey over the ammunition box (H).

Fig. 13. GPR time-slices over the test site using 450 MHZ (A-C) and 900 MHz (D-F) dominant frequency antennae with units in relative amplitudes. Some relatively high and relatively low amplitude anomalies correspond to target positions. See Table 2 for target descriptions.

Fig. 14. 450 MHz GPR processed selected 2D profiles. (A-C) Profile 9 (X=2 m) over target (6) single knife; (D-F) profile 12 (X=2.75 m) over target (8) WWI hand grenade; (G-I) profile 15 (X=3.5 m) over target (9) handgun and; (J-L) profile 18 (X=4.25 m) over target (10) ammunition box for control, semi-urban and patio environment scenarios respectively (all marked). See Table 1 for details.

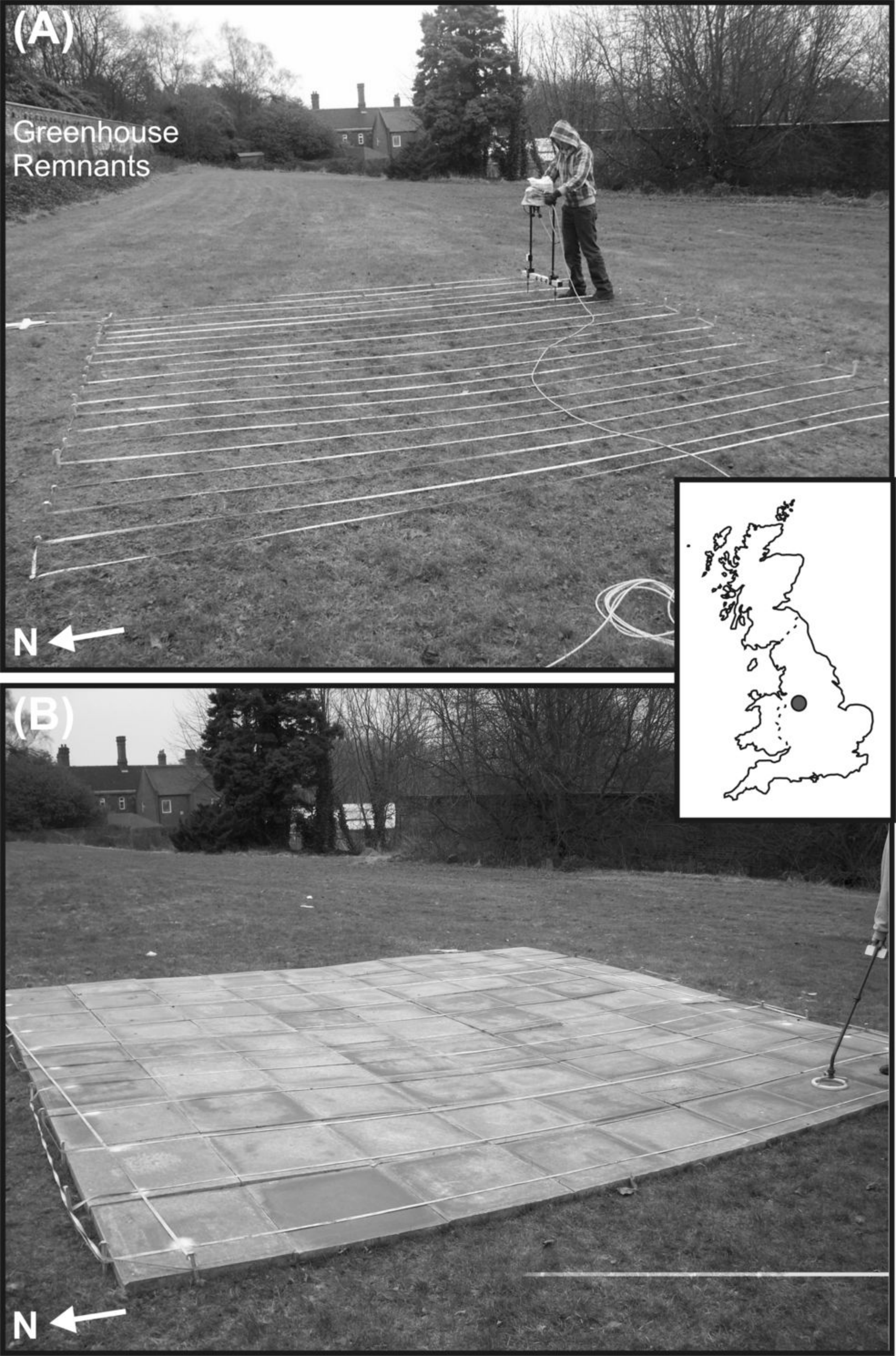
Fig. 15. 900 MHz GPR processed selected 2D profiles. (A-C) Profile 9 (X=2 m) over target (6) single knife; (D-F) profile 12 (X=2.75 m) over target (8) WWI hand grenade; (G-I) profile 15 (X=3.5 m) over target (9) handgun and; (J-L) profile 18 (X=4.25 m) over target (10) ammunition box for control, semi-urban and patio environment scenarios respectively (all marked). See Table 1 for details.

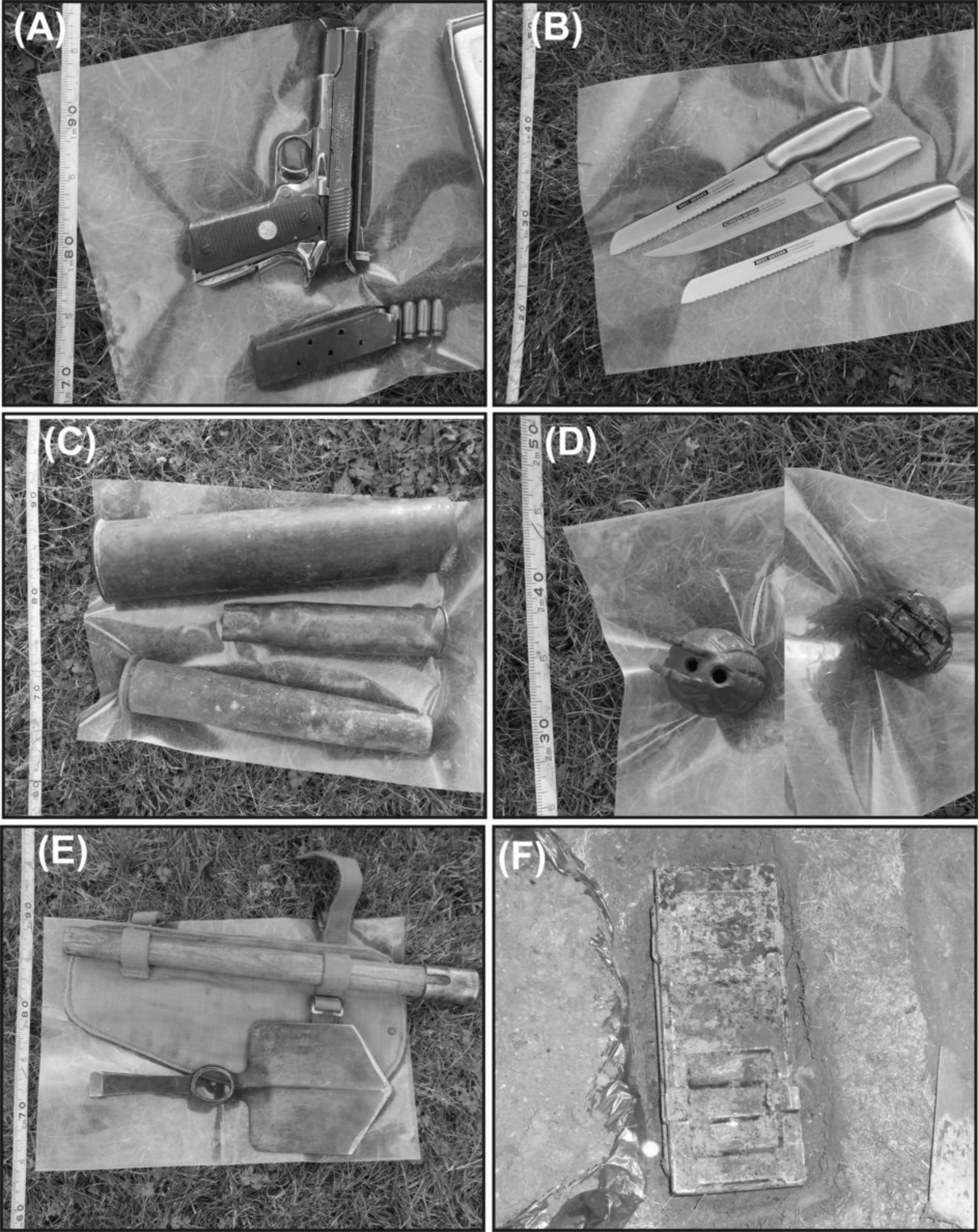
Fig. 16. Summary graph showing percentage total of target detection success rates for the different geophysical techniques trialled in semi-urban, patio and rural environments (see key). Note rural environment results are from Rezos *et al.* (2010) and Dionne *et al.* (2010) for metal detector and conductivity surveys respectively.

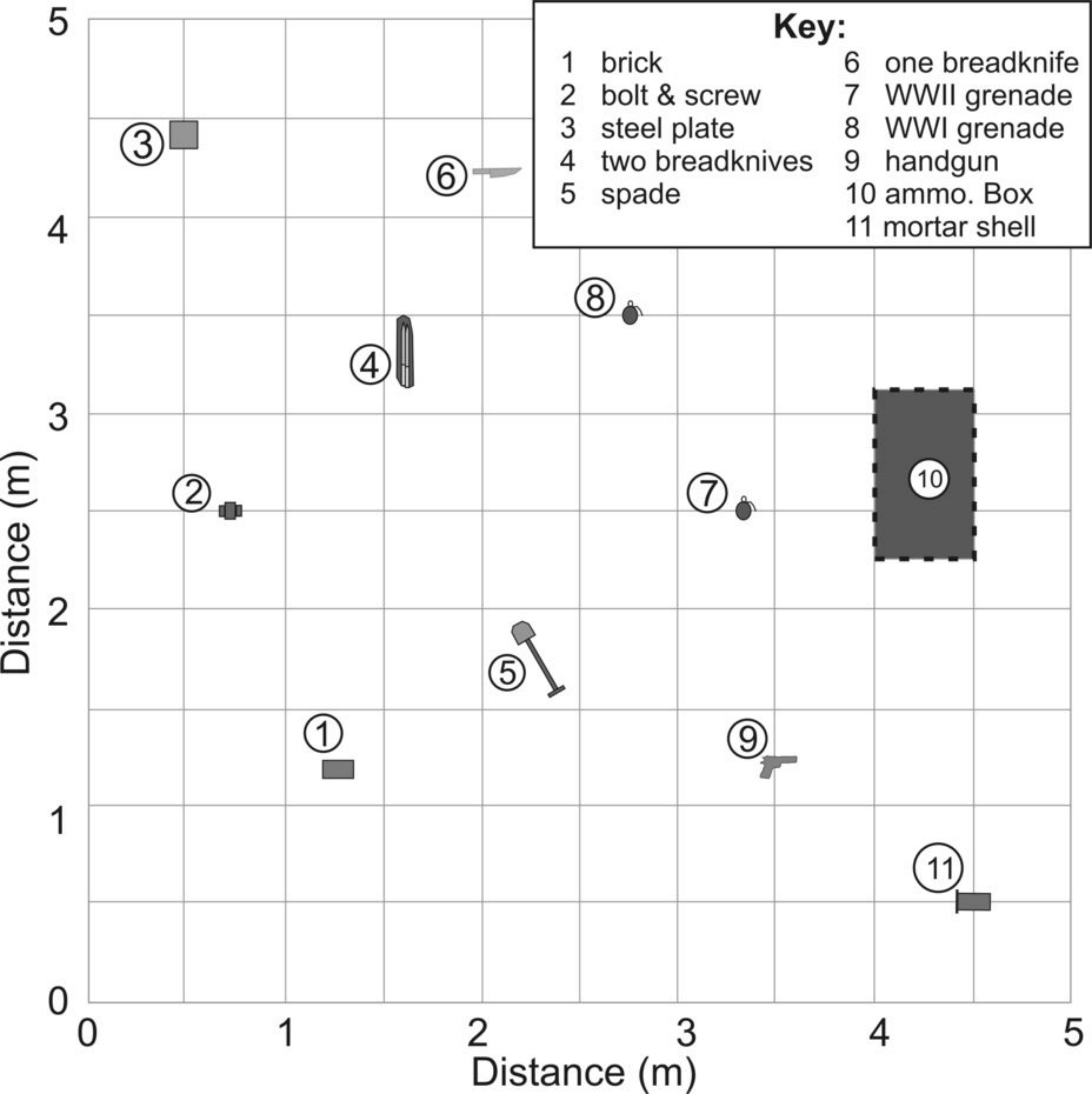
TABLE CAPTIONS

TABLE 1. Summary statistics of geophysical data collected during this 5 m by 5 m study area. Survey types are: (C) Control, (S) Semi-urban and (P) Patio environments respectively. Bgl = below ground level. Survey line spacings were 0.25 m unless otherwise stated.

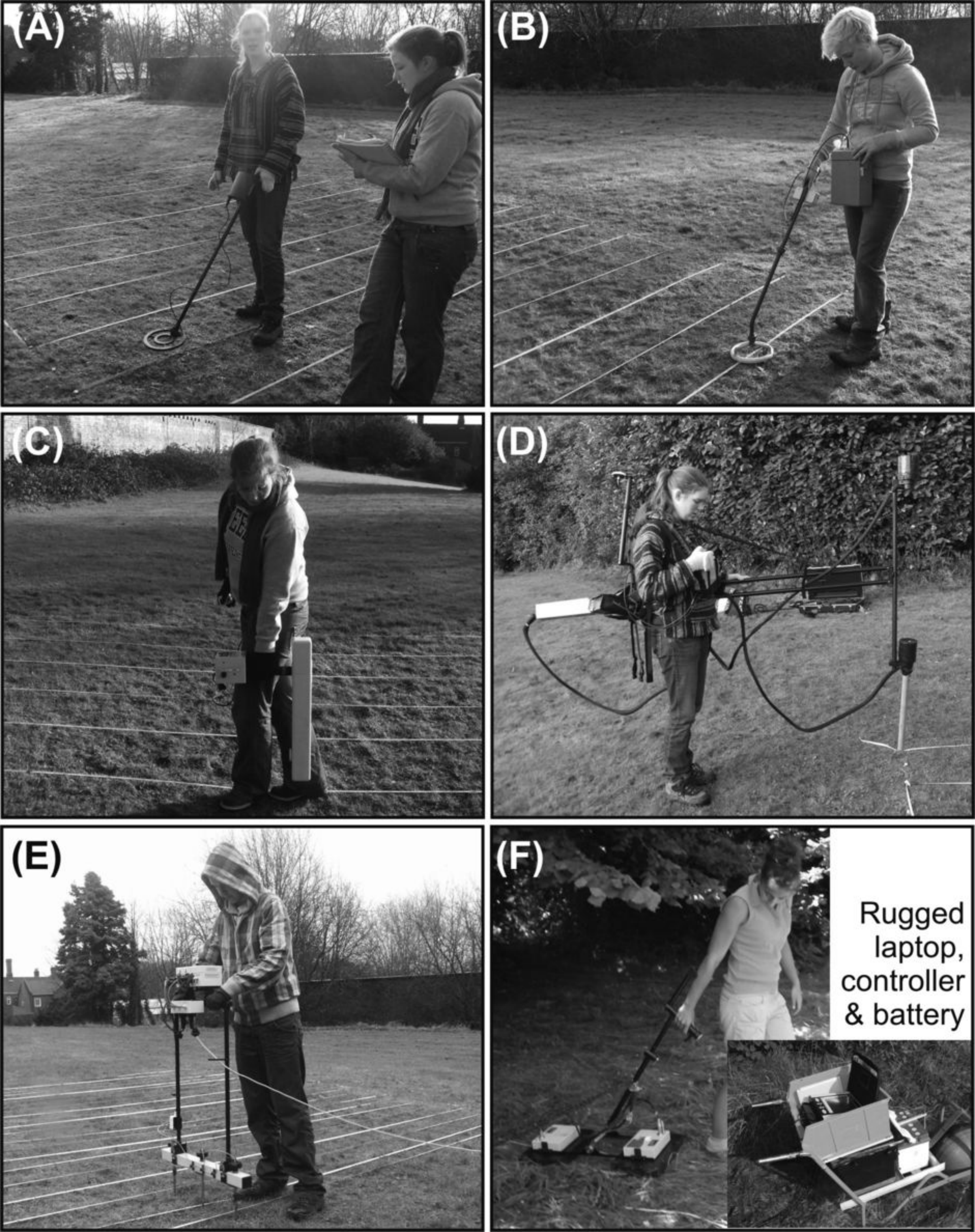
TABLE 2. Description of buried forensic objects used in this study and their known properties (captions show photographs in Fig. 2). Object numbers refer to those shown in Fig. 3 and in geophysical datasets.

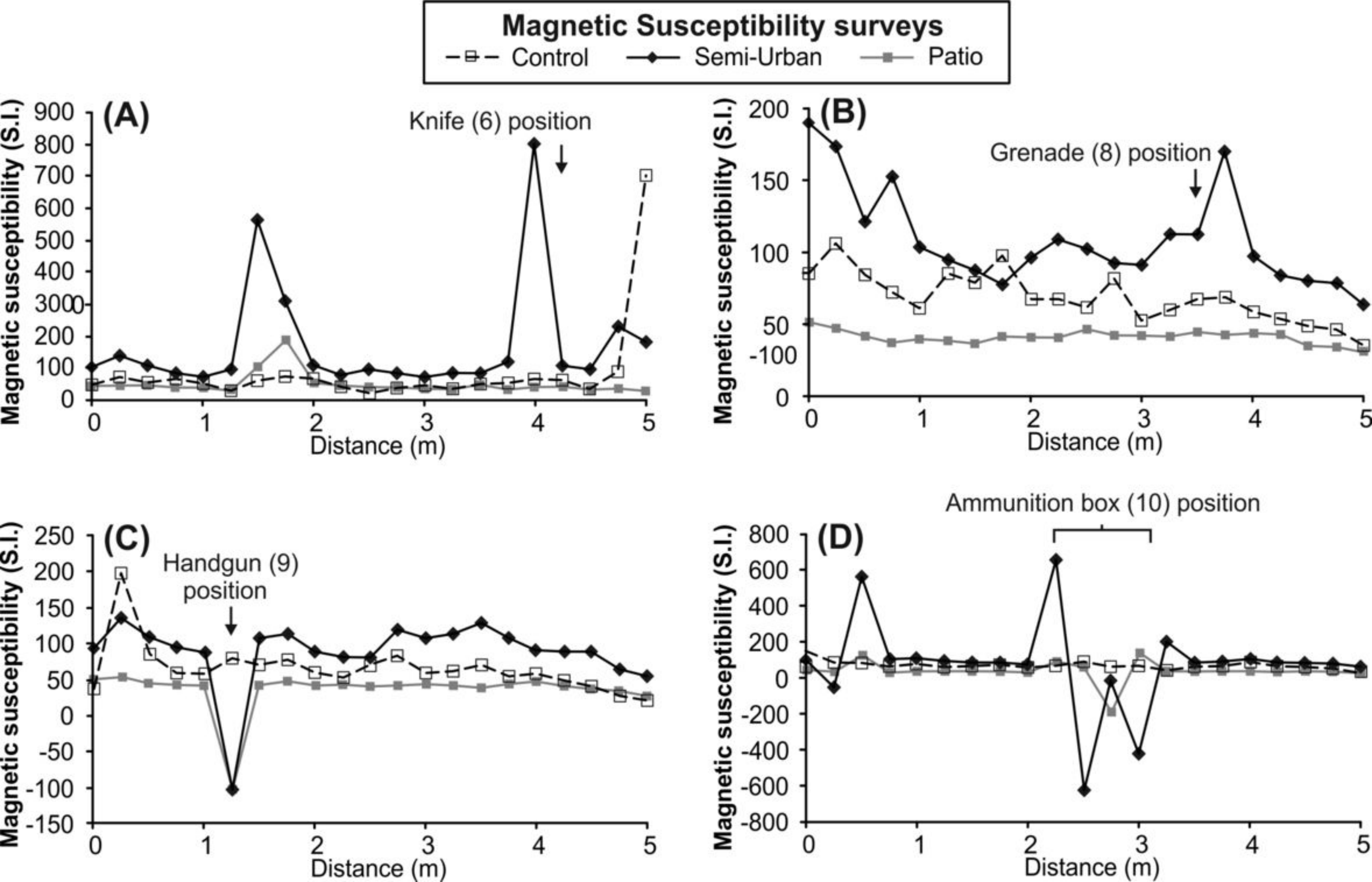

(A)
Greenhouse
Remnants
N
(B)
N


(A)
(B)
(C)
(D)
(E)
(F)

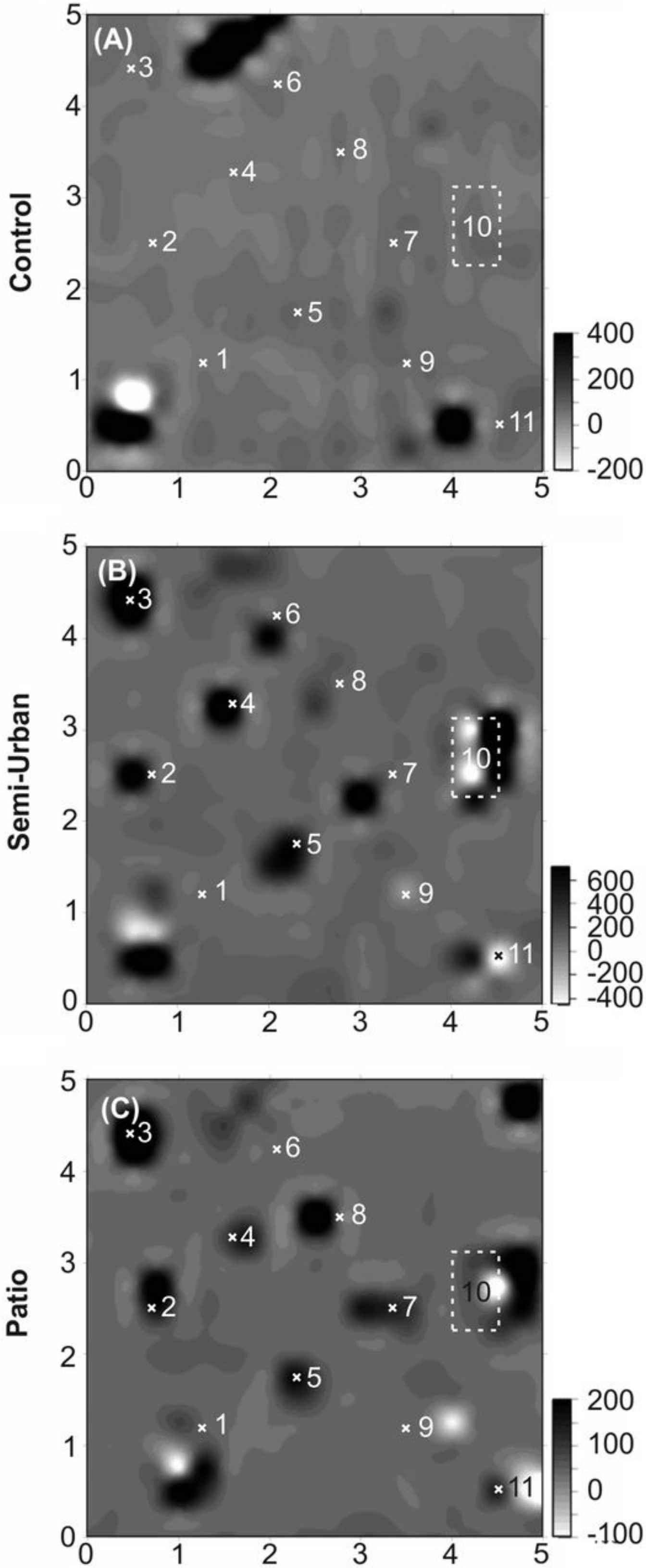


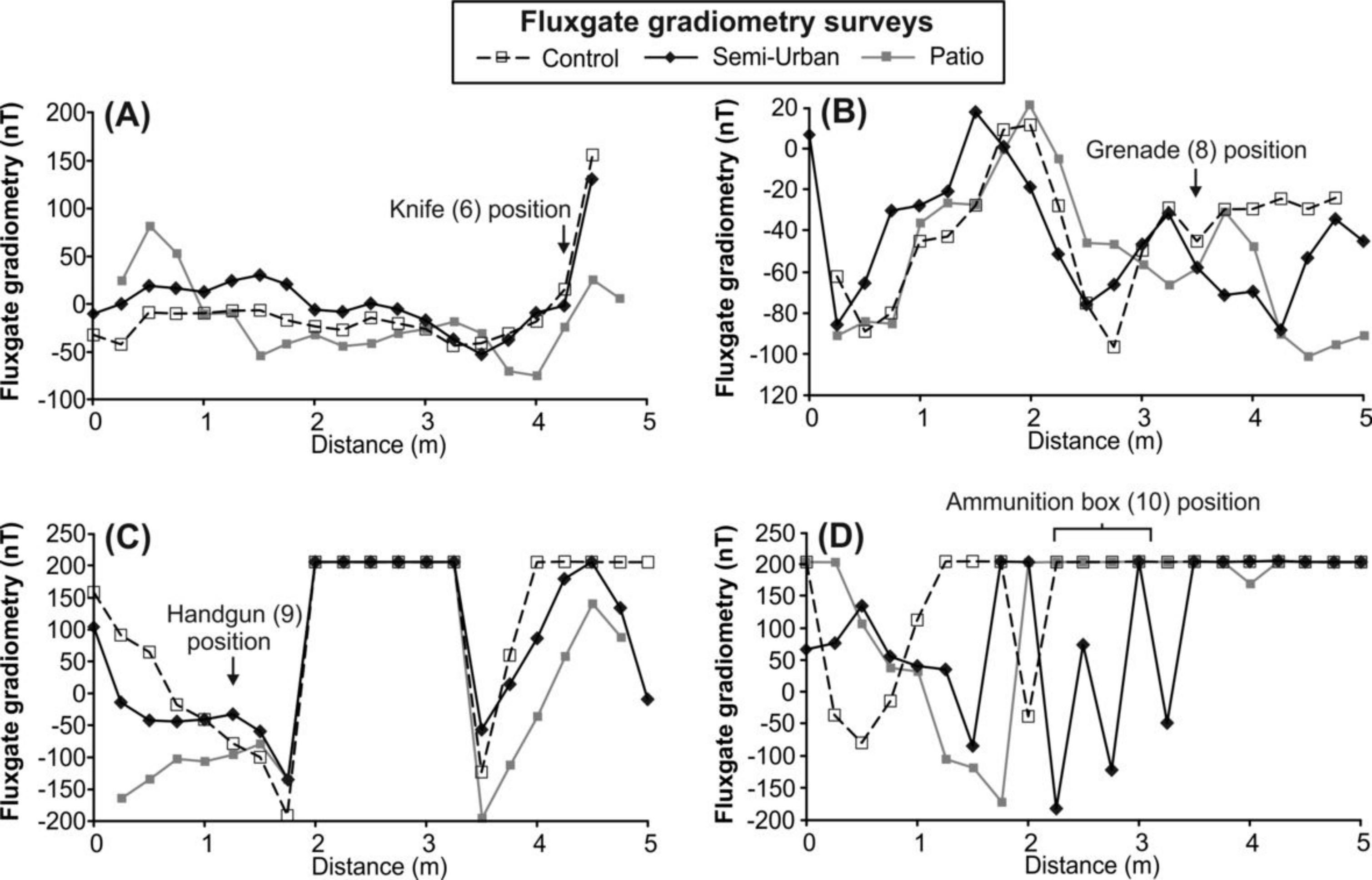
Key:
1 brick
2 bolt & screw
3 steel plate
4 two breadknives
5 spade
6 one breadknife
7 WWII grenade
8 WWI grenade
9 handgun
10 ammo. Box
11 mortar shell
Distance (m)
Distance (m)
0
1
2
3
4
5


(A)
(B)
(C)
(D)
(E)
(F)
Rugged
laptop,
controller
& battery

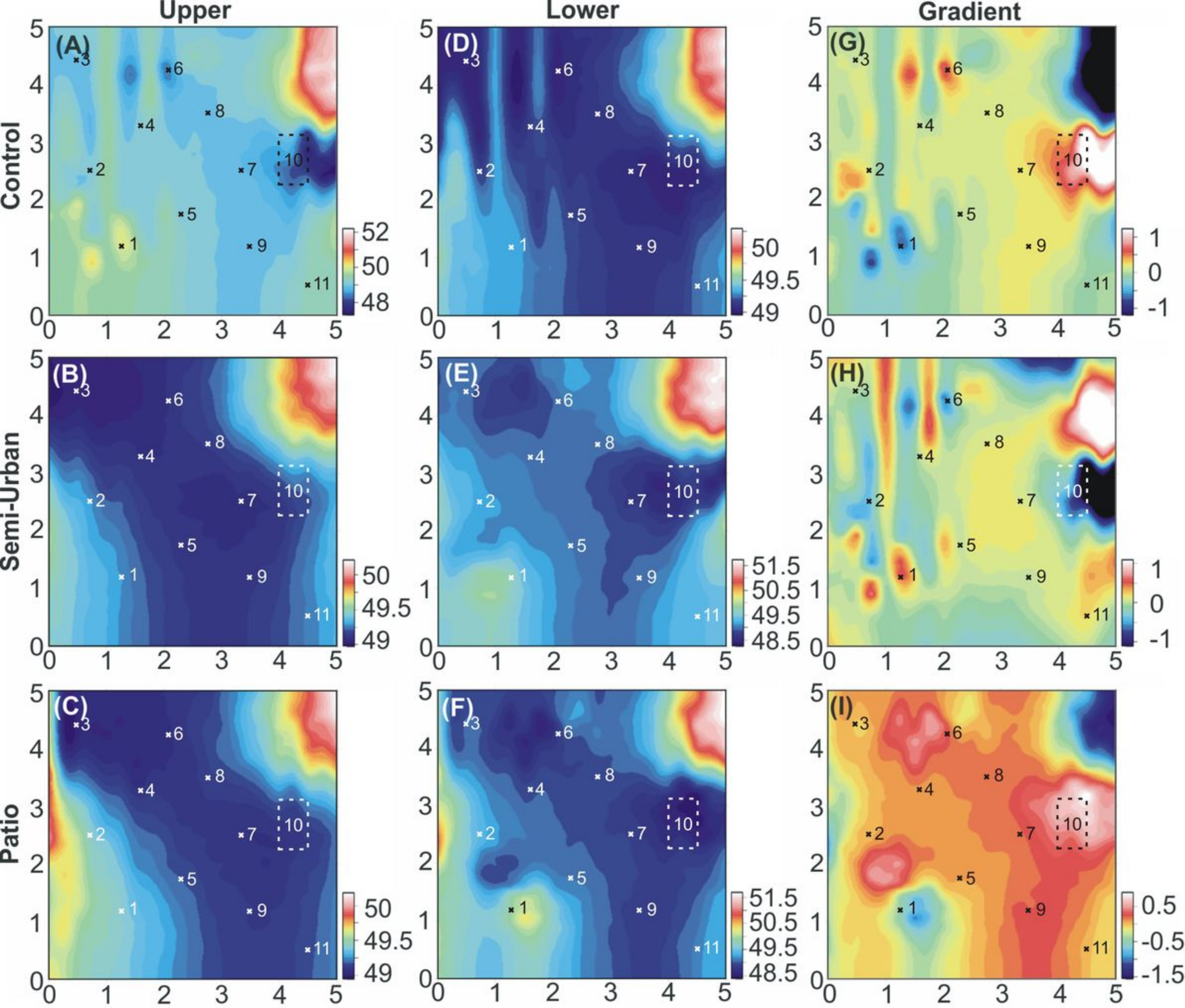


Magnetic Susceptibility surveys
Control
Semi-Urban
Patio
(A)
Knife (6) position
Magnetic susceptibility (S.I.)
Distance (m)
(B)
Grenade (8) position
Magnetic susceptibility (S.I.)
Distance (m)
(C)
Handgun (9) position
Magnetic susceptibility (S.I.)
Distance (m)
(D)
Ammunition box (10) position
Magnetic susceptibility (S.I.)
Distance (m)

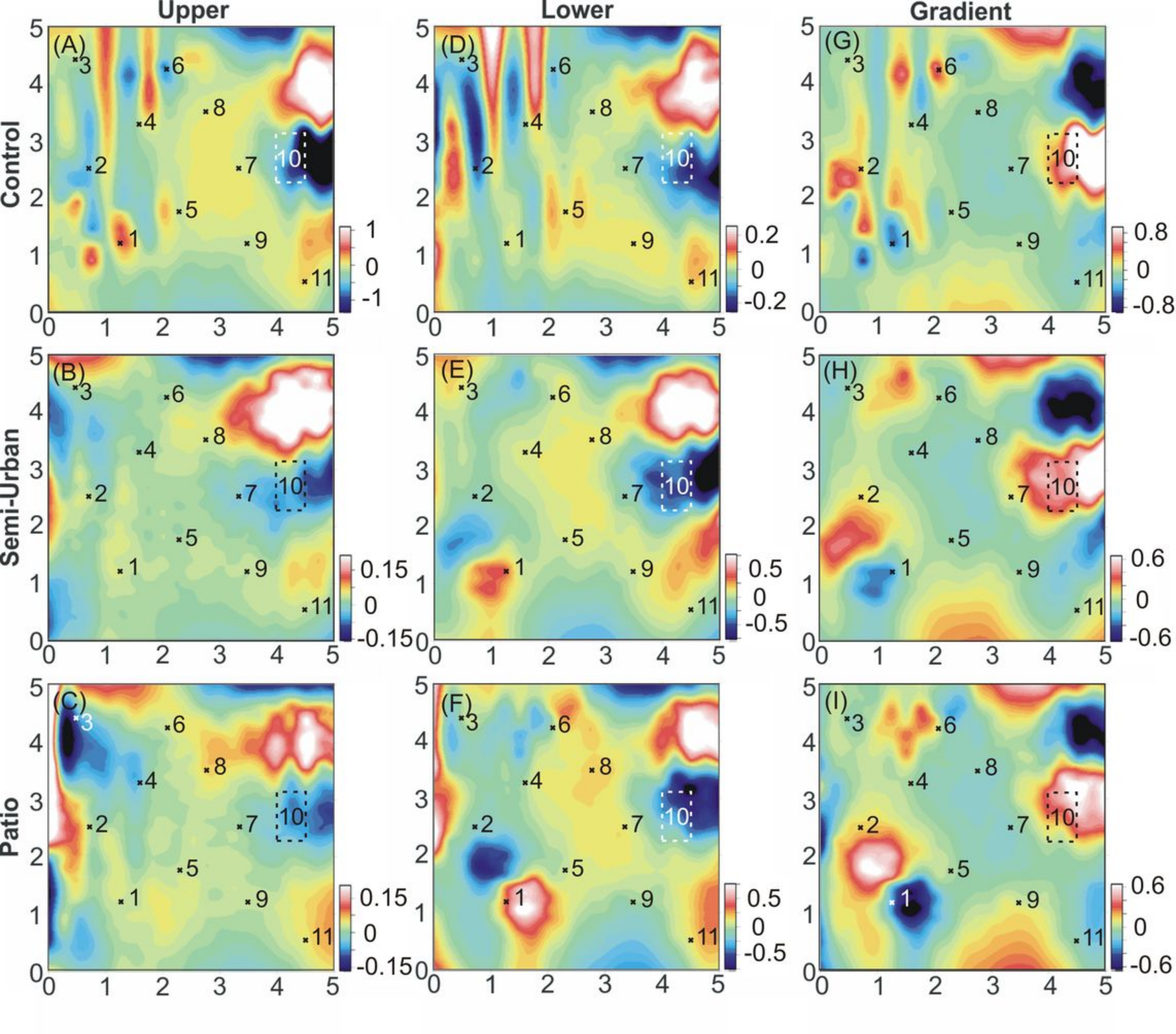

Control
(A)
Semi-Urban
(B)
Patio
(C)
0
1
2
3
4
5
1
2
3
4
5
6
7
8
9
10
11
400
200
0
-200
600
400
200
0
-200
-400
200
100
0
-100



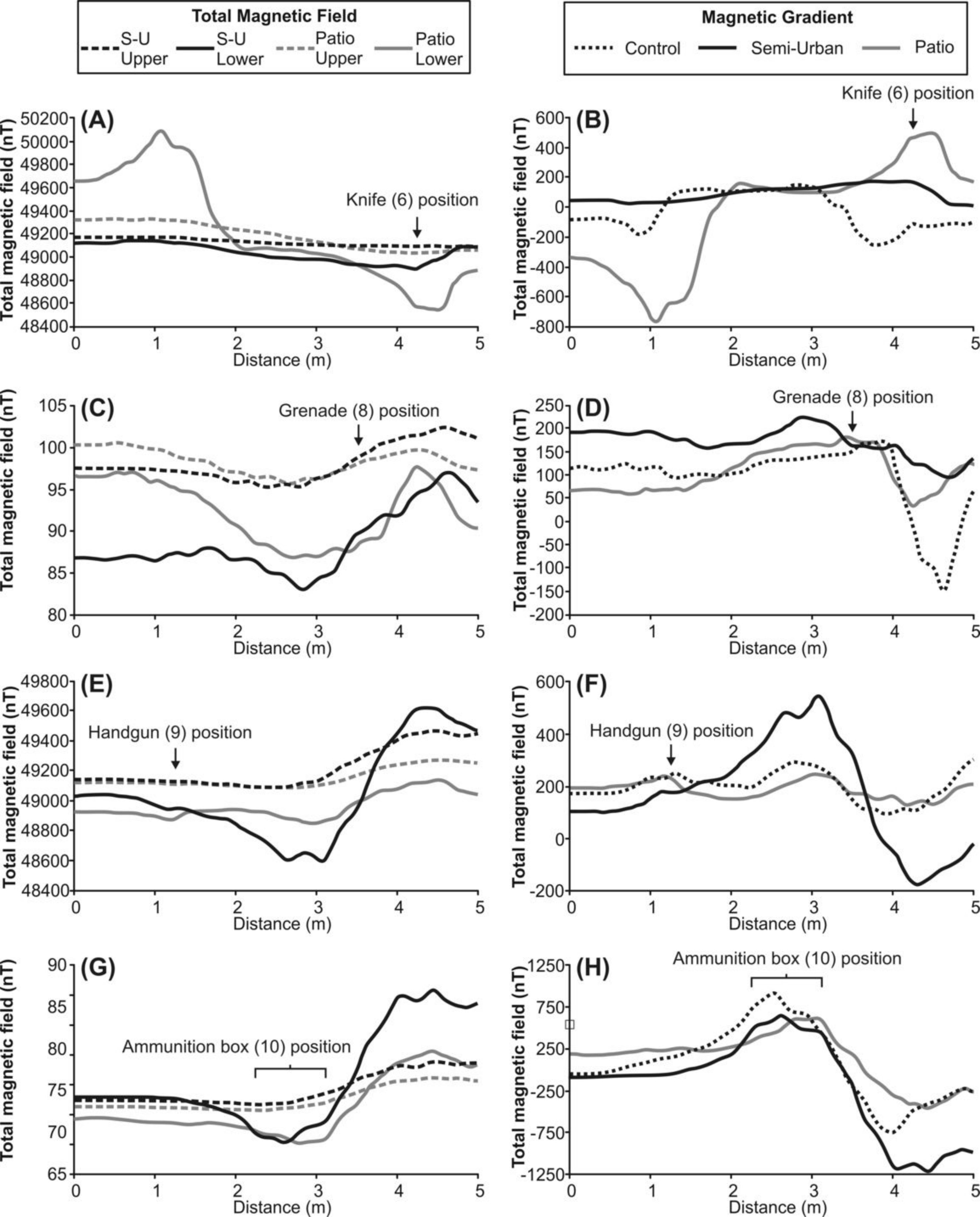
Fluxgate gradiometry surveys
Control
Semi-Urban
Patio
(A)
Knife (6) position
Fluxgate gradiometry (nT)
Distance (m)
(B)
Grenade (8) position
Fluxgate gradiometry (nT)
Distance (m)
(C)
Handgun (9) position
Fluxgate gradiometry (nT)
Distance (m)
(D)
Ammunition box (10) position
Fluxgate gradiometry (nT)
Distance (m)



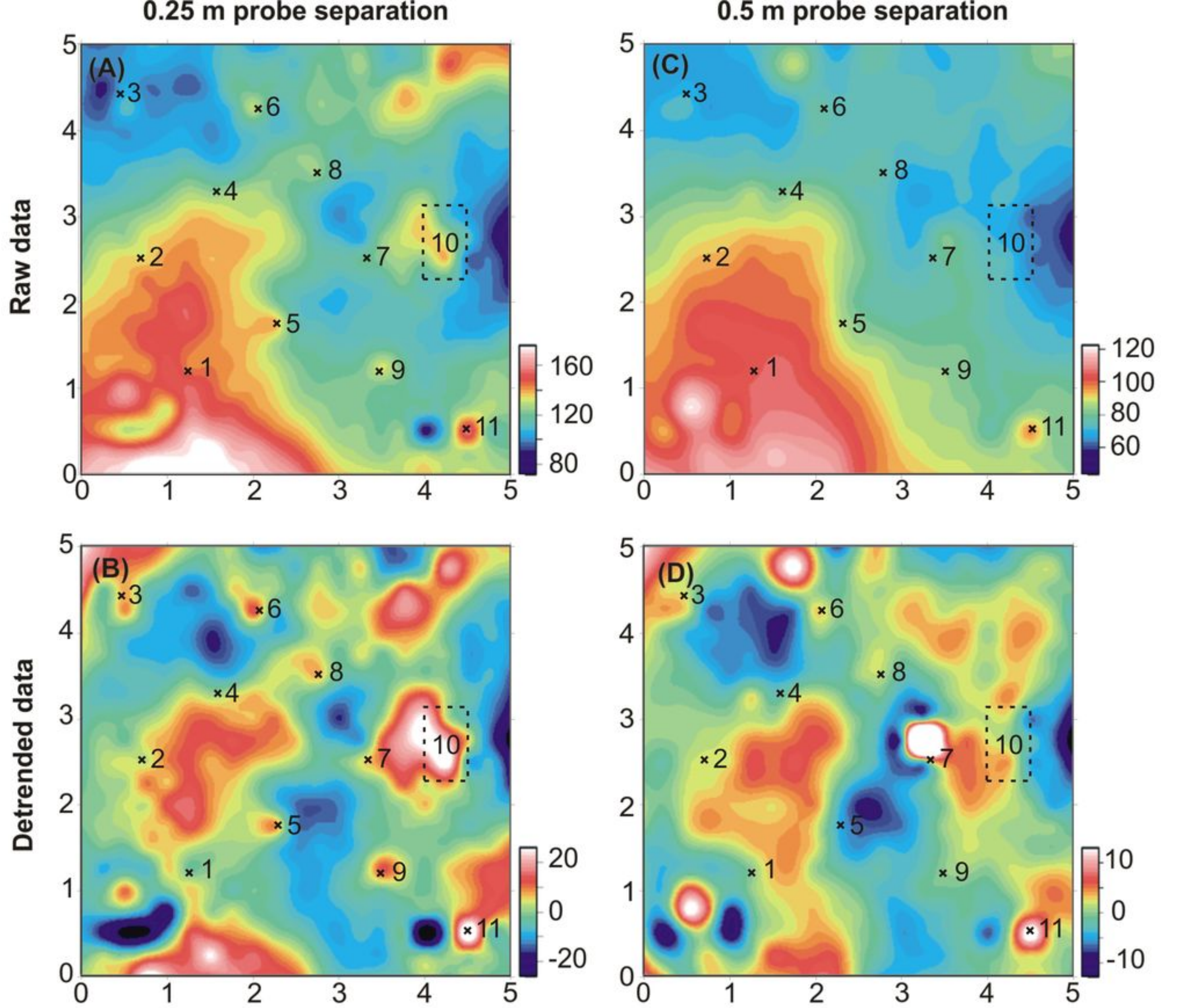
Upper
Lower
Gradient
Control
Semi-Urban
Patio
(A)
(B)
(C)
(D)
(E)
(F)
(G)
(H)
(I)



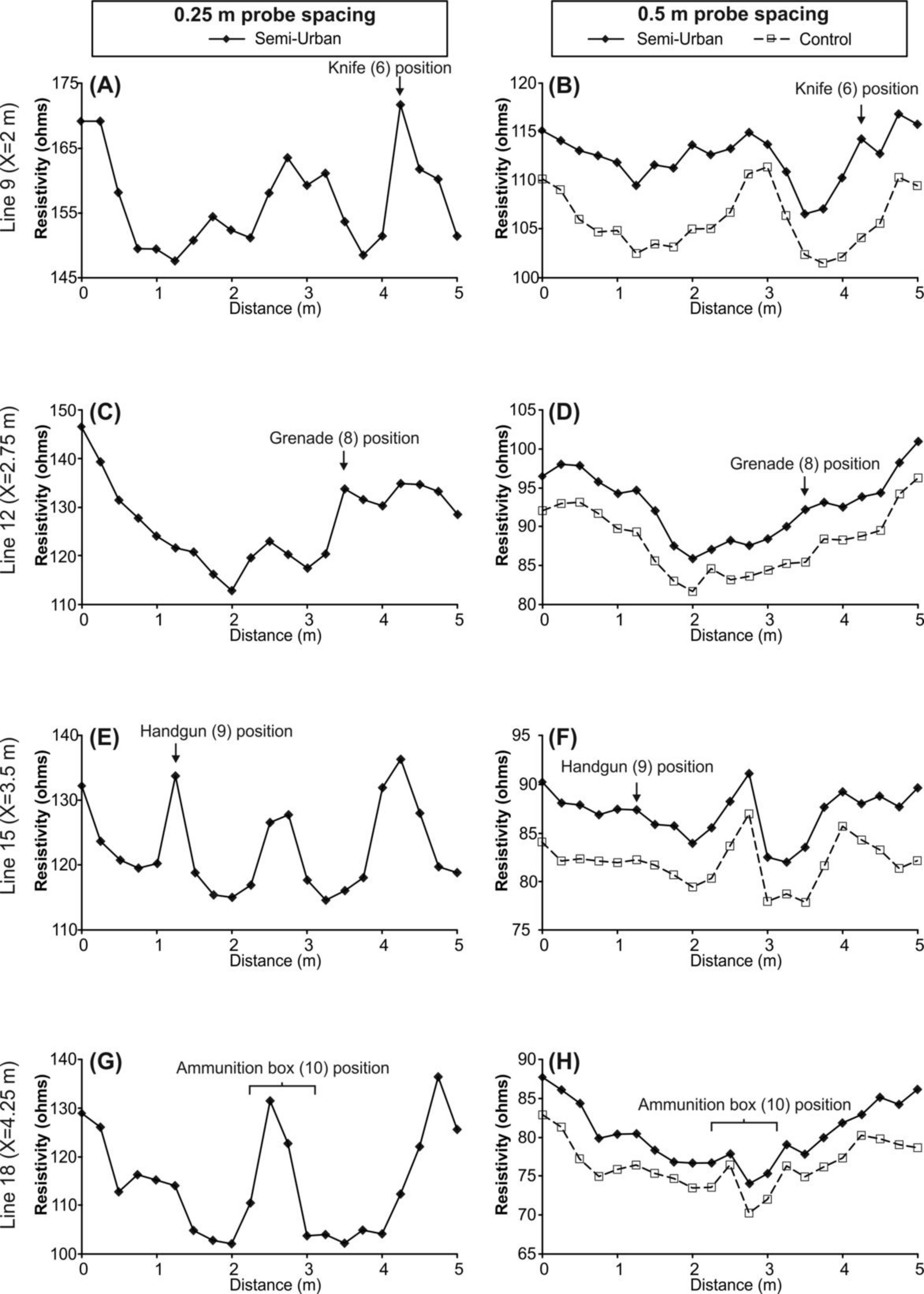
Upper
Lower
Gradient
Control
Semi-Urban
Patio
(A)
(B)
(C)
(D)
(E)
(F)
(G)
(H)
(I)
1
0
-1
0.2
0
-0.2
0.8
0
-0.8
0.15
0
-0.15
0.5
0
-0.5
0.6
0
-0.6

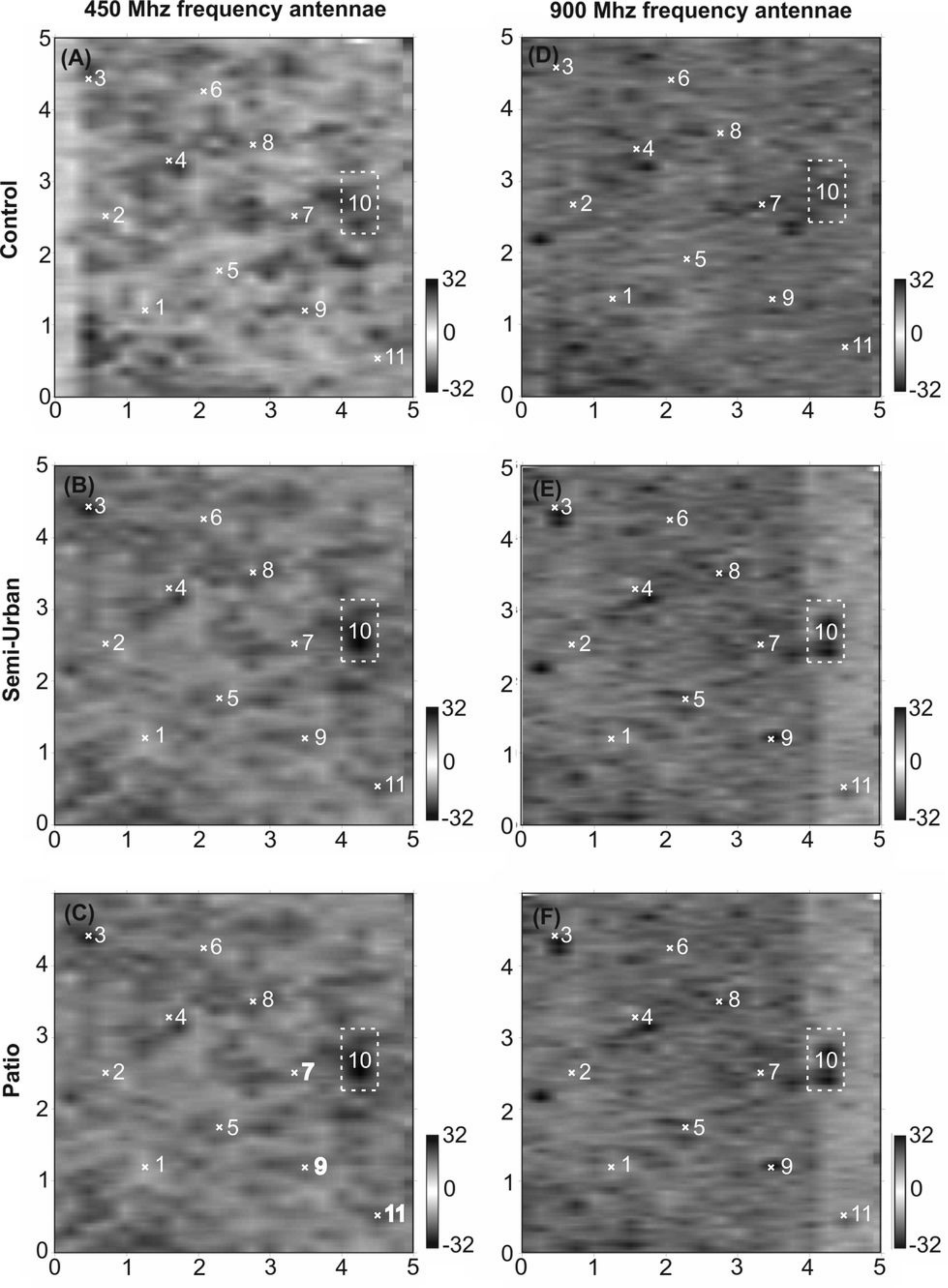


Total Magnetic Field
S-U Upper
S-U Lower
Patio Upper
Patio Lower
Magnetic Gradient
Control
Semi-Urban
Patio
(A)
Knife (6) position
(B)
Knife (6) position
(C)
Grenade (8) position
(D)
Grenade (8) position
(E)
Handgun (9) position
(F)
Handgun (9) position
(G)
Ammunition box (10) position
(H)
Ammunition box (10) position
Total magnetic field (nT)
Distance (m)

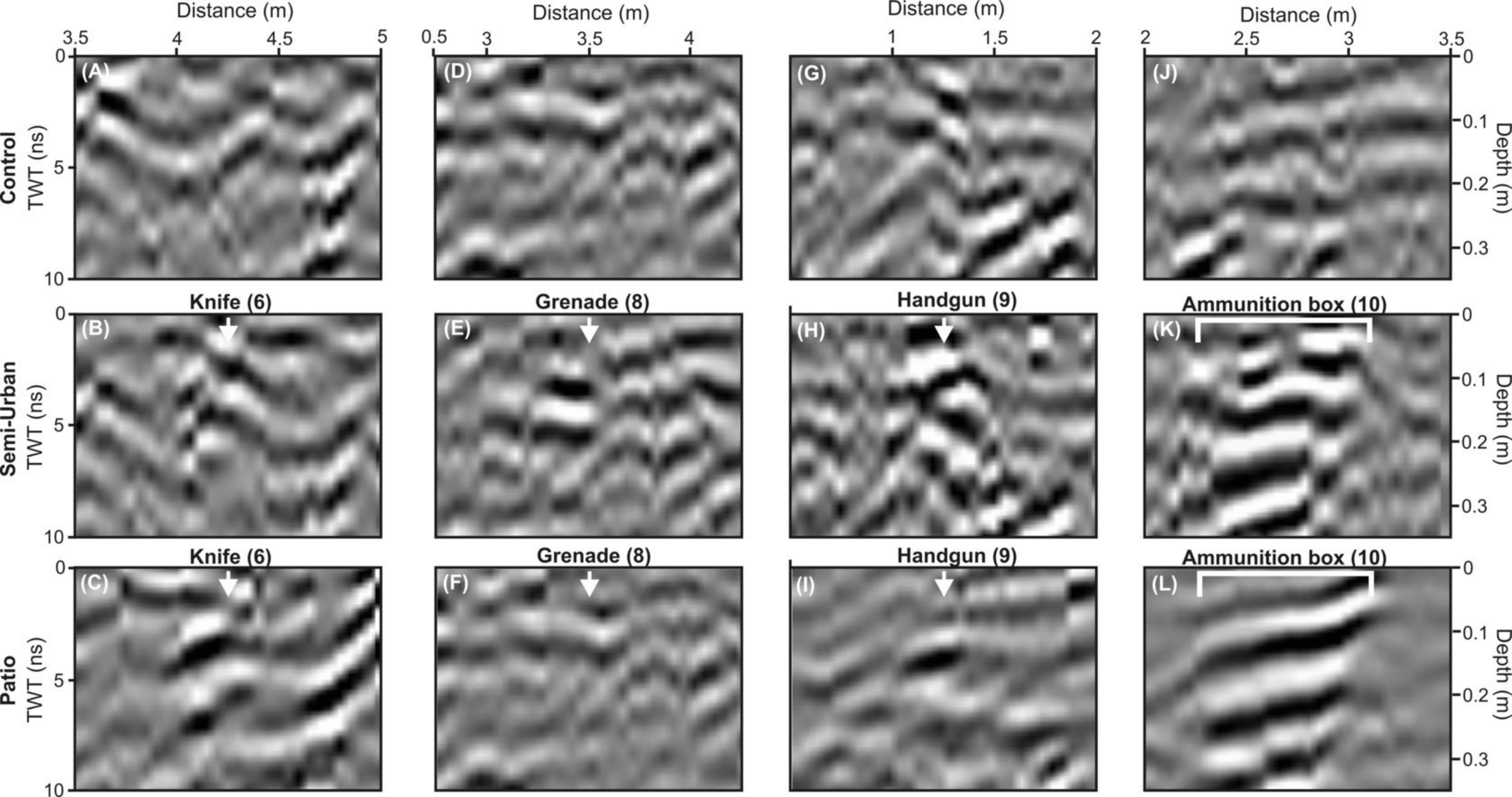


0.25 m probe separation
0.5 m probe separation
Raw data
Detrended data
(A)
(B)
(C)
(D)
1
2
3
4
5
6
7
8
9
10
11
160
140
120
100
80
60
20
0
-20
10
-10

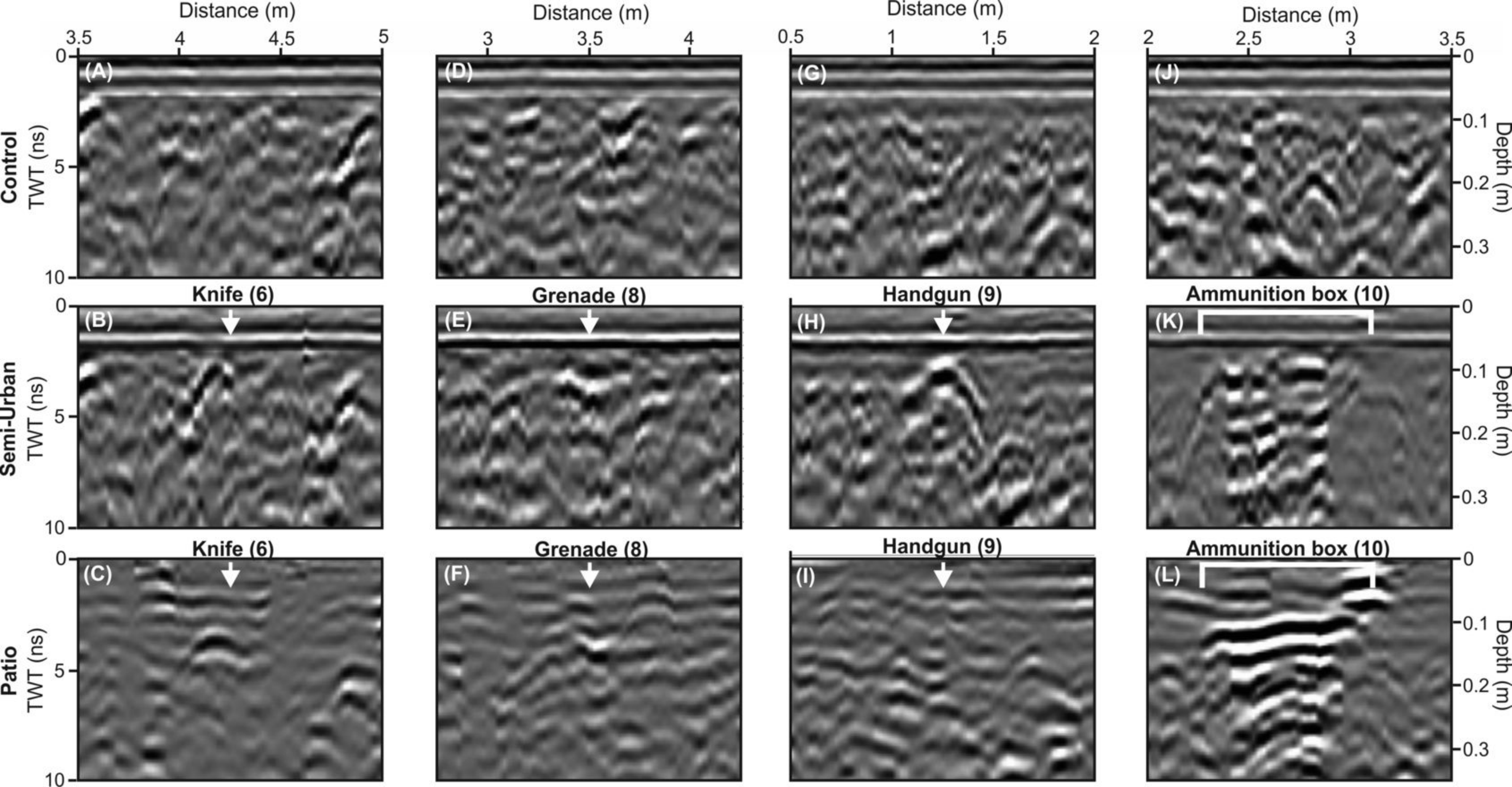

0.25 m probe spacing
Semi-Urban
0.5 m probe spacing
Semi-Urban
Control
Line 9 (X=2 m)
Line 12 (X=2.75 m)
Line 15 (X=3.5 m)
Line 18 (X=4.25 m)
(A)
Knife (6) position
(B)
Knife (6) position
(C)
Grenade (8) position
(D)
Grenade (8) position
(E)
Handgun (9) position
(F)
Handgun (9) position
(G)
Ammunition box (10) position
(H)
Ammunition box (10) position
Resistivity (ohms)
Distance (m)



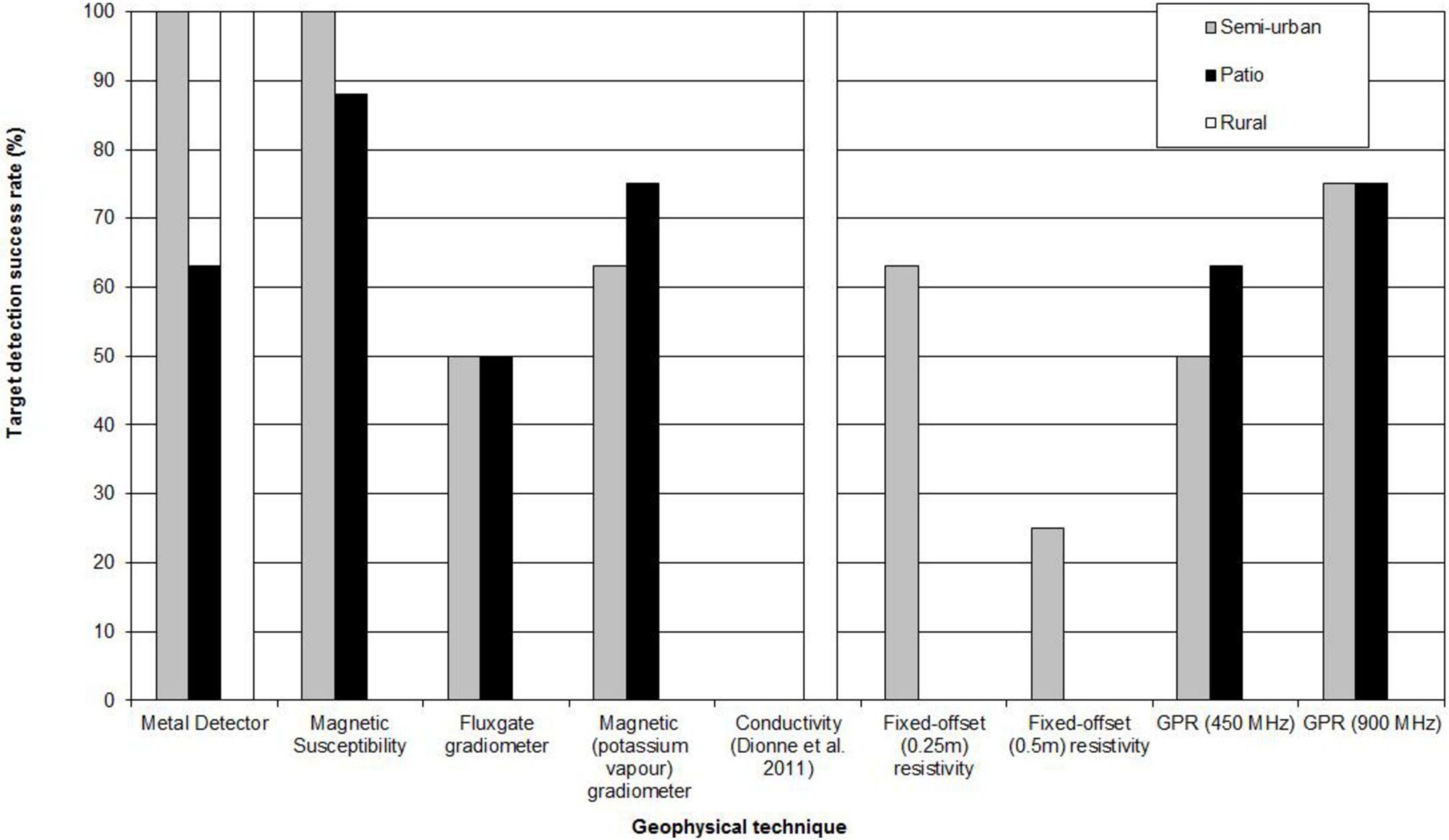
450 Mhz frequency antennae
900 Mhz frequency antennae
Control
Semi-Urban
Patio
(A)
(B)
(C)
(D)
(E)
(F)
1
2
3
4
5
6
7
8
9
10
11
32
0
-32



Distance (m)
3.5
4
4.5
5
0.5
3
3.5
4
1
1.5
2
2
2.5
3
3.5
0
5
10
0
0.1
0.2
0.3
Depth (m)
Control
TWT (ns)
(A)
(D)
(G)
(J)
Knife (6)
Grenade (8)
Handgun (9)
Ammunition box (10)
(B)
(E)
(H)
(K)
Semi-Urban
TWT (ns)
Patio
TWT (ns)
(C)
(F)
(I)
(L)



Distance (m)
3.5
4
4.5
5
3
3.5
4
0.5
1
1.5
2
2
2.5
3
3.5
Control
TWT (ns)
Semi-Urban
TWT (ns)
Patio
TWT (ns)
Depth (m)
0
5
10
0.1
0.2
0.3
(A)
(B)
(C)
(D)
(E)
(F)
(G)
(H)
(I)
(J)
(K)
(L)
Knife (6)
Grenade (8)
Handgun (9)
Ammunition box (10)



Target detection success rate (%)
100
90
80
70
60
50
40
30
20
10
0
Semi-urban
Patio
Rural
Metal Detector
Magnetic Susceptibility
Fluxgate gradiometer
Magnetic (potassium vapour) gradiometer
Conductivity (Dionne et al. 2011)
Fixed-offset (0.25m) resistivity
Fixed-offset (0.5m) resistivity
GPR (450 MHz)
GPR (900 MHz)
Geophysical technique

Geophysical technique	Survey date (& type)	Equipment setup time (mins.)	Data acquisition time (mins.)	Station spacing (m)	Instrument precision	Advantages / Disadvantages
Metal Detector (Bloodhound Tracker™ IV all-metal))	10-11-09 (C), 10-12-09 (S) & 25-02-10 (P)	1	30	N/A	Unknown	Easy to operate. Picks up all metallic objects. Limited penetration depth
Magnetic Susceptibility (Bartington™ MS.1 with 0.3m diameter probe)	10-11-09 (C), 10-12-09 (S) & 25-02-10 (P)	1	90	0.25	~1 S.I.	Easy to operate. Limited to ~8cm bgl.
Fluxgate gradiometer (Geonics™ FM15)	10-11-09 (C), 10-12-	60	45	0.25	0.1 nT	Can detect subtle targets. Difficult to

	09 (S) & 25-02-10 (P)					calibrate & needs careful acquisition.
Magnetic gradiometer (GSMP-40™ K+ vapour, two sensors 1 m vertical separation)	10-11-09 (C), 10-12-09 (S) & 22-03-10 (P)	60	30	~0.05 (collected at 0.05 s)	0.01 nT	Small sample spacing, collects both total field & gradient data. Expensive.
Ground Penetrating Radar (PulseEKKO™ 1000) using 450 MHz antennae	02-11-09 (C), 10-12-09 (S) & 25-02-10 (P)	30	60	0.05	~0.1 m	Resolves fairly small objects & depth to target(s).
Ground Penetrating Radar (PulseEKKO™ 1000) using 900 MHz	02-11-09 (C), 10-12-09 (S) & 25-	30	90	0.025	~0.05 m	Resolves small objects & depth to target(s). Slow to

antennae	02-10 (P)					collect.
Bulk ground resistivity (Geoscan™ RM15-D) using 0.5m spaced probes	29-10-09 (C) & 10-12-09 (S)	10	45	0.5	~0.25 m	Relatively quick to collect. Will detect objects up to 1 m bgl. Not usable on patios.
Bulk ground resistivity (Geoscan™ RM15-D) using 0.5m spaced probes	29-10-09 (C) & 10-12-09 (S)	10	60	0.25	~0.125 m	Will detect objects up to 0.5 m bgl. Not usable on patios.

TABLE 1. Summary statistics of geophysical data collected during this 5 m by 5 m study area. Survey types are: (C) Control, (S) Semi-urban and (P) Patio environments respectively. Bgl = below ground level. Survey line spacings were 0.25 m unless otherwise stated.

Number	Forensic Buried Object	Size (m)	Description
1	Brick	0.17 x 0.11	Clay house-brick, orientated horizontally
2	Bolt and screw	0.08 x 0.05	Unknown metal alloy
3	Steel plate	0.2 x 0.2 x 0.05	Stainless steel, flat, square plate, orientated horizontally.
4	Breadknives (Fig. 2b)	0.3 x 0.05	Two domestic stainless steel kitchen bread knives wrapped in thin plastic bag. Orientated N-S.
5	Spade (Fig. 2e)	Handle: 0.4 x 0.07 Head: 0.32	1943 allied wooden-handled entrenchment tool with metallic head, orientated NW-SE.
6	Knife (Fig. 2b)	0.3	One domestic stainless steel kitchen bread knife, orientated E-W.
7	WWII Grenade (Fig. 2d)	0.08 diameter	World War 2 allied decommissioned metallic hand grenade, orientated vertically.
8	WWI Grenade (Fig. 2d)	0.08 diameter	1915 No. 5 Mk 1 allied decommissioned metallic hand grenade, orientated vertically.
9	Handgun (Fig. 2a)	0.18 x 0.14	Colt Government Cup Replica .45 calibre automatic replica handgun with solid brass ammunition. Most likely zinc alloy with stainless steel finish. Wrapped in thin plastic bag & orientated E-W.
10	Mortar shell (Fig. 2c)	0.37 x 0.17	Brass spent mortar shell: 1943, 75mm M18, orientated E-W.
11	Ammunition box (Fig. 2f)	0.55 x 0.4 x 0.45	UK mortar ammunition metallic box containing 2 small WW2 spent mortar shells (Fig. 2c), orientated N-S.

TABLE 2. Description of buried forensic objects used in this study and their known properties

(captions show photographs in Fig. 2). Object numbers refer to those shown in Fig. 3 and in geophysical datasets.